Airborne determination of the temporo-spatial distribution of benzene, toluene, nitrogen oxides and ozone in the boundary layer across Greater London, UK

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Abstract

Highly spatially resolved mixing ratios of benzene and toluene, nitrogen oxides (NO_x) and ozone (O_3) were measured in the atmospheric boundary layer above Greater London during the period 24th June to 9th July 2013 using a Dornier 228 aircraft. Toluene and benzene were determined in-situ using a proton transfer reaction mass spectrometer (PTR-MS), NO_x by dual channel NOx chemiluminescence and O_3 mixing ratios by UV absorption.

Average mixing ratios observed over inner London at 360±10 m a.g.l. were 0.20±0.05, 0.28±0.07, 13.2±8.6, 21.0±7.3 and 34.3±15.2 ppbv for benzene, toluene, NO, NO_2 and NO_x respectively. Linear regression analysis between NO_2, benzene and toluene mixing ratios yield a strong covariance indicating that these compounds predominantly share the same or co-located sources within the city~~ and that a significant fraction of NO_x is directly emitted as NO_2.~~

Average mixing ratios measured at 360±10 m a.g.l. over outer London were always lower than over inner London. Where traffic densities were highest, the toluene/benzene (T/B) concentration ratios were highest (average of 1.8 ± 0.~~3~~5 ppbv ppbv^{-1}) indicative of strong local sources. Daytime maxima in NO_x, benzene and toluene mixing ratios were observed in the morning (~ 40 ppbv NO_x, ~350 pptv toluene and ~200 pptv benzene) and for ozone in the mid-afternoon (~ 40 ppbv O_3) all at 360±10 m a.g.l.

1 Introduction

Ground level ozone (O_3) is a secondary pollutant, produced from photochemical reactions involving volatile organic compounds (VOCs) and nitrogen oxides ($NO_x = NO + NO_2$). Ozone has significant detrimental effects on human health and vegetation while NO_2 and some VOCs also have, themselves, direct effects on health. Whilst the basic atmospheric chemistry leading to O_3 formation is generally well understood, there are substantial uncertainties associated with the magnitude and speciation of emissions of both VOCs and NO_x from urban areas, leading to uncertainties in the detailed understanding of urban photochemistry and air pollution.

In urban areas the dominant anthropogenic sources of VOCs are vehicular exhaust, fuel evaporation and emissions from the commercial and industrial use of solvents (Karl et al., 2009;Langford et al., 2010). Vehicular emissions are the predominant source of VOCs to the atmosphere in urban and suburban areas, accounting for > 50% of the total (Watson et al., 2001;Na et al., 2005;Kansal, 2009) with a wide range of VOCs emitted directly due to fuel evaporation and from vehicular exhaust as unburnt fuel and as partially oxidized fuel components. The dominant urban sources of NO_x are combustion processes, including vehicles. In the UK as a whole, about 50% of NO_x is thought to be derived from vehicles, although this percentage is larger in urban areas (Lee et al., 2015).

VOC and NO_x emissions from airports are also of importance, originating due to a combination of emissions from aircraft exhaust, ground support equipment (GSE) exhaust and evaporative losses during aircraft refuelling (Carslaw et al., 2006). High mixing ratios of aromatic compounds, such as toluene and benzene, and low NO_x mixing ratios have been previously observed in jet engine exhaust immediately after ignition, attributed to low engine temperature causing incomplete combustion (Schürmann et al., 2007). Previous aircraft exhaust studies have shown toluene/benzene (T/B) ratios observed during engine ignition are up to 3.1 ppbv ppbv^{-1}, typical of kerosene fuel. At higher engine temperatures, i.e. during taxiing, higher aromatics tend to crack leading to a reduced amount of these species, but increasing amounts of benzene. Thus for aircraft taxiing, a T/B ratio of ~0.5 ppbv ppbv^{-1} was previously observed (Spicer et al, 1985). Similarly higher NO_x mixing ratios are observed due to higher engine combustion. As well as the contribution from aircraft, additional emissions from airport environments occur during the handling of aircraft with GSE. The GSE vehicles are mostly diesel powered, leading to relatively high emission rates of the oxides of nitrogen. During aircraft refuelling, gaseous air-fuel mixtures are released from the aircraft tanks through fuel vents which can be discriminated by the observed T/B ratio, since kerosene fuel tends to have an enhanced amount of aromatic compounds. VOC emissions during engine refuelling were previously found to account for 2.7% of the total VOC emissions of Zurich airport (Schürmann et al., 2007).

~~In the UK, spatially disaggregated NO_x and VOC emission rates are estimated by the National Atmospheric Emission Inventory (NAEI), which provides emission estimates for specific pollutants by source sector at 1 km^2 resolution. Uncertainties in these emission estimates propagate through into uncertainties in models of air quality, and leads to uncertainties in the likely effectiveness of control policies on both background and peak VOCs, O_3 and NO_2 mixing ratios in the UK. There are therefore considerable economic and societal pressures to ensure the precision and accuracy of these emissions estimates.~~

~~Validation of the NAEI emission estimates is provided, indirectly and in part,~~ Background and peak UK VOCs, O_3 and NO_2 mixing ~~ratios by the continuous hourly data of VOC and NO_x mixing ratios measured in the~~ are determined hourly by the national monitoring networks such as the Automatic Hydrocarbon Network (AHN) and the Automatic Urban and Rural Network (AURN), both operated by the Department of Environment, Food and Rural Affairs). Hourly mixing ratios of NO_x species are currently measured at 130 network sites with selected VOCs measured at 4 sites. Within Greater London these sites form part of the London Air Quality Network (LAQN). However, measurements from these networks suffer from the limitations of being made at relatively few sites and so may not be representative of mixing ratios over larger spatial scales.

The development of fast-response analytical instruments for NO_x and VOCs means that the mixing ratios of these analytes can now be measured at high spatial resolution from low-flying aircraft. The advantages of in-situ aircraft measurements are that they provide information on the horizontal and vertical distributions of air pollutants over a large spatial area allowing continuous gradients of mixing ratios to be observed across cities and their surrounding rural areas.

In this study, we investigate the mixing ratios of O_3, benzene, toluene, NO, NO_2 and NO_x across the Greater London region during several flights using the Natural Environment Research Council (NERC) Atmospheric Research and Survey Facility Dornier 228 aircraft between 24th June and 9th July 2013. The aim of this work was to (i) quantitatively determine the vertical, horizontal spatial and temporal distribution of VOCs, NO_x and ozone mixing ratios across London from an airborne platform, with a view to identify dominant emission sources in the region using measured ~~toluene to benzene~~ T/B concentration ratios and (ii) wherever possible, compare these fast response airborne measurements with hourly ground-level measurements made by the national monitoring networks.

2 Method

2.1 NERC Dornier 228

The NERC Dornier 228 is a twin-engine turbo-prop powered, non-pressurised aircraft operated by the Airborne Research and Survey Facility (ARSF) based at Gloucester airport in central England. The aircraft has a cabin volume of 14 m^3 and operated with a crew of 2 pilots and 4 scientists for the duration of the flights. The aircraft has a minimum and maximum airspeed of 65 and 95 m/s respectively producing a maximum range of 2400 km~~(5 hours at 500kg).~~ The aircraft has a maximum payload of 5970 kg including fuel, with a maximum operational altitude for science of 4500 m.

2.2 Flight description

~~Eleven Six~~ research flights (RF) totalling 15 hours in duration were conducted between the hours of 8:30 – 17:20 UTC (table 1). Figure 1a shows all flight legs conducted during the project, overlaid on a transport map of SE England. Here we will focus on data obtained in transects across London~~ (~27 hours of research flights).~~ Figure 1b shows a map of Greater London on which typical repeated south-westerly to north-easterly flight legs of ~50 km are plotted. Identical flight legs across Greater London were chosen due to tight air traffic regulations and to allow data analysis in both a temporal and spatial domain. The grey area represents the Greater London boundary, the black area the inner London boundary and the blue area London's congestion charging zone (CCZ) in which road traffic is heavily regulated and subject to financial charging. Airspeed and altitude were fixed during the flights across Greater London with mean values of 73±3 m s^{-1} and 360±10 m a.g.l respectively (table 1).

A north-westerly wind direction was observed during the flights, perpendicular to the flight transects (table 1). Perpendicular wind directions are useful in providing a cross section of pollutant mixing ratios across London. RF 1 focussed on vertically profiling the PBL above London. Boundary layer (BL) height determinations were made from a combination of airborne observations and ground based measurements. Approximately hourly lower cloud base altitude determinations were made from Heathrow airport using laser cloud based recorder (LCBR) observations. The lowest observed cloud base was interpreted as BL height. Where cloud based observations were not available (during clear skies), temporally interpolated BL height determinations from aircraft observations were used. Briefly, before commencing the city transects, a spiral descent from 2500 to 350 m a.g.l was performed 70 km south of London (position BL 1, figure 1b). Similarly, immediately after completing the city transects, a spiral ascent from 350 to 2500 m was performed directly north of London (position BL 2, figure 1b). These manoeuvres were performed to determine the height of the BL before and after the flights.

2.3 Meteorological and GPS sampling

Core equipment on the aircraft consisted of an Aircraft Integrated Meteorological Measurement System (AIMMS-20) turbulence probe (Aventech Research Inc.) mounted in an underwing PMS type pylon. The instrument is capable of precisely defining the aircraft altitude and velocity to within fractions of one metre per second with a temperature and humidity measurement precision of approximately 1%. This information is combined with fully compensated air-data measurements to compute wind speed with an accuracy of 0.5 knot and wind direction accuracy of 5 – 10 degrees (Beswick et al., 2008). The 3D position of the aircraft was measured using an IPAS 20 (Leica) inertial position and altitude system at an accuracy of 0.05 – 0.3 metres. All variables were acquired at a data acquisition rate of 20 Hz.

2.4 NO_x sampling

NO_x was measured from the aircraft using a fast time resolution (10Hz), high sensitivity NO_x chemiluminescence system built by Air Quality Design, Inc. The instrument has a dual channel architecture for independent quantification of NO and NO_2. Each channel has a sample flow of 1.5 L min^{-1} to ensure the required fast response time. Both sample flows are continually humidified to ensure that any changes in ambient humidity do not change the instrument sensitivity due to quenching of the chemiluminescence by water vapour. A detailed review of a similar system was described by (Lee et al., 2009), being a single channel instrument which operates using the same principles at the Cape Verde Atmospheric Observatory. NO_2 was quantified in a second channel by photolytic conversion to NO using blue light LED diodes centred at 395nm. The 395nm wavelength has a specific affinity for NO_2 photolytic conversion to NO, giving high analyte selectivity within the channel. Recent work (Pollack et al., 2010) evaluated the relative high NO_2 affinity for conversion of NO_2 to NO using 395nm blue light LED's. They highlighted the low probability of other species within the gaseous chemical matrices such as nitrous acid (HONO), being affected by the 395nm light, so in turn reducing possible non NO_2 species interfering with the measurement. NO_x was then quantified by ozonation of the subsequent total NO present in the reaction vessel after conversion with NO_2 derived from the difference between NO_x and NO mixing ratios.

The instrument was calibrated by adding a small flow (5 sccm) of a known NO concentration (5 ppmv – Air Liquide) in the ambient sample flow, resulting in around 10ppbv of NO. The conversion efficiency of the NO_2 converter was measured during each calibration by gas phase titration of the NO to NO_2 by addition of O_3. NO_2 mixing ratio data is corrected for using the measured 90% photolytic conversion efficiency. In flight calibrations were always carried out above the boundary layer, thus ensuring low and stable background levels of NO_x. Typically calibrations are carried out at the beginning and end of a flight, with sensitivities and conversion efficiency interpolated between the two and applied to all data. In this work, the 10Hz data has been averaged to 1Hz, with detection limits for the 1Hz data ~~were~~ being ~75pptv for NO and 100pptv for NO_2 with approximate total errors at 1ppbv being 10 and 15% for NO and NO_2 respectively.

2.5 Ozone sampling

Ozone was quantified in-situ, using a Thermo Scientific 49i UV absorption instrument generating data every 4 seconds. A mercury lamp emitting UV light was used, with absorption at 254 nm being proportional to O_3 concentration. The measurement uncertainty was estimated to be ±0.8 ppbv.

2.6 VOC sampling

Benzene and toluene mixing ratios were determined simultaneously using an Ionicon (Innsbruck, Austria) high sensitivity proton transfer reaction mass spectrometer (PTR-MS) fitted with a stainless steel ringed drift tube (9.6 cm) and three Pfieffer turbo-molecular pumps. This instrument has been described in detail elsewhere (Karl et al., 2009;de Gouw and Warneke, 2007;Hewitt et al., 2003;Hayward et al., 2002). Therefore only instrument setup, operation and flight modifications are outlined here. The instrument, normally housed in one cabinet, had been re-engineered by the manufacturers into two racks suitable for mounting into the aircraft. To mitigate shock and vibration to the PTR-MS during flight, the instrument racks, mass spectrometer and MD4 diaphragm pump were individually shock mounted using stainless steel spring mountings (vibrachoc). A pressure controller was added (Bronkhorst) which regulates the inlet flow (50-500 ~~STP~~ sccm), such that pressure upstream of the controller is maintained at a constant value. As a result the PTR-MS drift tube pressure is independent of fluctuations in ambient pressure caused by varying flight altitude. Ambient sample air was only exposed to heated (70°C) Teflon and stainless steel tubing, minimizing memory effects, inlet losses and the build-up of impurities in the inlet system. Considerable efforts were made to prevent VOC contamination of the PTR-MS inlet during operation on the ground and during take-off. On the ground the PTR-MS inlet remained closed (and all sample tubing capped). Approximately 3 hours before each flight the instrument voltages were switched on to allow for primary ion count stabilisation and instrument calibration. During this time dry zero grade air (BOC) was purged through the zero air generator and PTR-MS inlet in series to minimise instrument background and to prevent the build-up of contaminants. Immediately prior to take off, the sample flow was instantaneously switched to dry zero grade air contained in a 1L silica coated stainless-steel can (Thames Restek, UK) within the aircraft, which was then continuously sampled until the aircraft had reached an altitude of 2500m, allowing the PTR-MS to be fully operational during take-off.

VOC measurements were obtained at a sampling rate of 5 Hz and a repetition rate of ~2 Hz. In this work, the 2Hz mixing ratios data has been averaged to 1Hz for analysis. The target protonated masses and likely contributing compounds were *m/z* 79 (benzene) and *m/z* 93 (toluene). Additionally, both the primary ion count *m/z* 21 ($H_3{}^{18}O^+$), its first water cluster ($H_3{}^{18}O\ H_2{}^{18}O^+$) at *m/z* 39 and $O_2{}^+$ at *m/z* 32 were determined. PTR-MS drift tube pressure, temperature and voltage were held constant at 2.0 mbar, 40°C and 480 V respectively, maintaining an E/N ratio of approximately 110 Td. For flights at ~360 m a.g.l, the *m/z* 21 primary ion count ranged between (4 – 7) x 10^7 ion counts per second (cps) with an average of 6 x 10^7. Ion counts of *m/z* 32 ranged between (0.8 – 3) x 10^6 cps, with an average of 2 x 10^6 cps, which represented 3% of the primary ion signal. Ion counts of *m/z* 39 ranged between (1 – 5) x 10^6 cps with an average of 3 x 10^6 cps, which represented 6% of the primary ion signal.

Toluene and benzene calibrations were carried out approximately 2 hours prior to each flight using an in-house built dynamic dilution calibration system. This involved the dynamic dilution of a 500 ppbv certified gas standard (Apel, Riemer) with humidity controlled zero grade air (BOC gases) to mixing ratios near typically observed levels. Zero air humidity was calibrated over 20 -80% RH in triplicate to assess humidity effects on sensitivity during the campaign. Benzene and toluene, do not react with the hydrated hydronium ions generated at higher ambient air humidity within the PTRMS drift tube(Warneke et al., 2001). To account for this humidity dependent PTRMS sensitivity toward benzene and toluene, these compounds were normalised against the hydronium ion counts only. Typical instrument sensitivities observed during the campaign ranged between 380 – 480 icps ppbv^{-1}, 6 – 8 normalised ion counts per second (ncps), and 400 – 600 icps ppbv^{-1}, 6 – 9 ncps, for benzene and toluene respectively. Instrument uncertainties were 16±5 and 21±9 % for benzene and toluene respectively, calculated using the standard deviation of linear regression (Sm) of pre-flight calibrations. Instrument limits of detection (LoDs) for 1Hz averaged data were determined by the method outlined by Taipale and colleagues (Taipale et al., 2008) and were 13±8 and 18±11pptv for benzene and toluene respectively.

During flights, ambient air was sampled from the forward facing stainless steel isokinetic inlet along a heated (70°C) 5 m ¼” Teflon tube (0.21” ID) pumped by a stainless steel diaphragm pump (Millipore) at a flow-rate of 22L min^{-1}. A portion of this ambient air (~300 sccm) was diverted into the pressure controlled inlet of the PTR-MS instrument such that the overall delay time was < 3 s. To determine blank VOC mixing ratios, the remaining ambient air was purged into a custom built zero air generator which consisted of a 3/8” stainless steel tube packed with 1g of platinum coated quartz wool (Elemental Microanalysis) which efficiently removes VOCs (de Gouw et al., 2004). The zero air generator was operated at 350°C and 30 psi for the duration of the flights to maintain optimal operating conditions. . The catalytic converter does not remove water vapour from the sample stream, which is of particular importance as the instrument response from background impurities may depend upon sample air humidity. ~~The catalytic converter does not remove water vapour from the sample stream, which is of particular importance as background impurities may depend upon sample air humidity.~~ During flights, zero air was periodically back-flushed through the inlet system to determine instrument background.

2.7 LAQN ground monitoring sites

Data were obtained from three LAQN ground level monitoring sites for comparative purposes. These were:

(i) Marylebone Road (Westminster), an urban kerbside site in a street canyon, situated 1.5 m from the kerb of a frequently congested 6 lane road, the A501 (51.5225°N, 0.1546°W).

(ii) Horseferry Road (Westminster), an urban background monitoring station located within an area of mixed commercial and residential buildings (51.4947°N, 0.1319°W). The nearest road is the B323 Horseferry Road approximately 17 m north of the station.

(iii) Greenwich-Eltham (Eltham), a suburban background site situated in Greenwich within an education centre (51.4526°N, 0.0708°E). The site is approximately 25 m from the nearest road, the A210 Bexley Road. The surrounding area consists of trees, grassland, recreational areas and suburban housing.

These sites all monitor NO, NO_2 and NO_x at hourly resolution and O_3 at 15 minute resolution. However, only the Westminster-Marylebone Road and Greenwich-Eltham monitoring sites monitor benzene and toluene at hourly resolution. The locations are shown in figure S-1.

3 Results

3.1 Intercomparison of WAS TD-GCFID and PTR-MS

To compare the volume mixing ratios obtained with the on-board PTR-MS with those measured by gas chromatography with flame ionisation detection (GC-FID), whole air canister sampling (WAS) was conducted twice per flight using silica coated stainless steel cans (Thames Restek, UK) with subsequent GC-FID analysis for benzene and toluene (Hopkins et al., 2009;Hopkins et al., 2003). The WAS system avoids possible artefact formation or analyte loss that may occur on adsorbents if a pre-concentration sampling system is used (Cao and Hewitt, 1993, 1994a, b). Previous ground observations in several urban environments have shown generally good agreement between benzene and toluene mixing ratios obtained during PTR-MS and GC-FID intercomparisons (Rogers et al., 2006;Warneke et al., 2001). However (Jobson et al., 2010) suggest a 16% overestimation of benzene mixing ratios determined by PTR-MS compared to a GC method, attributed to the fragmentation of higher alkyl-benzenes (eg ethyl-benzene). Inter-comparison of the two sampling methods showed excellent agreement within uncertainty and in particular suggest that the PTR-MS demonstrated minimal bias due to the fragmentation of higher alkyl benzenes during this study, as shown figure S-2. Hence the PTR-MS signal obtained at m/z 79 is assumed to be due to benzene alone.

3.2 Interpretation of temporal trace gas profiles

Mixing ratios of VOCs, NO_x, O_3 and NO/NO_2 ratios from 27 individual flight-transects of Greater London during RF 2 – 6 were averaged to assess how they changed with respect to time over the 7 days of flights, table 2. As shown in figure 2, NO_x, benzene and toluene mixing ratios followed the typical diurnal pattern previously observed in urban areas with measured maxima during morning rush hours and a measured minimum at approximately 16:00 – 18:00 when O_3 reaches its maximum (Langford et al., 2010;Marr et al., 2013). The highest NO_x and VOC mixing ratios were observed in the morning at 10:30 local time, ~ 40 ppbv NO_x, ~350 pptv toluene and ~200 pptv benzene at 360±10 m a.g.l., when emissions from traffic related sources are highest and the mixing height relatively low. Mixing ratios decreased throughout the morning, probably due to a combination of boundary layer development leading to dilution and increasing OH oxidation leading to enhanced chemical removal, with mixing ratios stabilising later in the day at 10 – 20 ppbv NO_x and between 90 – 150 pptv benzene and toluene. ~~During the same period, O_3 mixing ratios were superficially anti-correlated to NO_x mixing ratios, increasing from morning minima until an evening maximum of 40 – 45 ppbv was observed. Subsequently, the low O_3 morning and daytime mixing ratios over Greater London were attributed to the destruction of O_3 by rapid titration with NO. As the day progresses, sunlight intensity becomes higher increasing the NO_x oxidation rate leading to decreased NO_2 and increased O_3 (Pudasainee et al., 2010).~~

~~Variations in O_3 mixing ratio are generally attributed to photochemical production in the mixing layer as well as transport from the upper layer (Dueñas et al., 2002)~~. Variations in O_3 mixing ratio are generally attributed to photochemical production in the mixing layer with some contribution from entrainment from the free troposphere (Dueñas et al., 2002). In London, the low O_3 morning mixing ratios were attributed to the destruction of O_3 by rapid titration with NO, which is emitted during the morning rush hour and highest during the morning. As the day progresses, sunlight intensity becomes higher increasing the radical concentration and hence NO to NO_2oxidation rate from the reaction of NO with peroxy radicals. Subsequent photolysis of NO_2 leading to increased O_3 throughout the day (Pudasainee et al., 2010), with this rate of O_3 production being a function of NO_x and VOC levels as well as sunlight intensity.

Recent studies of annually averaged daily VOC mixing ratios in London from the 191 m high BT Tower have shown that benzene and toluene mixing ratios typically display two day-time maxima, one occurring around 9:00 and a second larger peak occurring between 18:00 and 21:00 coinciding with morning and evening peak traffic periods (Langford et al., 2010;Lee et al., 2015). NO_x mixing ratios are highest when traffic flow peaks, with higher O_3 mixing ratios corresponding to lower NO_x mixing ratios and vice versa during a 24 hour period (Im et al., 2013;Lu and Wang, 2004;Mazzeo et al., 2005). This indicates that patterns in VOC and NO_x emission have a larger effect on observed mixing ratios in the boundary layer than does boundary layer dynamics.

3.3 Horizontal spatial distribution of VOCs and NO_x mixing ratios

The predominant wind directions observed during the flights were north-westerly (RF 2-6), perpendicular to the flight transects, (table 1). Research flights 2-6 were used to provide a cross section of pollutant mixing ratios across London. The relative spatial distribution of VOC and NO_x mixing ratios across greater London during these flights were superficially consistent, with average mixing ratios for each flight leg only changing temporally (figure 2), hence only RF 5 is shown here.

Figures 3 and 4 show 1 km averaged mixing ratios of VOCs and NO_x respectively during RF 5 against latitude across Greater London. Both VOCs and NO_x mixing ratios show significantly higher mixing ratios in inner London. For all compounds the highest mixing ratios were observed within inner London at 360±10 m a.g.l. particularly directly downwind of the London CCZ. Average mixing ratios observed within inner London were 0.20±0.05, 0.28±0.07, 13.2±8.6, 21.0±7.3 and 34.3±15.2 ppbv for benzene, toluene, NO, NO_2 and NO_x respectively. Mixing ratios for benzene, toluene, NO, NO_2 and NO_x for all flights are shown in table 2.

~~Benzene, toluene and NO_x have shared anthropogenic sources with very few biogenic contributions in an urban environment.~~ Vehicular emissions are considered to be an important source for VOCs and NO_x in Greater London (Langford et al., 2010;Lee et al., 2015). Toluene has a shorter atmospheric lifetime than benzene due to faster photochemical removal by OH (rate constants of $1.45 \pm 0.06 \times 10^{12}$ k, cm^3 $molecule^{-1}$ s^{-1}; $6.03 \pm 0.17 \times 10^{12}$ k, cm^3 $molecule^{-1}$ s^{-1} for benzene and toluene respectively at 298 K; (Ohta and Ohyama, 1985)), thus the ~~toluene to benzene~~ T/B ratio can indicate the photochemical age of the pollution carried by air masses (Warneke et al., 2001;Atkinson, 2000). Very close to the source of emissions (e.g. at the kerbside), the ratio of VOC mixing ratios should be similar to those in the emissions themselves. As toluene is more rapidly removed by oxidation, the T/B ratio progressively decreases as air is transported over longer distances away from the source. Vehicular exhaust emission ratios from combustion during transient engine operation is dependent on gasoline composition but within Europe typically yield T/B ratios between 1.25 – 2.5 ppbv $ppbv^{-1}$ (Heeb et al., 2000). The introduction of catalytic converters to vehicular exhausts significantly has been shown to decrease this T/B ratio, attributed to the reduced catalytic conversion efficiency for benzene with respect to alkylated benzenes (Heeb et al., 2000). Hence observed ambient T/B mixing ratios will be a product of the photo-chemical age of the air mass since emission, vehicular fleet composition, gasoline composition and the ratio of vehicles using catalytic converters.

Recent long-term VOC measurements made at two ground level sites in central London dominated by traffic sources, Marylebone Road and North Kensington ~~Recent long-term VOC measurements made at two ground level sites in central London (Marylebone Road and North Kensington; (Valach et al., 2014) both dominated by traffic sources,~~ showed average T/B ratios of 1.6±0.3 ppbv $ppbv^{-1}$ and 1.8±0.3 ppbv $ppbv^{-1}$ respectively. These T/B ratios are similar to the average T/B concentration ratio of 1.8 ± 0.5 ppbv $ppbv^{-1}$ observed within inner London in this study, where traffic sources are likely to be the highest (figure 3). Average T/B concentration ratios in suburban (latitude 51.30 – 51.35°) and south-western Greater

London (latitude 51.35 – 51.42°) were 1.1 ± 0.3 ppbv $ppbv^{-1}$ and 1.3 ± 0.4 ppbv $ppbv^{-1}$ respectively. This could be interpreted as increasing air mass age from emission and suggests that the sources of benzene and toluene in these regions are likely the product of local emission and horizontal advection from inner London.

Linear regression analysis between NO, NO_2 NO_x, benzene and toluene mixing ratios yielded correlation coefficients (R^2) ranging between 0.12 and 0.64. The weakest linear regressions were observed between toluene and NO (R^2 = 0.12, n = 7500) and benzene and NO (R^2 = 0.14, n = 6500), not shown. The strongest linear regressions were observed between toluene and benzene (R^2 = 0.51, n = 6500) and toluene and NO_2 (R^2 = 0.64, n = 7500) (figure 5). A strong covariance exists between ~~trimodal distribution between~~ benzene, toluene and NO_2 mixing ratios indicating that these compounds potentially share the same or co-located sources within the Greater London area, most likely vehicular emission. However the measured NO_2/NO concentration ratio at 360m a.g.l is likely to be dominated by photochemistry rather than emission sources (Atkinson et al.2000).

Figure 5 also suggests a secondary source contribution to toluene that is not shared with NO_2 or benzene and hence is not related to traffic emissions. This secondary source is localised to a discrete peak in observed toluene in SE London within the borough of Lambeth (latitude 51.455°, longitude -0.141°). This was observed during three of the seven flight transects in which toluene mixing ratios at 360±10 m a.g.l. increased from 0.25 ppbv to 0.6 ppbv with a T/B ratio of up to 3 ppbv $ppbv^{-1}$, as seen in figure 3. Toluene has numerous anthropogenic sources including evaporative fuel losses, industrial solvents, paint thinners and the manufacturing of ink and paints. Direct toluene emissions from industrialised areas in Mexico city with T/B ratios of up to 8.5 - 12.5 ppbv $ppbv^{-1}$ have previously been reported (Karl et al., 2009). In the absence of any identifiable industrialised areas upwind of the region of high T/B ratios in Lambeth, this peak is possibly due to the horizontal advection of industrial emissions from outside of London, or some unidentified localised source of toluene.

The influence of NO_x and VOC emission from London Heathrow Airport (LHA) during this study was investigated with plume dispersion modelling using the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. The model isolates the region of the flight track influenced by potential pollutant outflow from LHA during the flight. Four hour averaged forward dispersion forecasting from LHA was modelled for RF1 and RF5 ~~from LHA~~ between 14:00 – 16:00 and 9:00 – 12:00 local time respectively. The lower and upper limits of the averaged dispersion layer were 300 – 400m agl, similar to the measured average flight altitude ~~of 366 ± 7.2 m agl~~ during ~~RF 5~~ these flights. During RF1 and RF 5 the transport time from LHA to the flight transect was approximately 25-50 minutes, calculated from the average observed horizontal wind speed and the ~20 km downwind distance (figure 6).

Figure 6 shows the region of ~~RF 5~~flight transects which were influenced by LHA outflow (51.39 – 51.45° latitude). On entering the LHA outflow plume, NO_x mixing ratios at 360±10 m a.g.l. during both RF1 and RF5 were observed to double increasing from ~15 to 30 ppbv, suggesting a strong NO_x source. As shown in figure 4 for RF5, the NO/NO_2 ratio also gradually increased across the plume from 0.5 up to 0.8 ppbv $ppbv^{-1}$, which is consistent with previous studies that have found higher NO mixing ratios in aircraft exhaust (Spicer et al., 1994;Schäfer et al., 2000). Toluene and benzene mixing ratios showed a negligible increase from ~0.20 – 0.26 and ~0.15 – 0.18 ppbv at 360±10 m a.g.l. across the plume respectively, with T/B ratios of 1.5 - 1.7 ppbv $ppbv^{-1}$ indicative of vehicular exhaust emission as the dominant VOC source. Previous ground observations (Carslaw et al., 2006) at LHA suggested that approximately 27% of the annual mean NO_x and NO_2 were due to airport operations at the airport boundary. At background locations 2–3 km downwind of the airport they estimated that the upper limit of the airport contribution to be less than 15%. Our measurements are in qualitative agreement with this study, suggesting that even though Heathrow is an important emission source of NO_x, observed mixing ratios of NO_x close to the airport are dominated by road traffic sources. As LHA was ~ 20 km upwind of the flight transects, our observed mixing ratios are likely to be heavily influenced by emissions during advection from LHA to the measurement locations ~~and local sources within inner London~~ and as such conclusions drawn from this data is tentative.

3.4 Interpretation of vertical trace gas profiles

To date the influence of vertical transport on the distribution of trace gases in the urban boundary layer has primarily been studied with respect to vertical profiles of ozone, which are typically with in-situ instruments mounted on tethered balloons (Beyrich et al., 1996;Güsten et al., 1998;Newchurch et al., 2003). Vertical profiling of VOCs, NO, NO_2 and

NO_x have also been studied using a combination of in-situ measurements from tethered balloons and ground based differential optical absorption spectroscopy (DOAS) over several American (Wang et al., 2003;Stutz et al., 2004;Velasco et al., 2008;Hu et al., 2012) and European cities (Glaser et al., 2003). To the author's knowledge, the work herein represents the first vertical boundary layer profiling of both VOCs and NO_x species using research aircraft over a European city.

Vertical profiling of VOCs, NO_x and O_3 above Greater London in this study was conducted during RF 1 on 24/6/13 between the hours of 17:00 -18:00 local time. Vertical profiling consisted of three sequentially stacked flights conducted at 350 m agl (17:00 – 17:20), 510 m agl (17:20 – 17:40) and 650 m agl (17:40 – 18:00). The trace gas mixing ratios observed at each altitude were then averaged along the ~35 km flight path over Greater London. These concentration profiles were then compared with hourly averaged upwind LAQN kerbside measurements made at 17:00 from the Marylebone Road air quality monitoring station to interpret how trace gas mixing ratios change vertically from the street canyon to above the urban canopy. At its closest point, flight legs were ~ 6 km downwind of the Marylebone Road measurement site. During RF 1, a predominantly north westerly wind direction was observed with a mean wind direction and wind speed of 285.1±17.1° and 13.1 m/s respectively. Hence, the vertical concentration profiles observed represents a composite of local emission and horizontal advection of the Greater London region.

Figure 7 shows the comparison between the measured trace gas concentration profiles over Greater London and the Marylebone Road kerbside measurements. The measured concentration distributions of both benzene (0.15 ± 0.01 ppbv) and toluene (0.16 ± 0.01 ppbv) and their corresponding T/B ratio (1.1 ± 0.3 ppbv ppbv^{-1}) were vertically uniform with increasing altitude, suggesting rapid mixing between 350 – 650 metres. In this case VOC losses due to reaction with the OH radical are evidently too slow to produce observable concentration gradients in the vertical distribution. This suggests that turbulence mixes the species up to 650 m agl much faster than the OH radical depletes them. Over urban areas turbulence is promoted throughout the day due to thermal forcing produced by the urban energy balance (Velasco et al., 2008).

Both NO and NO_2 show a large decrease in mixing ratios between measurements at the kerbside and at 360±10 m a.g.l. (43 and 4.4 ppbv for NO respectively and 28 and 17ppbv for

NO_2). In contrast to NO and NO_2, O_3 measurements were lowest at the kerbside site, 17 ppb, increasing to 32 ppbv at 360±10 m a.g.l. The daytime vertical profiles of NO, NO_2 and O_3 are caused due to a combination of turbulent mixing and three main simultaneous competing effects. The chemical production of NO_2 by NO titration with O_3 and RO_2, causing higher NO_2 and lower O_3 mixing ratios closer to the surface due to higher surface NO mixing ratios. Photochemical production of NO and O_3 from NO_2 and subsequent O_3 destruction. NO_2 and ozone dry deposition processes which dominate closer to the surface (Wesely and Hicks, 2000).

The vertical profiles of NO_x and O_3 are superficially anti-correlated with altitude. The observed O_3 profiles, with lower values close to the ground and higher values aloft, agree in their general behaviour with other observations (Beyrich et al., 1996;Glaser et al., 2003;Güsten et al., 1998) The vertical profiles of O_3 and O_x (the sum of O_3 and NO_2) show the importance of NO emission for O_3 depletion, with reduced surface O_3 mixing ratios closer to the ground largely compensated by a corresponding increase in NO_2. As a result, O_x exhibits a very uniform vertical concentration between 350 – 650 m agl. However, O_x mixing ratios are ~~substantially~~ reduced at ground level possibly due to enhanced deposition in proximity to the surface. ~~likely due to enhanced O_3 titration with NO, associated with the proximity of the Marylebone road site to the vehicular emission source.~~

3.5 Comparison of airborne measurements with LAQN ground sites

Data obtained from three LAQN air quality ground monitoring stations located in three typical urban environments (urban kerbside: Marylebone Road; urban background: Westminster-Horseferry Road; and suburban background: Greenwich-Eltham) were compared against airborne mixing ratios at 360±10 m a.g.l. to assess how O_3 and its precursors are distributed across the city. Dispersion modelling using the NOAA HYSPLIT model was used to highlight regions of the flight track most influenced by pollutant outflow from each of the ground monitoring stations. Briefly, four hour averaged forward and reverse dispersion forecasting was modelled for Marylebone Road, Westminster and Eltham respectively during flights with a prevailing north westerly wind direction (RF 1, RF4 - 6, table 1). RF 2 and 3 were not used in the comparison due to low observed wind speeds, < 5 m s^{-1}. The lower and upper limits of the averaged dispersion layer were 300 – 400 m agl, similar to the measured average flight altitude of 360±10 m a.g.l during RF 1, RF4 - 6. Airborne mixing ratios for comparison were given as the arithmetic average and 1 standard deviation of the hourly measurements within the dispersion plume. The approximate transport times from Marylebone Road, Westminster and Eltham to the flight transect ranged between 3 – 7, 7 – 15 and 14 – 28 minutes respectively, calculated from the observed horizontal wind speed and the downwind/upwind distance for each ground station during each flight (figure S-1).

Figure 8 shows a linear regression analysis between airborne and ground mixing ratios of benzene, toluene, NO, NO_2, NO_x and O_3. Strong positive correlations are observed for all species at all three ground sites with R^2 values ranging from 0.54 – 0.97 (n = 7). Ground mixing ratios of both VOCs and NO_x species were significantly higher at the Marylebone Road kerbside site relative to the urban background (Westminster) and suburban background (Eltham) sites. Average mixing ratios observed at ground level for benzene and toluene respectively were 0.12±0.05; 0.21±0.08 ppbv at Marylebone Road and 0.07±0.01; 0.13±0.03 ppbv at Eltham, with T/B ratios of 1.7-1.8 ppbv $ppbv^{-1}$ indicative of vehicular emissions as the dominant source at both sites. NO_x mixing ratios were also significantly higher at Marylebone Road (121.96±45.28 ppbv) than Westminster (40±4.45 ppbv) and Eltham (10.02±4.28). For O_3, the mean mixing ratios observed at Westminster (13.56±4.9 ppbv) were lower than at Eltham (19.14 ± 3.2 ppbv) whilst the lowest mixing ratios were at the Marylebone Road site (9.23±8.42 ppbv). The O_3 mixing ratios at these sites are anti-correlated to that of NO (figure 8), through enhanced NO emission and subsequent titration of O_3 in proximity to busy road networks.

Also of interest, NO/NO_2 ratios were higher at the Marylebone Road site (0.62±0.25) than at Westminster (0.50±0.15) and Eltham (0.25±0.09). Historically, vehicular diesel and petrol emissions of NOx were dominated by emissions of NO (NO/NO_2 ratios of 0.9 ≤). However, recent developments in diesel emission technology, specifically diesel oxidation catalysts and particulate filters, have caused significant increases in direct vehicular NO_2 emissions in the UK and Europe. Current diesel emission control technology deliberately produces enhanced NO_2 mixing ratios to oxidise and reduce black carbon particulates in the vehicular exhaust gas (Carslaw and Rhys-Tyler, 2013). Increasing numbers of diesel vehicles in Central London with this emission reduction technology could have contributed to the low NO/NO_2 ratios observed from all three ground air monitoring stations observed during this study. This is in good agreement with the ~~trimodal distribution~~ observed covariance in benzene, toluene and NO_2 mixing ratios shown in figure 5, potentially indicating these species have common sources, most likely from vehicular emission. However the measured NO/NO_2 concentration ratio at 360m a.g.l is likely to be dominated by photochemistry rather than emission sources (Atkinson et al.2000).

Airborne mixing ratios of O_3 were consistently higher than those at ground level, consistent with the ground surface in London acting as a chemical sink for O_3, which is in good agreement with the measured vertical profile of O_3 shown in figure 7. Mixing ratios of the selective VOC and NO_x species observed at the roadside site at Marylebone Road were significantly higher than those of the airborne measurements. Assuming this difference is due entirely to mixing, this reduction in mixing ratio crudely indicates a dilution factor of 2 - 6 between the roadside site in the Marylebone Road and the 355 m sampling point. This agrees well with comparisons made during REPARTEE I which concluded a dilution factor of ~5 for NO_x mixing ratios between Marylebone Road and the 190 m sampling point on the BT tower (Harrison et al., 2012), well above the surrounding building height. Dilution factors for VOC and NOx species at Westminster and Eltham ranged between 0.46 – 2.34 which are significantly lower than those observed at Marylebone Road. This difference in dilution factors is largely due to firstly the Marylebone Road measurement site being in central London, a very large source of VOCs and NO_x and being closest in proximity to the 6 lane frequently congested road. Secondly Marylebone Road is within an urban street canyon whose orientation serves to maximise mixing ratios of emissions therein. Street canyons are not as well ventilated as with more open locations such as urban and suburban sites which tends to result in increased surface mixing ratios (Pugh et al., 2012;Carslaw and Rhys-Tyler, 2013) .

4 Conclusions

Measurements of VOCs, NO_x and O_3 in the boundary layer were made in transects across Greater London at 360±10 m a.g.l. during the summer of 2013, with a view to identifying the dominant O_3 precursor sources within the region, and to better understanding the effects of chemical interactions between these pollutants and meteorological variables on urban air quality. Observed benzene, toluene and NO_x mixing ratios across Greater London were mostly due to traffic emissions, with the highest mixing ratios observed over inner London, where the density of traffic and other pollutant sources is higher than over outer London. The highest T/B ratios (1.8 ± 0.5 ppbv $ppbv^{-1}$) observed within inner London is indicative of local vehicular sources. Linear regression analysis of VOC and NO_x species which showed a ~~trimodal correlation~~ covariance between benzene, toluene and NO_2 mixing ratios, potentially indicating that their dominant sources are the same or are co-located throughout London. Modern diesel vehicles use emission control technology to reduce black carbon emissions but which also enhance the NO_2/NO ratio in the vehicle exhaust (Carslaw and Rhys-Tyler, 2013). As the measured NO/NO_2 concentration ratio at 360 m.a.g.l. is likely to be dominated by photochemistry rather than emission sources, VOCs correlate well with NO_2 but not NO due to its longer atmospheric lifetime (Atkinson et al.2000). ~~The reason these VOCs correlate well with NO_2, but not NO is possibly because of the ubiquity of diesel vehicles in London. However the measured NO_2/NO concentration ratio at 360m a.g.l is likely to be dominated by photochemistry rather than emission sources (Atkinson et al.2000).~~

Airborne mixing ratios were compared to kerbside data from three LAQN air quality ground monitoring stations within Greater London. Strong positive correlations were observed for O_3, NO, NO_2, NO_x, benzene and toluene species at all three ground sites with R^2 values ranging from 0.54 – 0.97 (n = 7) suggesting that airborne mixing ratios were characteristic of surface mixing ratios during the analysis period. NO_x and VOC mixing ratios observed at the Marylebone Road air quality monitoring site were 2 – 6 times higher than those observed at 360±10 m a.g.l due to a combination of its proximity to the emission sources, photochemical aging and dilution of the air mass during vertical mixing.

An increase in NOx mixing ratios from ~15 to 30 ppbv at 360±10 m a.g.l. was observed ~20 km downwind of LHA. Our measurements tentatively support previous studies that suggest that even though Heathrow is an important emission source of NO_x, observed mixing ratios of NO_x even quite close to the airport are dominated by road traffic sources. Since LHA was ~ 20 km upwind of the flight transects, these observed mixing ratios are likely to be heavily influenced by vehicular emissions during advection from LHA to the measurement location.

Author contribution

MD Shaw and JD Lee redesigned the PTR-MS and NOx chemiluminescence instruments for the aircraft. MD Shaw, JD Lee, A Harvey and B Davison designed the field experiment and carried it out. MD Shaw, JD Lee, A Vaughan, RM Purvis, AC Lewis and CN Hewitt were responsible for analysis/interpretation of the data.

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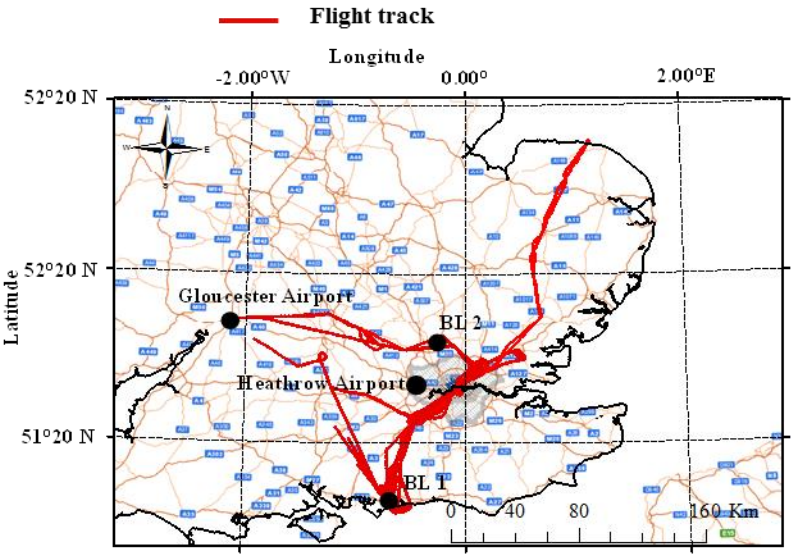
Table.1. Summary of meteorological and flight conditions during campaign.

RF	Date	Time (local)	Mean Wind direction (°)	Mean Wind speed (m s^{-1})	Mean True airspeed (m s^{-1})	Mean Flight altitude a.g.l (m)
1	24/6/13	15:30 – 18:20	285.9±17.1	13.6±3.3	81.1±3.9	603±28.9
2	26/6/13	16:00 – 18:00	287.5±17.0	3.8±1.0	70.7±3.4	349.8±15.1
3	27/6/13	9:40 – 12:15	277.6±20.9	4.2±1.4	69.6±2.7	354.1±11.1
4	27/6/13	14:20 – 17:50	275.1±24.5	6.6±1.6	72.6±5.4	343.1±31.7
5	3/7/13	10:40 – 13:00	280.7±11.0	6.3±1.3	71.9±4.0	366.1±7.2
6	4/7/13	15:20 – 16:55	240.7±11.3	7.5±1.4	72.5±4.5	365.1±18.3

Table.2. Summary of mixing ratios (ppbv) observed over inner London during campaign.

	RF1	**RF2**	**RF3**	**RF4**	**RF5**	**RF6**
Benzene						
Mean	0.08	0.09	0.22	0.10	0.20	0.10
Median	0.07	0.09	0.15	0.09	0.19	0.10
SD	0.06	0.05	0.06	0.05	0.05	0.05
5th percentile	0.01	0.03	0.06	0.03	0.09	0.03
95th percentile	0.178	0.20	0.27	0.17	0.22	0.19
N	16500	13900	14100	2560	7620	11260
Toluene						
Mean	0.17	0.12	0.28	0.15	0.28	0.12
Median	0.16	0.12	0.27	0.15	0.25	0.11
SD	0.07	0.08	0.11	0.07	0.07	0.09
5th percentile	0.08	0.06	0.05	0.05	0.12	0.01
95th percentile	4.34	0.26	0.39	0.32	0.38	0.28
N	16500	13900	14100	2560	7620	11260
NO						
Mean	3.83	2.06	17.46	8.81	13.20	4.80
Median	3.46	2.44	16.19	7.76	12.43	3.41
SD	2.16	2.50	7.42	1.88	8.60	3.61
5th percentile	1.06	0.70	3.49	1.91	1.98	1.23
95th percentile	7.82	7.94	25.71	7.44	21.33	12.17
N	82500	69500	70500	12800	38100	56300
NO$_2$						
Mean	15.19	11.99	22.95	18.64	21.02	12.17
Median	13.59	11.44	26.54	22.13	20.23	10.65
SD	6.10	8.29	13.17	7.89	6.38	7.31
5th percentile	7.56	7.91	11.45	10.21	6.03	3.65
95th percentile	26.49	31.90	52.13	35.08	25.97	19.60
N	82500	69500	70500	12800	38100	56300
NO$_x$						
Mean	19.02	16.05	40.41	27.45	34.3	16.97
Median	17.49	17.91	36.02	26.78	32.40	15.95
SD	7.96	10.39	19.87	9.67	15.20	8.50
5th percentile	8.71	9.00	15.53	12.16	9.35	5.20
95th percentile	33.62	39.36	76.08	42.69	44.54	30.04
N	82500	69500	70500	12800	38100	56300



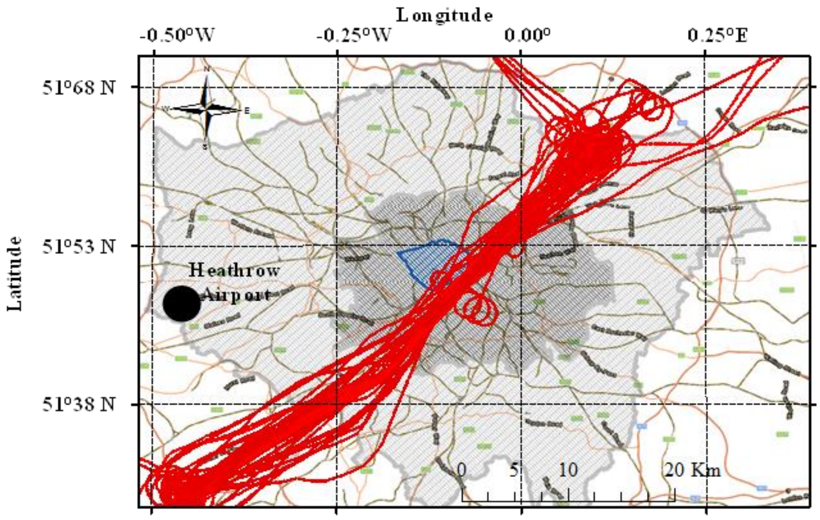


Figure 1a: top map showing all NERC Dornier-228 flights overlaid on UK transport map.

Figure 1b: bottom map showing total flight legs across Greater London. Grey area; Greater London boundary, black area; inner London boundary, blue area; London CCZ.

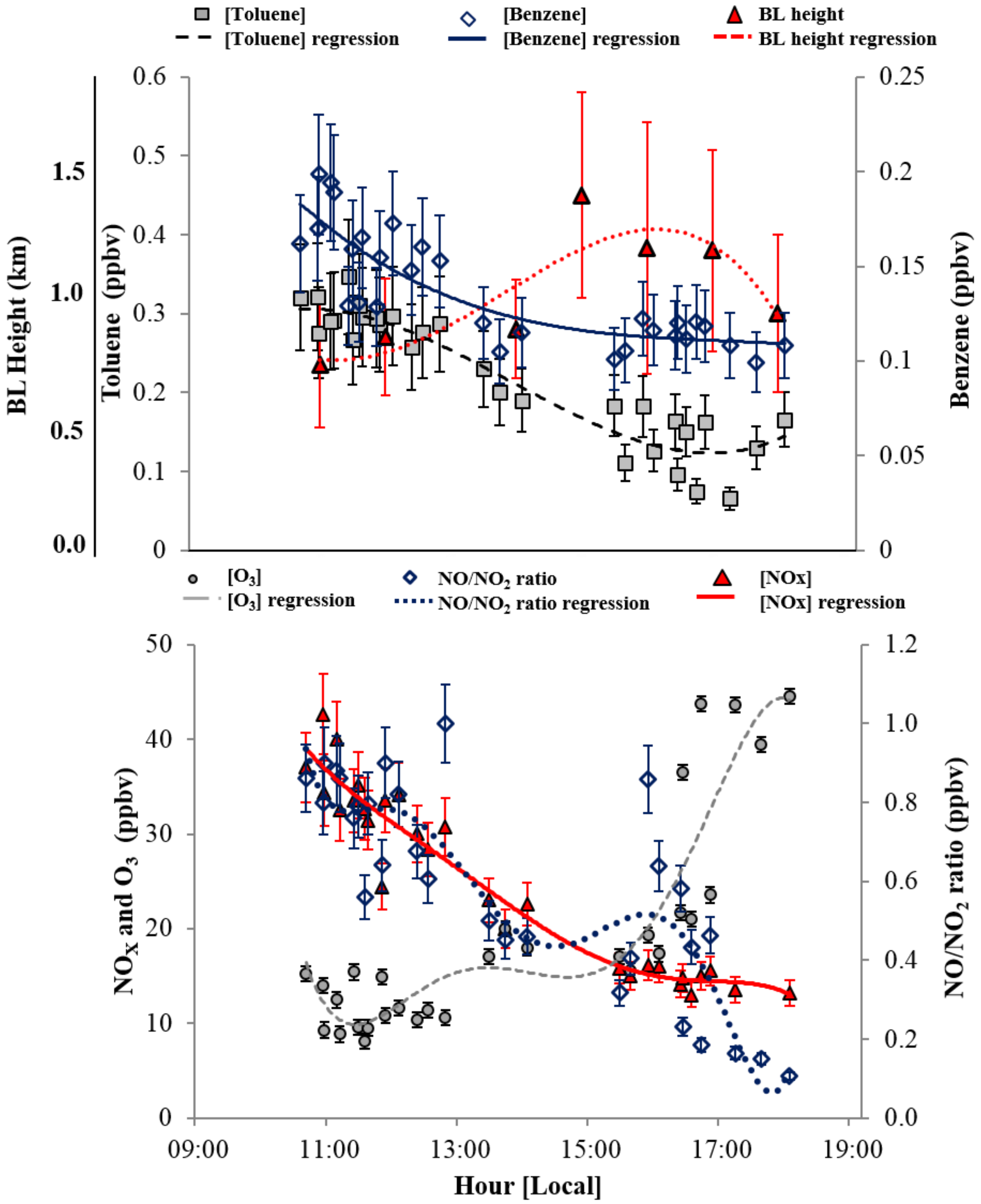


Figure 2. Top: time series of averaged benzene and toluene concentrations observed at 360±10 m a.g.l. during RF 2-6. Bottom: time series of averaged NO/NO$_2$ ratios and O$_3$, NO$_x$ concentrations during RF 2-6.

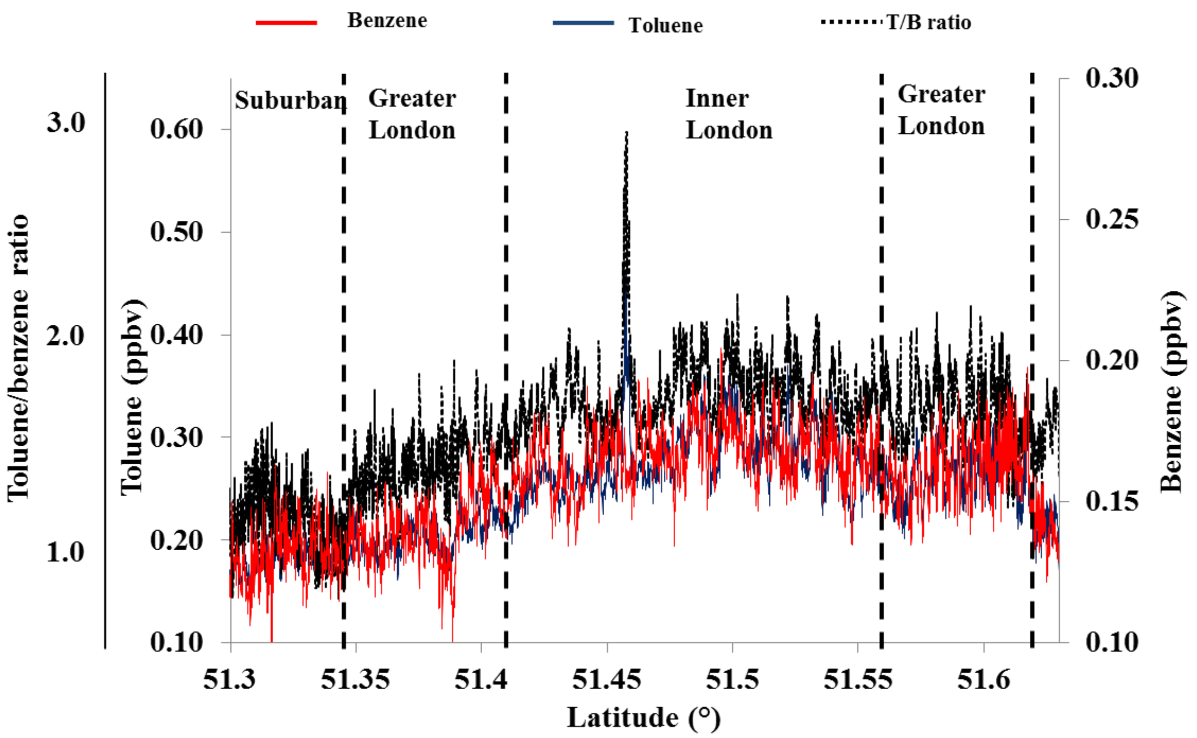


Figure 3. City cross section of 1km averaged benzene, toluene mixing ratios and T/B instantaneous ratios (ppbv ppbv^{-1}) at 360±10 m a.g.l. across Greater London during RF 5.

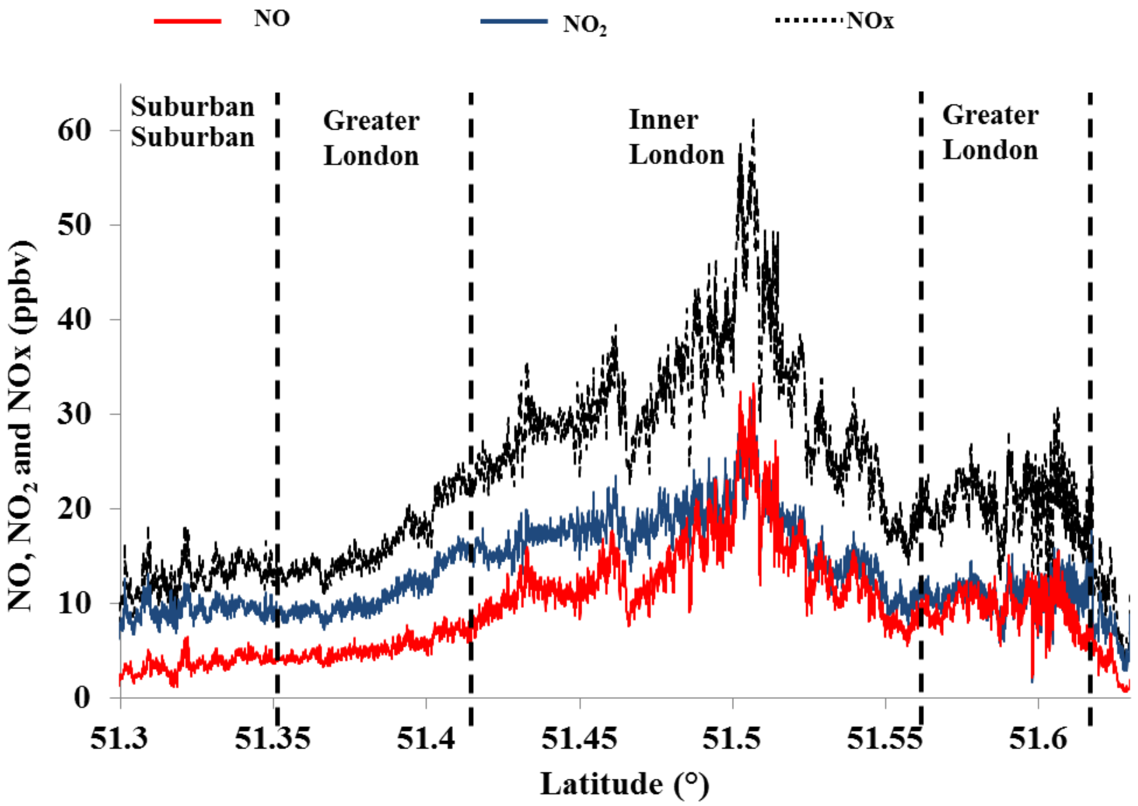


Figure 4. City cross section of 1km averaged NO NO_2 and NO_x mixing ratios across Greater London at 360±10 m a.g.l. during RF 5.

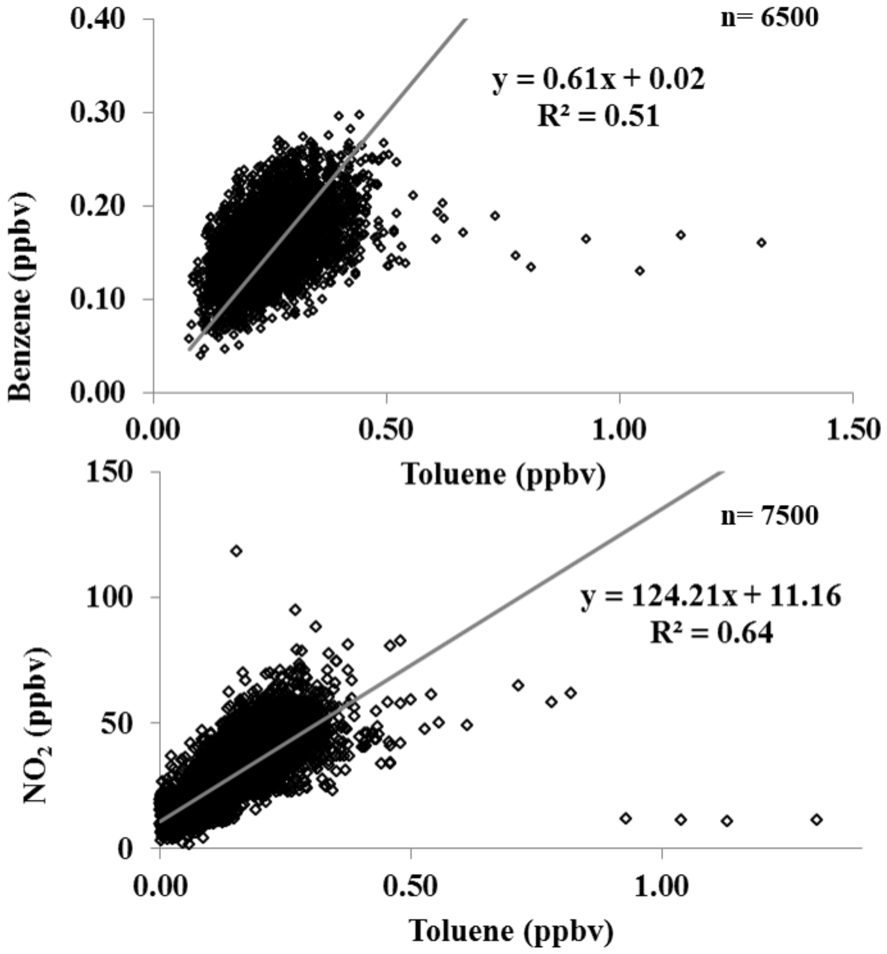


Figure.5. Top: linear regression analysis of benzene against toluene mixing ratios at 360±10 m a.g.l. during RF 5. Bottom: linear regression analysis of NO_2 against toluene mixing ratios at 360±10 m a.g.l. during RF 5.

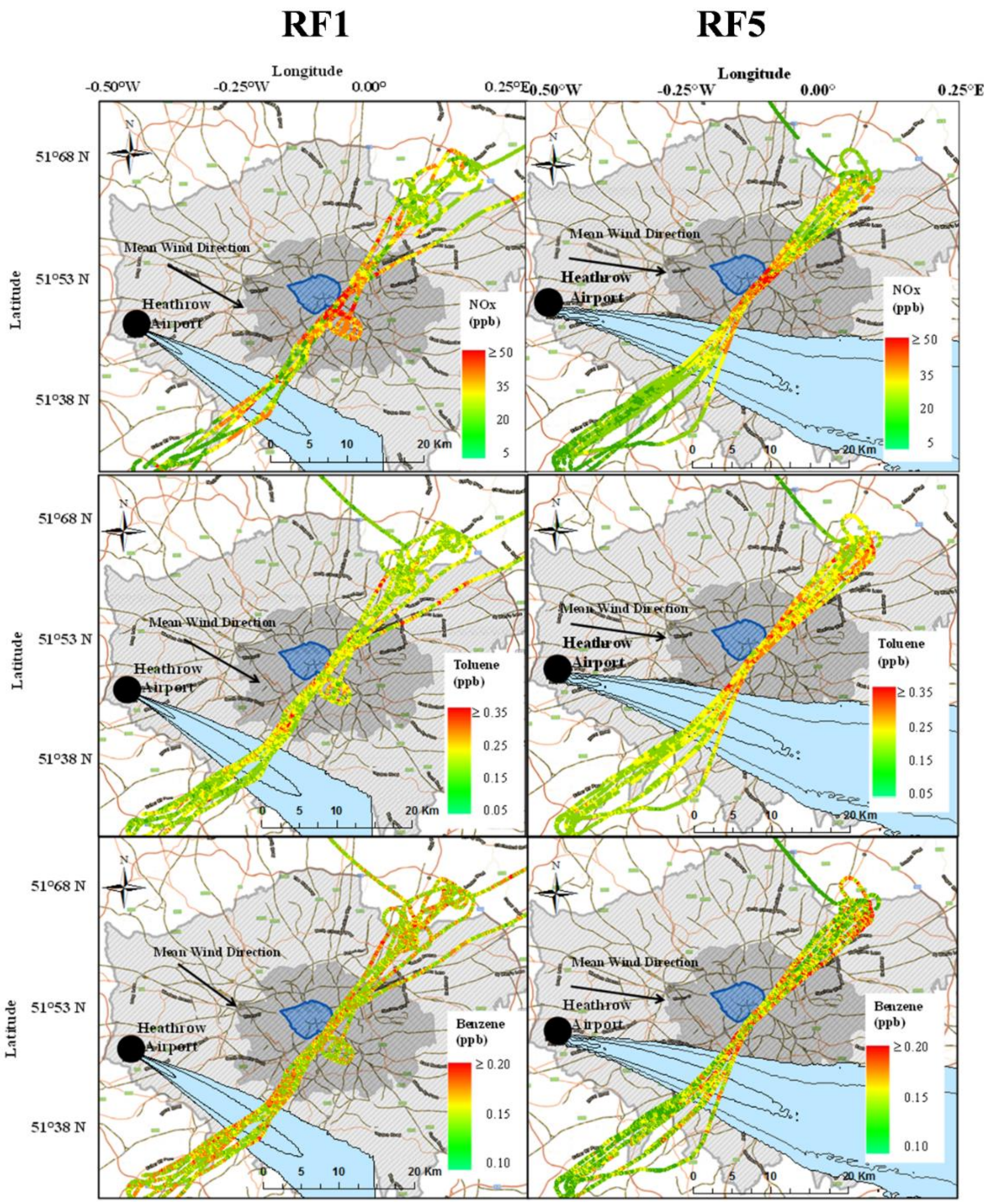


Figure 6. Top: NOx concentration data (7 metre resolved at 360±10 m a.g.l.) during RF1 (left) and RF5 (right) overlaid on UK transport map. Middle: Benzene concentration data (35 metre resolved at 360±10 m a.g.l.) during RF 1 (left) and RF5 (right) overlaid on UK transport map. Bottom: Toluene concentration data (35 metre resolved at 360±10 m a.g.l.) during RF1 (left) and RF5 (right) overlaid on UK transport map. Grey area; Greater London boundary, black area; inner London boundary, dark blue area; London CCZ, light blue area; 4 hour averaged HYSPLIT dispersion trajectory.

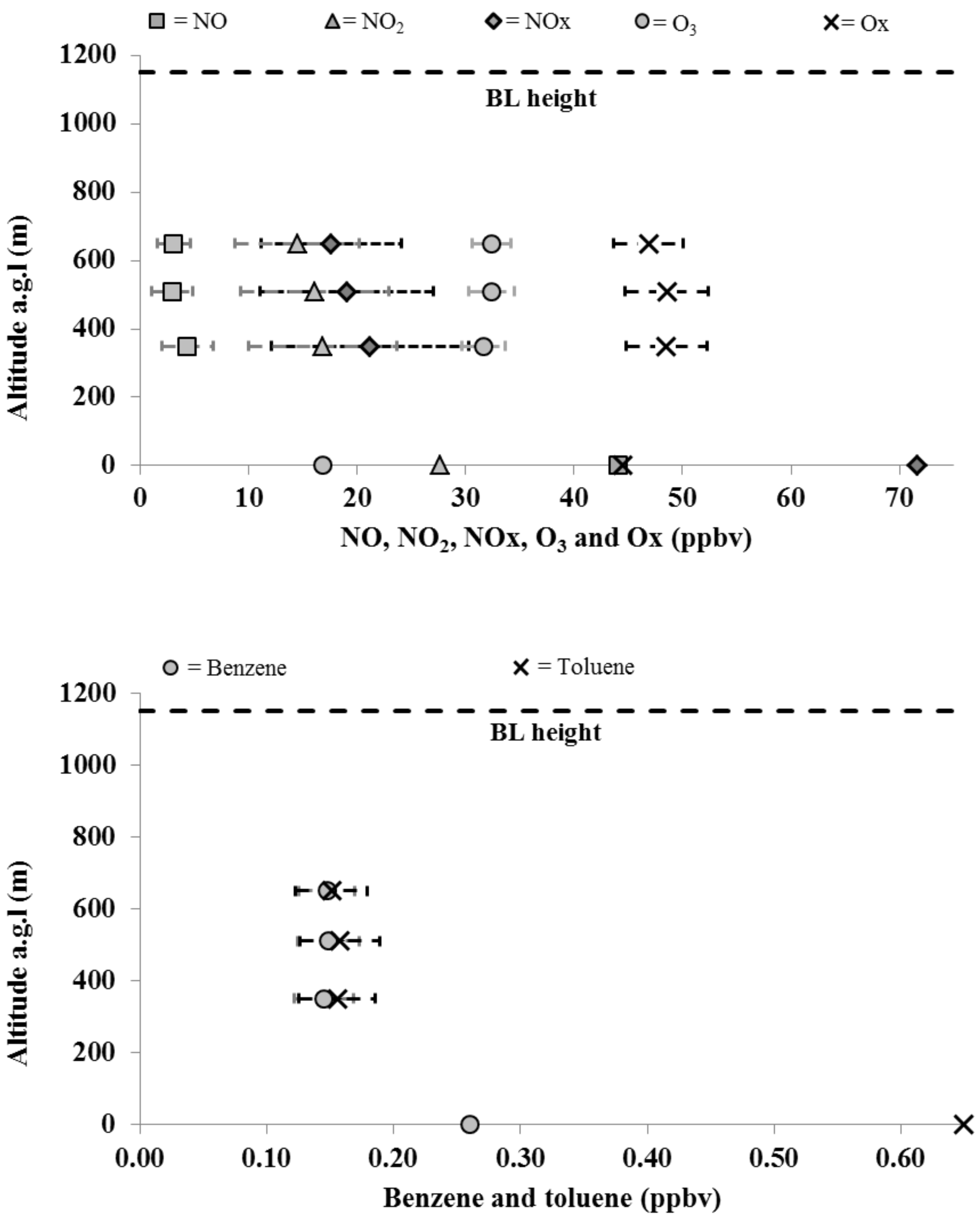


Figure 7. Average vertical profiles of O_3, NO, NO_2, O_x, benzene and toluene across London during RF1, 17:00 – 18:00 on the 24th of June 2013. X error bars represent standard deviation (1σ) of mixing ratios observed during each flight leg. Mixing ratio at ground level is hourly average from the LAQN Marylebone road air quality monitoring station.

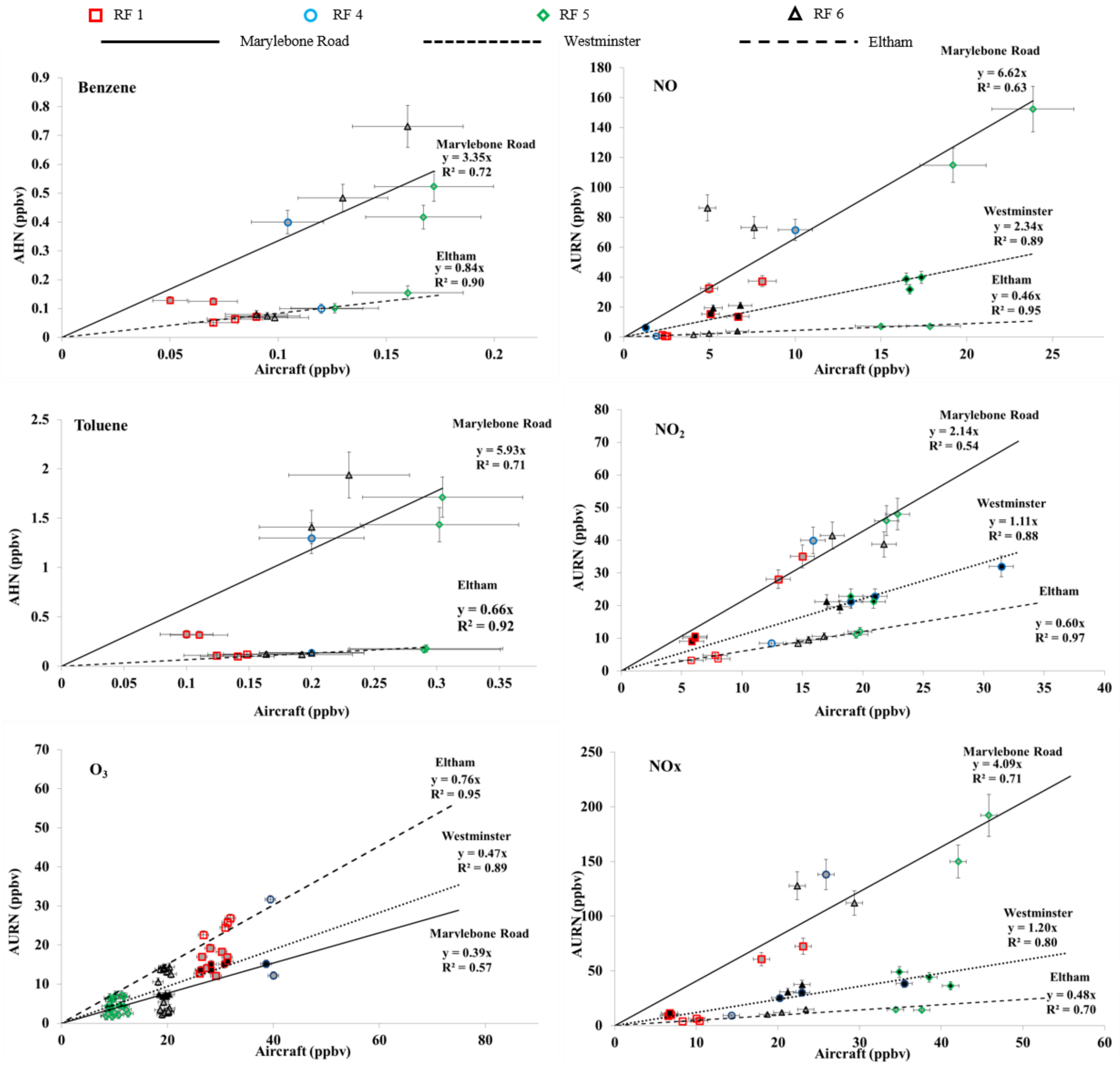


Figure 8. Linear regression analysis between airborne (at 360±10 m a.g.l.) and hourly ground measurements at Greenwich-Eltham (empty), Westminster-Horseferry road (black) and Marylebone Road (grey) from the LAQN monitoring network during RF1, 4, 5 and 6.

Response to Anonymous Referee 1

1.1

I feel the authors have missed an opportunity to look at the evolution of the London plume in flights 7-10 where the flight track is parallel to the wind direction. Surely these data provide a unique opportunity to compare concentrations of ozone and its precursors both up and downstream of London from which an approximate emission estimate can be derived and compared to NAEI emission estimates? In my mind an analysis of this sort would offer far more scientific value than reporting the city cross section concentrations. At the very least it would be interesting to see how the T/B ratios change as the London plume evolves.

1.2

This was not the focus of the research flights. The measurement of plume evolution should be carried out by perpendicular transects the plume at different distances from the emission source (Hopkins et al., 2009). Flying only parallel to the wind direction can create anomalies in the data interpretation as it's difficult to know the width of the plume which can lead to the potential of sampling different point sources/other plumes. We have not calculated emission estimates from these flights as the errors would be two large. Our flights were not designed for a mass balance calculation as described by Hopkins et al (2009) , i.e we did not spend enough time flying upwind and downwind of London.

Hopkins, J. R., Evans, M. J., Lee, J. D., Lewis, A. C., Marsham, J., McQuaid, J., Parker, D. J., Stewart, D. J., Reeves, C. E., and Purvis, R. M.: Direct estimates of emissions from the megacity of Lagos, Atmospheric Chemistry and Physics, 9, 8471-8477, 2009.

1.3

As a result of this comment, and due to the comments of reviewer 3 we have removed flights 7-10 from this manuscript.

2.1

Page 27338, line 3, change “is” to “are”

2.2/2.3

Changed

3.1

Page 27338, line 7. In the context of ground level ozone and its precursors I am curious as to why you focus on benzene and toluene and not for example isoprene which has a greater ozone forming potential. A short sentence to justify your choice of compounds is warranted. Furthermore, why do you limit the number of VOCs you measure to just two compounds surely you could have increased your duty cycle without compromising the spatial resolution of the data?

3.2/3.3

The primary focus of this project was to calculate highly spatially resolved (1km) VOC and NOx Eddy covariance fluxes across greater London from an airborne platform, only mixing ratio data is presented here. EC flux data will be made available in later publications. In order to obtain VOC mixing ratio data with a PTR-QMS suitable for virtually disjunct Eddy covariance flux calculation requires a minimum quadrupole ion dwell time of 0.2 secs per VOC at an acquisition rate of 2Hz. Hence only 2 compounds could be scanned for simultaneously. Benzene and Toluene were chosen as their emissions within urban regions are dominated by anthropogenic sources, and their measured ratios can be used to indicate the emission source type (e.g. vehicular, Industrial). The following text has been added “with a view to identify dominant emission sources in the region using measured toluene to benzene (T/B) concentration ratios”

4.1

Page 27341, line 6, change to “...adding a small flow..”

4.2/4.3

Changed

5.1

Page 27341, line 14, Please could you clarify the rate at which data were acquired and used in the paper. Earlier we are told they it was 10 Hz but here it suggests it is 1 Hz.

5.2/5.3

Data was acquired at 10Hz (for the purposes of Eddy Covariance flux calculations), however it has been averaged to 1Hz in this work as we are only looking at concentrations. This is now made clear in the text.

6.1

Page 27341, line 2, change to "setup"

6.2/6.3

changed

7.1

Page 27343, line 9. Please could you clarify your use of the humidity controlled zero air. Did you modulate the zero air humidity to reflect ambient RH conditions or did you calibrate over a range of RH to assess the effect on instrument sensitivity?

7.2

Zero air Humidity was calibrated over a range of RH% (0,20,40,60 and 80% RH each in triplicate) to assess the effect on PTRMS sensitivity. The normalisation of both benzene and *toluene icps against the primary icps takes into account changing ambient humidity as described in Warneke et al 2001.*

7.3 *"Zero air humidity was calibrated over 20 -80% RH in triplicate to assess humidity effects on sensitivity during the campaign" now added to manuscript.*

8.1

Page 27343, line 19. Please include the inner diameter of the tube – this is the value that actually matters.

8.2/8.3

Inner tube diameter now added to discussion. Manuscript now reads "During flights, ambient air was sampled from the forward facing isokinetic inlet along a heated (70°C) 5 m ¼" Teflon (PFA) tube (0.21" ID) pumped by a stainless steel diaphragm pump (Millipore) at a flow-rate of 22L min^{-1}*."*

9.1

Page 27345, line 9. I am pleased to see you have taken the time to compare the PTRMS measurements with the GC-FID WAS samples. This always provides additional confidence in the reported measurements. I see the benzene bias is half of that reported by Jobson et al., 2010 at 8%. This potentially reflects the differing operating conditions of the two instruments, with less fragmentation in your system operating at 110 Td as opposed to theirs operating at 145 Td. The agreement for toluene is slightly less convincing with the PTR-MS underestimating by ∼20%. This warrants some further comment. Can you suggest why the disagreement is so large? Finally, a 20 % negative bias on the toluene concentrations and an 8% bias on the benzene measurements will undoubtedly have a significant impact on the T/B ratios reported which the authors should also comment on.

9.2/9.3

*It is unclear why the PTR-MS exhibited such a negative bias toward ambient toluene concentrations, the only explanation that we can provide is that perhaps this comparison is influenced by such small sample sizes used for the PTR-MS vs WAS GCFID comparison (benzene n=4, Toluene n=6). However, it is important to point out that the PTR-MS vs WAS GC-FID comparisons for toluene and benzene were technically within measurement uncertainty of PTR-MS alone. As stated on page 27343, lines 13-15 "Calculated uncertainties for the PTRMS during the campaign were 16±5 and 21±9 % for benzene and toluene respectively, calculated using the standard deviation of linear regression (Sm) of pre-flight calibrations". Also on page 27345 lines 9-11, "Inter-*comparison *of the two sampling methods showed excellent agreement within measurement uncertainty"*

Using the variance formula method of uncertainty propagation produces a PTRMS vs GCFID Toluene/Benzene concentration ratio total uncertainty of 30%. For a WAS-FID vs PTR/MS derived T/B ratio of (1.08/0.79) x 1.8 = 2.5± 0.75 ppbv ppbv-1, hence the ratios are equivalent within uncertainties.

10.1

Page 27349, line 11. It would be interesting to see the same plot for a different flight leg (R6) where the wind direction and hence LHA plume are slightly shifted. This might help separate the influence of local emissions from the LHA plume.

10.2/10.3

Additional plots for NOx, toluene and benzene during RF 1 (approx. 360m agl) have now been added to figure 6. The mean wind direction during RF 1 was slightly shifted when compared to the mean wind direction observed during RF 5. This has helped to visually separate the influence of localised emissions from the LHA plume. During both RF1 and RF5, NOx mixing ratios approximately doubled (approx. 15 -30 ppbv) on entering the LHA plume whereas toluene and benzene only showed a negligible increase in mixing ratios.

Response to Anonymous reviewer 2

1.1

From the introduction it seemed that one of the main objectives for this manuscript was to re-validate the National Atmospheric Emission Inventory (NAEI), which I think the authors did not do a good job in achieving this goal.

1.2

An objective of this manuscript was not to re-validate the NAEI. The aims of the manuscript are clearly stated as. "(i) quantitatively determine the vertical, horizontal spatial and temporal distribution of VOCs, NO_x *and ozone mixing ratios across London from an airborne platform, with a view to identify dominant emission sources in the region using measured toluene to benzene (T/B) concentration ratios and (ii) wherever possible, compare these fast response airborne measurements with hourly ground-level measurements made by the national monitoring networks." The NAEI was only mentioned within the introduction of the manuscript to put this work into a wider context.*

1.3

In order to clarify our aims we have removed all mention of the NAEI in the manuscript as we agree its discussion within the context of this manuscript is confusing.

2.1

With the re-validation of the NAEI objective in mind, why did the authors only report benzene and toluene measurements? The PTR-MS is a powerful instrument that can measure a vast array of VOCs? Did the authors have in mind another manuscript to do so? It looks like it is a waste of money and resources for both the aircraft and ground site campaigns to report emissions of 2 aromatic compounds.

2.2/2.3

See response to NAEI above. The primary focus of this research project was to calculate highly spatially resolved (1km) VOC and NOx Eddy covariance fluxes across greater London from an airborne platform, only mixing ratio data is presented here. EC flux data will be *made available in later publications. In order to obtain VOC mixing ratio data with a PTR-QMS suitable for virtually disjunct Eddy covariance flux calculation requires a minimum quadrupole ion dwell time of 0.2 secs per VOC at an acquisition rate of 2Hz. Hence only 2 compounds could be scanned for simultaneously. Benzene and Toluene were chosen as their emissions within urban regions are dominated by anthropogenic sources, and their ratios can be used to indicate the emission source type (eg vehicular, Industrial).*

3.1

Pages 27340-27432,it looks like there was different measurement rates depending on the instrument, for instance GPS data were collected at 20Hz, NOx at10 Hz, VOCs at 5 Hz, what did the author do to compare all their measurements is everything converted to 20 HZ to be able to compare with GPS data?

3.2/3.3

GPS, VOC and NOx data were averaged to 1Hz in this work for comparison and analysis. This is now made clear in the text.

4.1

Also, in the NOx sampling section, the acquisition frequency was 10 Hz but why the detection limit is reported at 1 Hz? The VOC sampling was at 5 Hz why did the author use a repetition rate at 2 HZ?

4.2/4.3

*NOx and VOC data was averaged to 1 Hz for analysis and comparison as we are only looking at ambient concentrations. Hence this is why the detection limits are both reported at 1Hz. This is now made clear in the text. The PTR-MS instrument conditions were chosen specifically to capture VOC data suitable for EC flux calculations, which will be the focus of later publications (see response to comment **2.2/2.3**).*

5.1

Page 27342, lines 11-12, the authors stated that they used a combination of stainless steel and Teflon tubing to minimize memory effect however on page 27343 lines 19-20 the author stated that the inlet was PFA? I think this caused some confusion so may be the authors can explain the setup better, which part of the inlet was made of Teflon and which part was made up of stainless steel?

5.2

The sample inlet was stainless steel, the sample line was Teflon.

5.3

Text now reads "During flights, ambient air was sampled from the forward facing stainless steel isokinetic inlet along a heated (70°C) 5 m ¼" Teflon tube (0.21" ID) pumped by a stainless steel diaphragm pump (Millipore) at a flow-rate of 22L min^{-1}*."*

6.1

Page 27347, lines 4-6, the authors specify that "benzene, toluene and NOx shared anthropogenic sources with very few biogenics" how did the authors reach this conclusion and was it based on their measurements? How big is the influence of biogenic emissions on Greater London?

6.2

Benzene, Toluene and NOx direct emissions are the result of anthropogenic sources in urban regions. There is the potential for O_3 *formation from biogenic VOC emission in London but this discussion is beyond the scope of this paper.*

6.3

The text "benzene, toluene and NOx shared anthropogenic sources with very few biogenics" has been removed from the manuscript.

7.1

Page 27347, lines 5-10 on the time scale of the flights and in an area that is highly influence by fresh vehicular emissions of toluene and benzene? How big of an influence is photochemical aging?

7.2

Photochemical aging of Toluene and Benzene in Greater London should be relatively small based upon their atmospheric lifetimes. Whilst NO/NO2 ratio will be affected on these timescales the total NOx mixing ratio would be conserved. However, the measured Toluene/Benzene ratios in surburban London ranged between 1.1 – 1.3±0.3 ppbv ppbv^{-1} compared to 1.8±0.5 ppbv ppbv^{-1} (at 360m a.g.l) observed within inner London which could be interpreted as increasing airmass age from emission and that sources of VOCs in suburban regions could be the product of local emission and horizontal advection from inner London (figure 3).

8.1

Page 27348, Lines1-5, It looks that within experimental error there is no difference in T/B ratio between suburban and south-western London, it looks that both are coming from fresh emissions so why did the authors use photochemical aging to interpret their results?

8.2/8.3

There is a very clear trend in that the T/B ratio is highest in central London where traffic density is likely highest and steadily decreases as we moved away from this region. Refer to figure 3. For instance.

T/B ratio over central London = 1.8 ± 0.5 ppbv ppbv^{-1}

T/B ratio over south-western Greater London (lat 51.35 – 51.42°) = 1.3 ± 0.4 ppbv ppbv^{-1}

T/B concentration ratios in suburban (lat 51.30 – 51.35°) = 1.1± 0.3 ppbv ppbv^{-1}

It is our opinion that one possible reason for this could be could be increasing air mass age from emission and suggests that the sources of benzene and toluene in outer London are likely the product of local emission and horizontal advection from inner London.

9.1

Page 27355, in the conclusion section the authors did not mention how well their measurements agree with NAEI

9.2

The objective of this manuscript was not to re-validate the NAEI. The aims of the manuscript are clearly stated as. "(i) quantitatively determine the vertical, horizontal spatial and temporal distribution of VOCs, NO_x *and ozone mixing ratios across London from an airborne platform, with a view to identify dominant emission sources in the region using measured toluene to benzene (T/B) concentration ratios and (ii) wherever possible, compare these fast response airborne measurements with hourly ground-level measurements made by the national monitoring networks."*

9.3

In order to clarify our aims we have removed all mention of the NAEI in the manuscript as we agree its discussion within the context of this manuscript is confusing.

10.1

Did the authors see more photochemical aging in the flights parallel to wind direction (were these considered to be transformation flights)?

10.2

This was not the focus of the research flights. The measurement of plume evolution should be carried out using perpendicular transects across the plume at increasing distances from the emission source (Hopkins et al., 2009). Flying continuously parallel to the wind direction (as in this study) can create anomalies in the data interpretation as it's difficult to know the width of the plume which can lead to the potential of sampling different point sources within other plumes.

10.3

As a result of this comment, and due to the comments of reviewer 1 we have removed flights 7-10 from this analysis.

Response to Anonymous Reviewer 3

1.1

As a general comment, I found several of the figures difficult to read, particularly Fig

2 and 8. Larger markers and perhaps some colour would help the reader to interpret these figures more easily.

1.2/1.3

Figures 2 and 8 adjusted. Marker size increased and marker colour added.

2.1

p. 27337, line 6. Is there a more recent reference you could use to describe emission

sources for anthropogenic VOCs? note marked changes in VOC emissions on decadal scales for Los Angeles and London;a 31-year old reference may not be relevant here.

2.2/2.3

3 references added to manuscript. Langford et al 2010 and Karl et al 2009.

Karl, T., Apel, E., Hodzic, A., Riemer, D., Blake, D., and Wiedinmyer, C.: Emissions of volatile organic compounds inferred from airborne flux measurements over a megacity, Atmos. Chem. Phys, 9, 271-285, 2009.

Langford, B., Misztal, P., Nemitz, E., Davison, B., Helfter, C., Pugh, T., MacKenzie, A., and Hewitt, C.: Fluxes and concentrations of volatile organic compounds from a South-East Asian tropical rainforest, 2010, 4293, p. 27337, line 12. ". . . about 50% of NOx is thought to be derived from vehicles,"

Lee, J., Helfter, C., Purvis, R., Beavers, S., Carslaw, D., Lewis, A., Moller, S., Nemitz, E., and Tremper, A.: Measurement NOx fluxes from a tall tower above central London, UK and comparison with emissions inventories. , Environ. Sci. Technol. DOI: 10.1021/es5049072, 2015.

3.1

p. 27337, line 28. "However, these networks only measure mixing ratios . . ." Please

describe what other measurements these networks should provide.

3.2/3.3

Text now reads "However, measurements from these networks suffer from the limitations of being made at relatively few sites and so may not be representative of mixing ratios over larger spatial scales".

4.1

p. 27339, line 17. "Parallel wind directions allow us to assess the horizontal advection and dispersion of pollutants across the city and their transport to suburban and rural regions." Was this done in the following text? I didn't see much discussion of RFs 7-10 beyond Tables 1 and 2. Perhaps these flights could be removed from the manuscript if they are not part of the discussion section.

4.2/4.3

Agreed flights RF 7-10 have been removed from the manuscript

5.1

p. 27341, line 12. "Typically calibrations are carried out at the beginning and end of a flight, with sensitivities and conversion efficiency Interpolated between the two and applied to all data." Was the data corrected for O3 and H2O (titration of NO and quenching of NO2 excited state, respectively)? Any idea how important those effects would have been to your set of sampling conditions?

5.2

Data was not corrected for H2O or O3, however, we actually humidify the sample flows so that any changes in ambient humidity to do affect instrument sensitivity.

5.3

This has now been added to the instrument description text. Changes in O3 are of minor importance and will have an effect of <0.5% on instrument sensitivity under the conditions experience on these flights.

6.1

p. 27341, line 18. "Ozone was quantified in-situ, using a Thermo Scientific 49i . . ." Is this instrument sufficiently fast to compare with other measurements?

6.2/6.3

We feel the 4 second averaging from this instrument (which is the instrument's fastest acquisition rate) is suitable for comparing to the 1s averaged data from the other instruments. Ozone was only compared to the faster data over diurnal or vertical profile averages, meaning there was always a significant number of overlapping points.

7.1

p. 27343, line 11. ". . . 6-8 normalised ion counts per second (ncps) . . ." Please describe how the data is normalized - which ion(s) are used for normalization?

7.2

As described previously (Warneke et al., 2001, generally a humidity dependent PTRMS sensitivity can be expected for two classes of compounds. These are substances, such as benzene and toluene, that do not react with the hydrated hydronium ions and substances with a proton affinity close to water, such as formaldehyde. To account for this humidity dependent PTRMS sensitivity toward benzene and toluene, these compounds were normalised against the hydronium ion counts only.

Warneke, C., Van der Veen, C., Luxembourg, S., De Gouw, J., and Kok, A.: Measurements of benzene and toluene in ambient air using proton-transfer-reaction mass spectrometry: calibration, humidity dependence, and field intercomparison, International Journal of Mass Spectrometry, 207, 167-182, 2001.

7.3

The following text has been added: "Benzene and toluene, do not react with the hydrated hydronium ions generated at higher ambient air humidity within the PTRMS drift tube(Warneke et al., 2001). To account for this humidity dependent PTRMS sensitivity toward benzene and toluene, these compounds were normalised against the hydronium ion counts only".

8.1

p. 27346, line 3. ". . . increasing the NOx oxidation rate leading to decreased NO2 and increased O3 (Pudasainee et al., 2010]." The authors of the cited work describe increased NO2 photolysis leading to decreased NO2 and increased O3. Oxidation of NOx could imply conversion of NOx to further oxidized species (e.g. HNO3). Also, the authors discuss Ox (NO2 + O3) later in the manuscript (Figure 7) with regards to RF 1. I wonder if a discussion of Ox here for RFs 2-6 would help to distinguish between O3 titration and production.

8.2/8.3

We have re-written this paragraph to clarify:

"Variations in O_3 mixing ratio are generally attributed to photochemical production in the mixing layer with some contribution from entrainment from the free troposphere (Dueñas et al., 2002). In London, the low O_3 morning mixing ratios were attributed to the destruction of O_3 by rapid titration with NO, which is emitted during the morning rush hour and highest during the morning. As the day progresses, sunlight intensity becomes higher increasing the radical concentration and hence NO to NO_2oxidation rate from the reaction of NO with peroxy radicals. Subsequent photolysis of NO_2 leading to increased O_3 throughout the day (Pudasainee et al., 2010), with this rate of O_3 production being a function of NO_x and VOC levels and well as sunlight intensity."

9.1

p. 27347, line 27. "These T/B ratios are similar to the average T/B concentration ratio of 1.8 ± 0.3 ppbv ppbv-1 observed within inner London in this study," The supplementary material indicates that the PTR/WAS-FID intercomparisons for benzene and toluene were 1.08 and 0.79, respectively. By my math, this would yield a WAS-FID derived T/B ratio of (1.08/0.79) x 1.8 = 2.5 ppbv ppbv-1. This would be slightly higher than the range of values reported by the ground sites. Do the ground sites use GC-FID? Are the ratios equivalent within uncertainties (I've not bothered to propagate the uncertainties here)?

9.2/9.3

The ground sites are part of the London Air Quality network and do use GC/FID. The PTRMS/WAS-FID comparisons are discrete comparisons made by comparing real-time insitu PTRMS measurements against whole air canister samples (approximately 2 per flight) which were analysed using a dedicated laboratory GC-FID (York University).

Using the variance formula method of uncertainty propagation produces a PTRMS vs GCFID Toluene/Benzene concentration ratio total uncertainty of 30%. For a WAS-FID vs PTR/MS derived T/B ratio of (1.08/0.79) x 1.8 = 2.5± 0.75 ppbv ppbv-1, hence the ratios are equivalent within uncertainties.

10.1

p. 27348, line 11. "This trimodal distribution between benzene, toluene and NO2 . . ." I don't think this is a tri-modal distribution, but rather these three species have significant covariance. A tri-modal distribution would be a population having three maxima over some range (e.g. particle concentration as a function of diameter, with nucleation, accumulation and coarse modes).

10.2/10.3

We agree. This has now been adjusted throughout the text.

11.1

p. 27348, line 16. "Figure 5 also suggests a secondary source contribution to toluene that is not shared with NO2 or benzene . . .” Is there any toluene source indicated in the NAEI that can reconcile the observed plume of toluene?

11.2/11.3

There is no specific toluene emission data available for the NAEI (2012). However, upon analysis of benzene and total VOC emission (NAEI 2012) using ArcGIS, no sources were evident within the region.

12.1

p. 27350, lines 1-19. “VOC and NOx emissions from airports . . .” This paragraph would be more appropriate in the introduction of the paper, as it presents a discussion of the literature rather than of the authors’ work. Also, please provide a reference for the first sentence of the cited paragraph.

12.2/12.3

We agree. The sentence has been moved to the Introduction section and the first paragraph has been cited.

13.1

p. 27352, line 15. “However, Ox mixing ratios are substantially reduced at ground level likely due to enhanced O3 titration with NO . . .” I don’t understand how enhanced O3 titration by NO would perturb the Ox mixing ratio, as O3 +NO yields NO2 (+ O2), and Ox is the sum of NO2 and O3. Why wouldn’t Ox be expected to be conserved here?

13.2/13.3

We agree and have corrected this error. The manuscript now reads “However, O_x mixing ratios are substantially reduced at ground level possibly due to enhanced deposition in proximity to the surface”.

14.1

p. 27353, line 28. “However, recent developments in diesel emission technology . .” I found this section of the discussion intriguing. Could an evaluation of weekday vs weekend mixing ratios provide some information to tease out effects from diesel emissions (e.g. Pollack et al., 2012, doi:10.1029/2011JD016772)? I’m not sure if there’s enough flight data for this, but the ground sites may prove useful here.

14.2/14.3

We agree that in principal this would be an intriguing idea. However a detailed traffic density and fleet composition at weekdays and weekends within Greater London would be required. Also we only have very limited flight data, with only a single flight made within the weekend period making a weekday vs weekend comparison tenuous. Ground data could be used for such an analysis but we feel that such an analysis would go beyond the scope of this manuscript.

15.1

p. 27355, line 12. “The reason these VOCs correlate well with NO2, but not NO is possibly because of the ubiquity of diesel vehicles in London.” I’m not sure the discussion provided sufficient evidence for this statement in the conclusions. The authors twice state “[h]owever the measured NO/NO2 concentration ratio at 360 m.a.g.l. is likely to be dominated by photochemistry rather than emission sources (Atkinson et al., 2000).” I can’t see how this statement can be reconciled with the sentence above, without further analysis and interpretation of the data (e.g., considering periods of high and low diesel traffic emissions).

15.2/15.3

We agree and retract the statement ““The reason these VOCs correlate well with NO2, but not NO is possibly because of the ubiquity of diesel vehicles in London.” Replaced with “As the measured NO/NO2 concentration ratio at 360 m.a.g.l. is likely to be dominated by *photochemistry rather than emission sources, VOCs correlate well with NO2 but not NO due to its longer atmospheric lifetime (Atkinson et al., 2000)".*

16.1

p. 27338, line 18. "... none pressurised aircraft ..." Change to "... non-pressurised aircraft ..."

16.2

Corrected.

17.1

p. 27338, p. 23. "... maximum range of 2400 km (5 hr at 500 kg)." I don't understand the parenthetical comment – to what does the 500 kg refer? Sorry if this is obvious to others.

17.2

Parenthetical comment removed

18.1

p. 27339, line 2. "Figure 1a shows all flight legs ..." There is no "a" or "b" in Figure 1 (Figure text refers to top and bottom).

18.2/18.3

Figure caption changed to

"Figure 1a: top map showing all NERC Dornier-228 flights overlaid on UK transport map. Figure 1b: bottom map showing total flight legs across Greater London. Grey area; Greater London boundary, black area; inner London boundary, blue area; London CCZ. "

19.1

p. 27341, line 6. “. . . by adding a small a flow . . .” change to “. . . by adding a small flow . . .”

19.2

Corrected

20.1

p. 27342, line 8. “. . . the inlet flow (50-500 STP sccm)” change to “. . . the inlet flow (50-500 sccm)”

20.2

Corrected

21.1

p. 27345, line 27. “O3 mixing ratios were superficially anti-correlated to NOx . . .” Is ‘superficially’ necessary here?

21.2

“Superficially” removed

22.1

p. 27347, line 26. “. . . showed T/B ratios of 1.6 (1.3-2.0) ppbv ppbv-1 . . .” Please define the meaning of the numbers in parentheses.

22.2

Corrected. Now reads "showed average T/B ratios of 1.6±0.3 ppbv ppbv^{-1} *and 1.8±0.3 ppbv* ppbv^{-1} *respectively"*

23.1

p. 27362. Table 1, RF2 is shown having an April flight date. Is this correct?

23.2

Corrected