AIRCRAFT OBSERVATIONS OF THE URBAN CO_2 DOME IN LONDON AND CALCULATED DAYTIME CO_2 FLUXES AT THE URBAN-REGIONAL SCALE

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1. INTRODUCTION

Traffic, industry and energy production and consumption within urban boundaries emit great amounts of CO_2 into the atmosphere, creating an urban increment of CO_2 compared to the surrounding rural atmosphere which is called '***urban domes***'. Monitoring *urban domes* is proposed as a means to evaluate the effectiveness of policies aiming to mitigate CO_2 urban emissions[1]. London is the biggest urban conurbation in Western Europe with more than 8m inhabitants, and it emitted ~45000 ktn CO_2 in 2010[2]. In order to develop and implement observational strategies to measure the contribution of London into the global carbon cycle, two airborne surveys were deployed in October 2011 and July 2012. The objectives of the campaigns were to measure the CO_2 dome over London and to calculate CO_2 emissions at the urban-regional-scale.

2. METHODS

2a. INSTRUMENTATION

Aircraft surveys in SE England and London were undertaken onboard of the NERC-ARSF aircraft (Fig. 1)

Aircraft: Dornier 228

Met data: AIMMS-20 Air probe

Particle counter: GRIMM Sky OPC

CO_2: - AOS Inc.

- PICARRO (only July 2012)

O_3: Thermo 49 i

CH_4 : PICARRO (only July 2012)

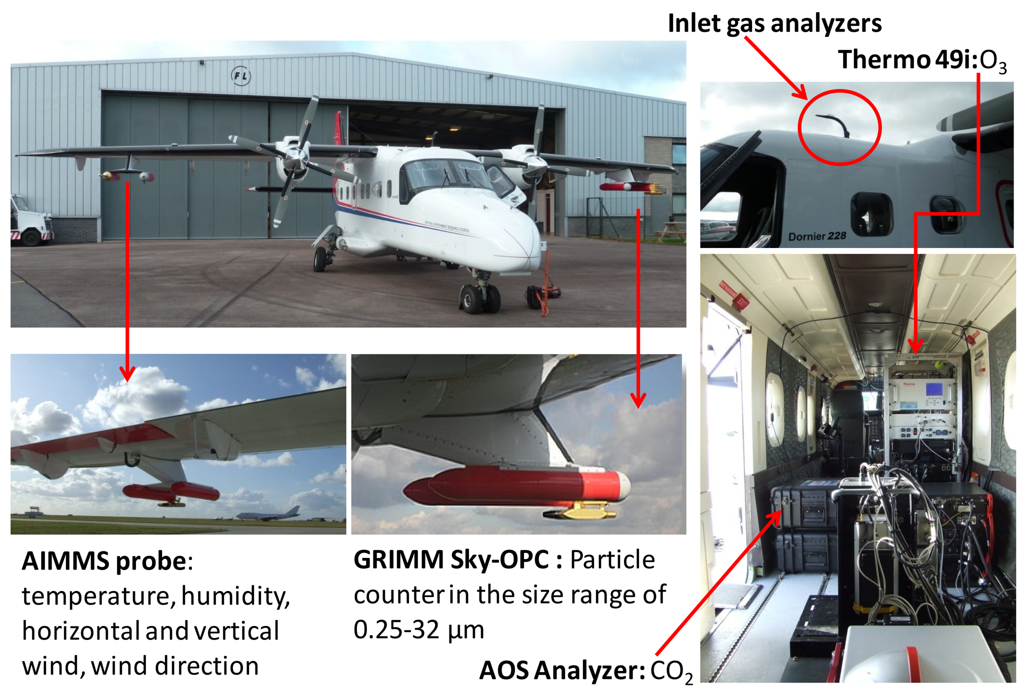

Fig. 1. Aircraft and instrumentation used in the surveys undertaken on October 2011 and July 2012.

2b. SURVEY DESIGN

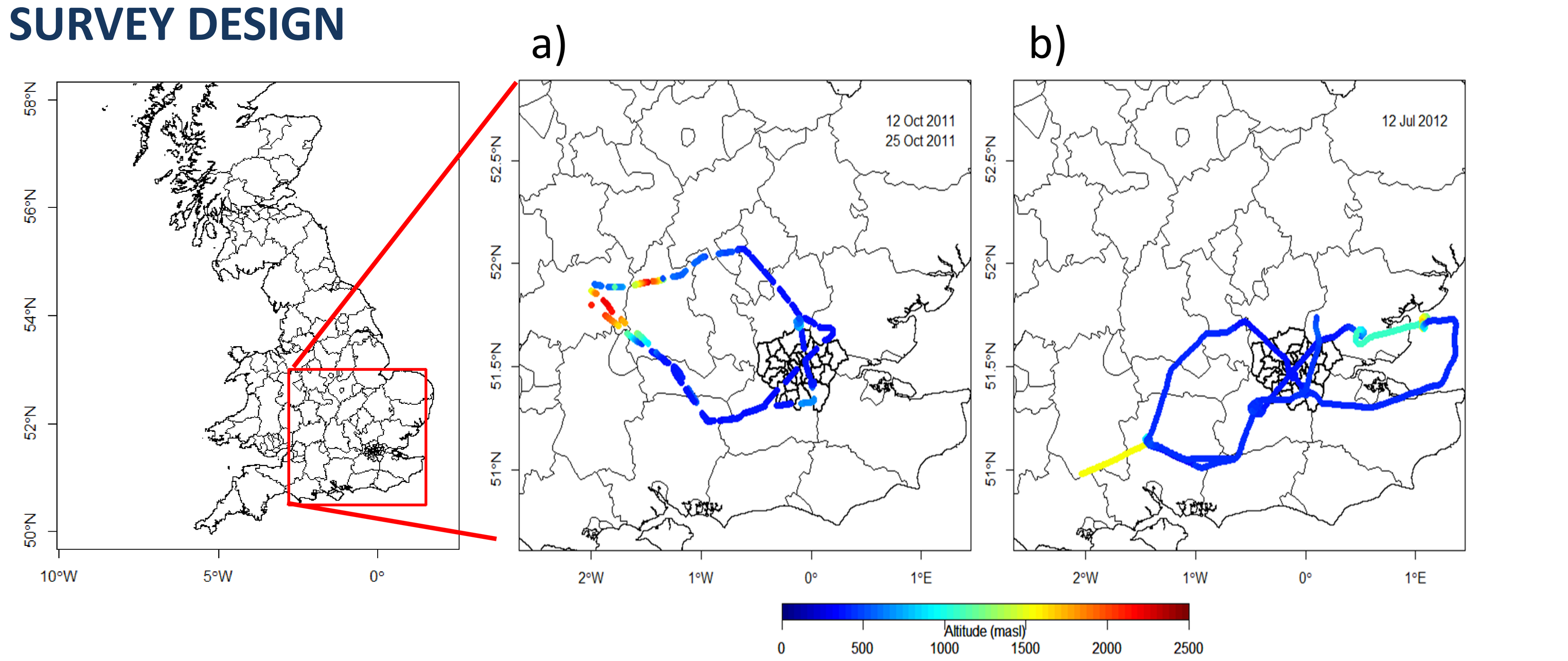

Fig. 2. Location map where aircraft surveys were undertaken in SE England. Flight tracks for the surveys carried out in October 2011 (a) July 2012 (b). Colour scale indicates the altitude of the aircraft. Thick black line delimitates London.

2c. INTEGRATIVE MASS BOUNDARY LAYER METHOD (IMBL)

Spatial and temporal integrated CO_2 surface fluxes are calculated by the IMBL method. It considers the Boundary Layer (BL) as a box where scalars are conserved[3,4]. The variation of the CO_2 concentration ($\partial[CO_2]$) in time (∂t) in the BL, termed as storage, can be split into three components: surface flux (F_{CO2}), entrainment flux (F_e) and advection flux (F_{adv}). Measuring changes on the $[CO_2]$ in time in the BL and characterizing the entrainment and the advection, surface emissions are calculated (Eq. 1).

$$F_{CO_2} = \underbrace{\langle h\rangle \frac{[CO_2]_2 - [CO_2]_1}{t_2 - t_1}}_{F_{stg}} - \underbrace{\left(\frac{h_2 - h_1}{t_2 - t_1} - w_+\right)\left([CO_2]_+ - \langle [CO_2]\rangle\right)}_{F_e} + \underbrace{\langle h\rangle \langle U\rangle \left\langle \frac{\Delta [CO_2]}{\Delta x}\right\rangle}_{F_{adv}} \quad \text{Eq. (1)}$$

h is the BL height (m); w_+ is the vertical wind at the top of the BL (m s^{-1}); ‹U› is the mean horizontal wind in the BL (m s^{-1}); $[CO_2]$ is the CO_2 concentration in the BL (mol m^{-3}) ; $[CO_2]_+$ is the CO_2 concentration above the BL(mol m^{-3}); ‹ $\Delta[CO_2]/\Delta x$ › is the CO_2 spatial gradient (mol m^{-2})

Eq. 1 has been applied either by calculating changes on the $[CO_2]$ in horizontal transects over London at 360 m at different times of the day; or by measuring changes of $[CO_2]$ above upwind conditions by sampling a vertical profile downwind London.

3. RESULTS

3a. CO_2 URBAN INCREMENTS IN LONDON

The increment of CO_2 mixing ratio in London compared to the surrounding measurements at 360 m of altitude depended on the weather conditions. Under low wind speeds (<8 m s^{-1}) the CO_2 mixing ratio peaked in central London and decreased towards the city boundaries (Fig. 3). The mean urban CO_2 increment was 3.7 ± 2.2 ppmv (Table 1). In windy days the structure of the urban dome was dispersed downwind with peak mixing ratios displaced from the urban centre along the main wind direction (Fig. 4). The CO_2 concentration measured in and outside London was statistically similar and low urban increments were measured (0.2 ± 0.6 ppmv).

Under low wind speed conditions (< 8 m s^{-1})

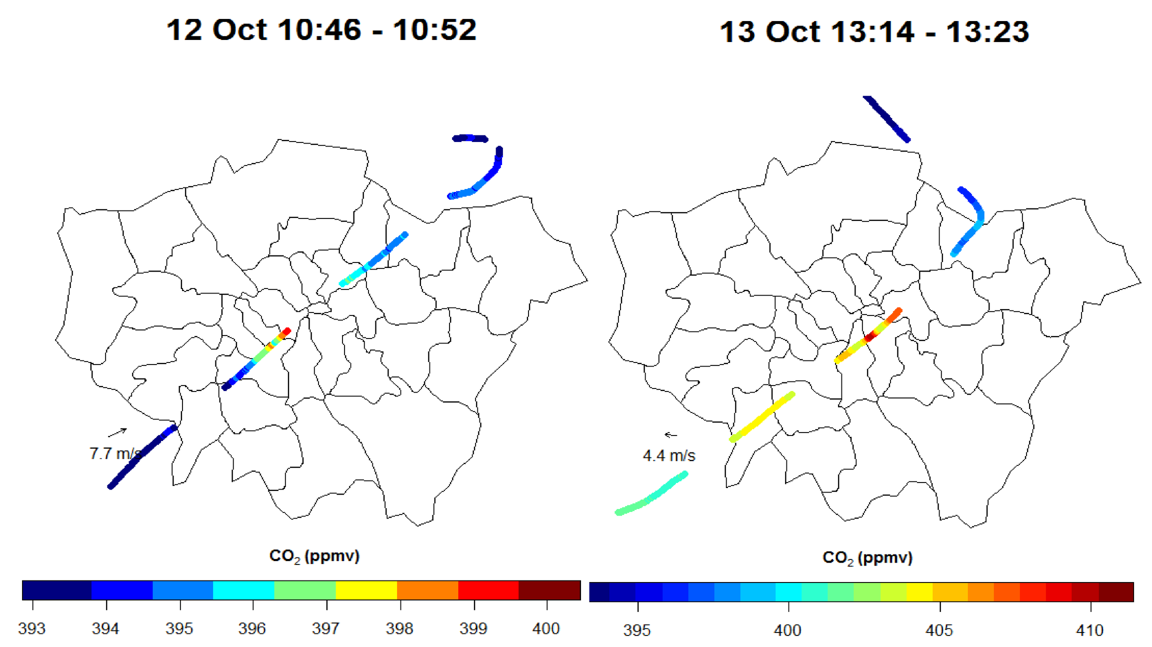

Fig. 3. Distribution of the CO_2 mixing ratio in and outside London under low wind speed conditions (< 8 m s^{-1}) as measured on the 12 and 13 Oct 2011 at 360 m of altitude onboard of the NERC-ARSF aircraft.

Under high wind speed conditions (> 8 m s^{-1})

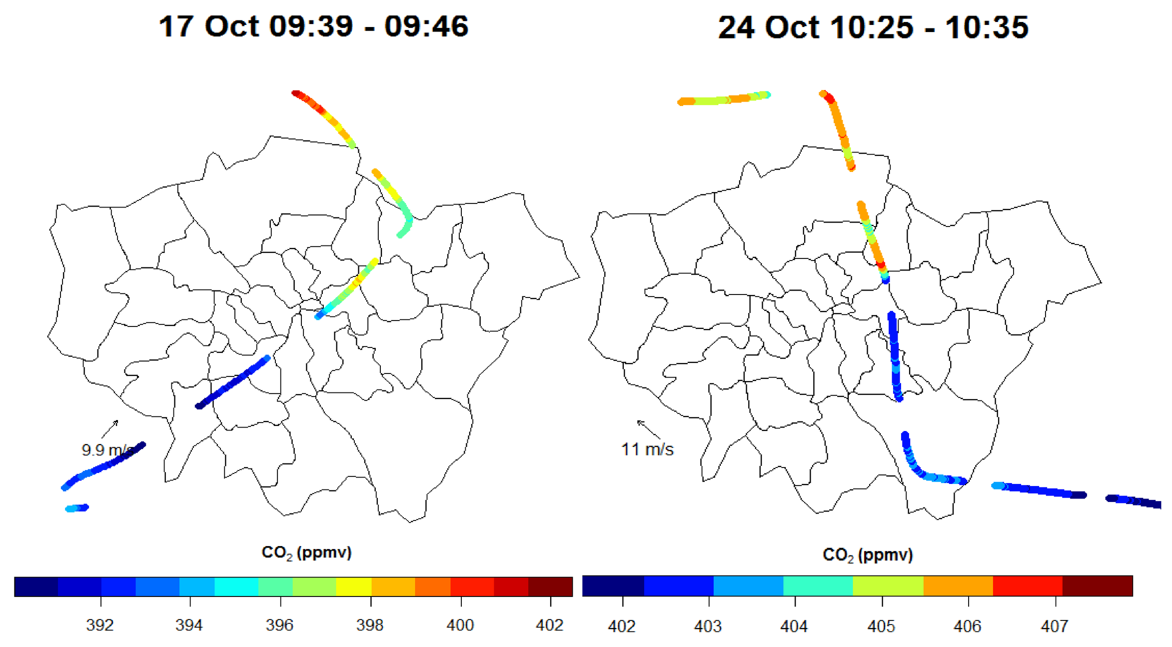

Fig. 4. Distribution of the CO_2 mixing ratio in and outside London under high wind speed conditions (> 8 m s^{-1}) as measured on the 17 and 24 Oct 2011 at 360 m of altitude onboard of the NERC-ARSF aircraft.

Table 1. Mean (±1σ) increment of CO_2 in the urban atmosphere at 360 m compared to the surrounding suburban and rural measurements; 1st, median and 3rd quartile for the surveys carried out under low (< 8 m s^{-1}) and under high (> 8 m s^{-1}) wind speed conditions.

ΔCO_2 (ppmv)	Low wind speed	High wind speed
X ± σ	3.7 ± 2.2	0.2 ± 0.6
1st quartile	1.9	-0.2
Median	3.5	0.2
3rd quartile	4.4	0.7

3b. URBAN REGIONAL CO_2 FLUXES IN LONDON

The surface CO_2 flux for London at the urban-regional scale was calculated by means of the IMBL method (Eq. 1) for 4 days in October 2011. In order to calculate the area that fluxes were representative for the Lagrangian Particle Dispersion Model FLEXPART[5] was run. IMBL fluxes were compared to the CO_2 emissions inventory reported by Department of Energy and Climate Change (DECC) for London in 2010 for the same representative area (Table 1) and with turbulent CO_2 fluxes observed by two eddy-covariance (EC)[6] towers located in central London (Fig. 5). The mean IMBL CO_2 flux was statistically similar as those reported by the emissions inventory and by the EC systems .

Table 1. Values used to calculate the spatial and temporal integrated CO_2 urban-regional scale flux (F_{CO2}) in London using the IMBL method, F_{stg} is the storage flux, F_e the entrainment and F_{adv} the advection term. F_{DECC} refers to the spatial integrated emissions for each survey calculated from the DECC emissions inventory[2].

	13 Oct	17 Oct	24 Oct	25 Oct
t_1 (UTC)	13:15	9:40	10:15	11:05
t_2 (UTC)	15:30	10:15	10:55	11:15
CO_2 (t_1) ±1σ (ppmv)	404.4 ± 3.5	394.8 ± 2.8	401.4 ± 0.3	394.6± 0.2
CO_2 (t_2) ±1σ (ppmv)	405.1 ± 8.0	392.8 ± 1.4	406.7 ± 0.4	398.7 ± 0.3
CO_{2+} ±1σ (ppmv)	391.3 ± 0.5	390.0 ± 0.4	401.0 ± 1.2	394.1 ± 0.2
‹CO_2› ±1σ (ppmv)	404.7 ± 5.8	393.7 ± 2.3	401.4 ± 0.3	394.6± 0.2
h_1 (m)	815	400	410	450
h_2 (m)	1180	1130	480	450
w_+ (mm s^{-1})	-2.5 ± 0.76	-0.18 ± 3.6	-2.2 ± 3.1	-5.6 ± 3.6
‹U› (m s^{-1})	4.5 ± 0.5	9.9 ± 1.5	---	---
‹$\Delta[CO_2]/\Delta x$› (µmolCO_2 m^{-2})	---	$(1.1 \pm 0.1)\cdot 10^{-2}$	---	---
F_{stg} (µmol CO_2 m^{-2} s^{-1})	$0.3 \pm 2.0\cdot 10^{-3}$	$-21.5 \pm 18.4\cdot 10^{-3}$	29.9 ± 0.1	119.0 ± 0.6
F_e (µmol CO_2 m^{-2} s^{-1})	-50.4 ± 9.2	-29.5 ± 18.5	-11.6 ± 1.6	-1.1 ± 0.8
F_{adv} (µmol CO_2 m^{-2} s^{-1})	---	-37.9 ± 6.1	---	---
F_{CO2}(µmol CO_2 m^{-2} s^{-1})	50.7 ± 9.2	46.0 ± 19.5	41.5 ± 1.6	120.0 ± 1.0
F_{DECC} (µmol CO_2 m^{-2} s^{-1})	38.0	45.0	57.2	133.5

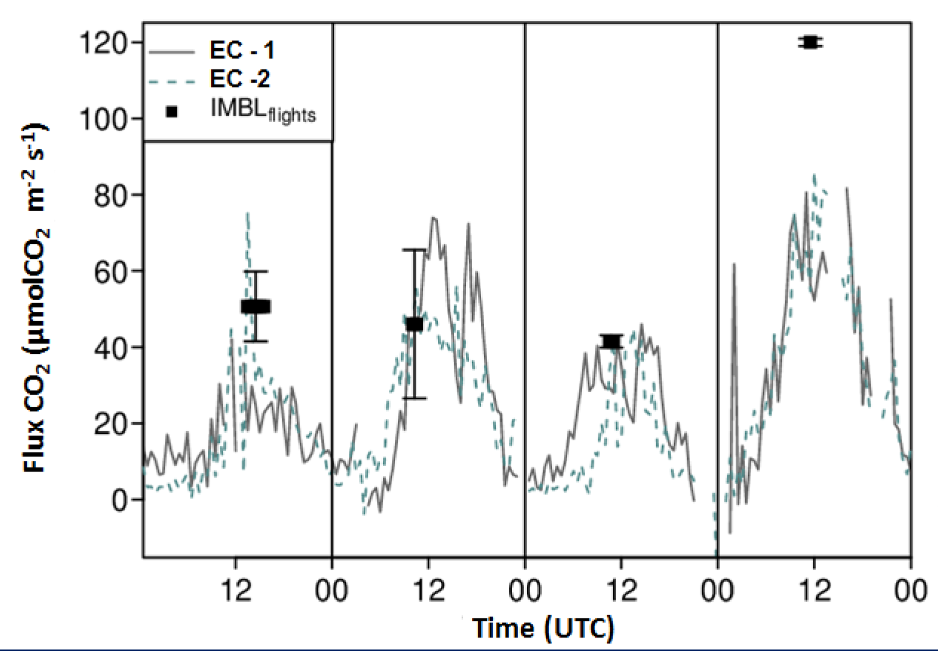

Fig. 5. Time series of turbulent fluxes of CO_2 as observed at two eddy covariance sites in central London (lines) and estimates from the aircraft observations (rectangles).

4. CONCLUSIONS

This study provides an example how aircraft surveys in urban areas can be used to estimate CO_2 surface fluxes at the urban-regional scale. It also presents an important cross-validation of two independent measurement-based methods to infer the contribution of urban areas to climate change in terms of CO_2 emissions that complement bottom-up emissions inventories.

REFERENCES [1]Committee on Methods for Estimating Greenhouse Gas Emissions (2010), The National Academia Press. [2]Department of Energy and Climate Change (2012), http://data.london.gov.uk/datastore/package/carbon-dioxide-emissions-borough. [3]Denmead, O. T., et al. (1996) Boundary-Layer Budgets for Regional Estimates of Scalar Fluxes, Global Chan. Biol., 2, 255–264. [4]Guenther, A., et al. (1996), Estimates of regional natural volatile organic compound fluxes from enclosure and ambient measurements, J. Geophys. Res., 101, D1, 1345-1359. [5]Stohl, A., et al. (2005), Technical note: the Lagrangian particles dispersion model FLEXPART version 6.2., Atmos. Chem. Phys. 5, 2461–2474. [6]Kotthaus, S., and Grimmond, C. S. B. (2012) Identification of Micro-scale Anthropogenic CO_2, Heat and Moisture Sources – Processing Eddy Covariance Fluxes for a Dense Urban Environment, Atmos. Environ., 57, 301-316, doi: 10.1016/j.atmosenv.2012.04.024.