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Effects of urban density on carbon dioxide exchanges: Observations of dense urban, suburban and woodland areas of southern England

H.C. Ward [a, c, *], S. Kotthaus [a, b], C.S.B. Grimmond [a], A. Bjorkegren [b], M. Wilkinson [d], W.T.J. Morrison [a], J.G. Evans [c], J.I.L. Morison [d], M. Iamarino [e]

[a] Department of Meteorology, University of Reading, Reading, RG6 6BB, UK
[b] Department of Geography, King's College London, London, WC2R 2LS, UK
[c] Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, UK
[d] Forest Research, Centre for Forestry and Climate Change, Alice Holt Lodge, Farnham, Surrey, GU10 4LH, UK
[e] Scuola di Ingegneria, Università degli Studi della Basilicata, 85100, Potenza, Italy

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ABSTRACT

Anthropogenic and biogenic controls on the surface–atmosphere exchange of CO_2 are explored for three different environments. Similarities are seen between suburban and woodland sites during summer, when photosynthesis and respiration determine the diurnal pattern of the CO_2 flux. In winter, emissions from human activities dominate urban and suburban fluxes; building emissions increase during cold weather, while traffic is a major component of CO_2 emissions all year round. Observed CO_2 fluxes reflect diurnal traffic patterns (busy throughout the day (urban); rush-hour peaks (suburban)) and vary between working days and non-working days, except at the woodland site. Suburban vegetation offsets some anthropogenic emissions, but 24-h CO_2 fluxes are usually positive even during summer. Observations are compared to estimated emissions from simple models and inventories. Annual CO_2 exchanges are significantly different between sites, demonstrating the impacts of increasing urban density (and decreasing vegetation fraction) on the CO_2 flux to the atmosphere.

1. Introduction

Carbon dioxide concentrations continue to increase globally, reaching 400 ppm on a daily basis at Mauna Loa in 2013 (The Keeling Curve, 2014). Over 70% of global greenhouse gas emissions are from urban areas (IEA, 2012). While a large number of studies have documented the seasonal dynamics of carbon fluxes of vegetated ecosystems (e.g. Schmid et al., 2000; Baldocchi et al., 2001; Aubinet et al., 2012), comparable measurements from urban areas remain relatively limited (see reviews by Velasco and Roth, 2010; Grimmond and Christen, 2012; Christen, 2014; Weissert et al., 2014). The earliest measurements in cities began in the mid-1990s (Grimmond et al., 2002; Nemitz et al., 2002), yet only very recently have multi-year urban fluxes been published (Pawlak et al., 2010; Bergeron and Strachan, 2011; Crawford et al., 2011; Järvi et al., 2012; Liu et al., 2012; Peters and McFadden, 2012). Thus understanding of CO_2 exchanges based on direct observations in regions with large urban fluxes is limited. Instead, estimates of emissions are mostly based on fuel consumption inventories, but these tend to have coarse spatial and temporal resolution and do not include biogenic processes such as photosynthetic uptake by urban vegetation (Järvi et al., 2012; Crawford and Christen, 2014). However, to explore the potential impacts of urban planning schemes and policy decisions, or to make predictions about future climates, improved understanding of processes relevant to the urban carbon balance is required. Pataki et al. (2011) highlight the need for more rigorous evaluation of urban greening schemes, which should include both positive and negative impacts on the ecosystem as a whole, realistic cost-benefit analyses and consideration of site-specific and species-dependent behaviour.

Per unit area, annual CO_2 exchanges measured in urban areas greatly exceed those from nearby natural ecosystems: average annual CO_2 release in Helsinki is forty times larger than the uptake by a nearby wetland and eight times larger than the uptake by a boreal forest (Järvi et al., 2012). In highly-vegetated Baltimore,

* Corresponding author. Department of Meteorology, University of Reading, Reading, RG6 6BB, UK.
E-mail address: h.c.ward@reading.ac.uk (H.C. Ward).

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however, net CO_2 release is similar in magnitude to the net uptake of nearby forests (Crawford et al., 2011). Few campaigns have quantified CO_2 exchanges for different urban densities concurrently. Coutts et al. (2007) presented fluxes from two suburban sites in Melbourne, and Bergeron and Strachan (2011) compared fluxes from urban, suburban and agricultural sites in Montreal. Measurements of CO_2 concentration across urban-to-rural gradients in the US include the work of Strong et al. (2011) in Salt Lake Valley and Briber et al. (2013) in Boston. Given the apparent inability of vegetation to assimilate large enough quantities of CO_2 to offset emissions (Pataki et al., 2011; Weissert et al., 2014), quantifying the effect of human behaviour on CO_2 exchange becomes an even more critical area for research. Approaches include long-term observational campaigns which encompass policy changes, for example Song and Wang (2012) assessed the impact of traffic reduction due to the Beijing Olympics in 2008, and combining measurements and models to better inform the attribution of measured CO_2 emissions to various human activities such as building energy use, transport and metabolism (e.g. Christen et al., 2011; Strong et al., 2011).

The objective of this study is to relate observed CO_2 exchanges to physical processes, through consideration of meteorological conditions and surface characteristics. Direct eddy covariance measurements of CO_2 fluxes from three very different land uses (urban, suburban and woodland) over the same period are compared. The sites are located within one of the most densely populated regions of Europe: southern England. This region, which includes London, has been extensively modified by human activities in both rural and urban areas. Atmospheric controls are considered first, by comparing the meteorology observed at each site. After demonstrating the similarity in climatic conditions, links between CO_2 flux and surface characteristics (e.g. land cover, urban density) are explored.

2. Materials and methods

2.1. Description of sites

In this paper measurements undertaken at three sites 70–100 km apart and at approximately the same latitude in southern England (Table 1, Fig. 1) are compared. These are a dense urban environment in central London (U); a predominantly residential suburban site in Swindon (S); and a deciduous oak woodland at the Alice Holt Research site (W). Additional details are provided elsewhere (London (Kotthaus and Grimmond, 2012; 2014a,b); Swindon (Ward et al., 2013); Alice Holt (Wilkinson et al., 2012)).

Across the sites there is a gradient of impervious to pervious land cover, with London having 81% of the plan area covered by roads and buildings, Swindon 49% and Alice Holt effectively 0% (Table 1). The heights of the roughness elements (i.e. buildings and trees) are similar in London and Alice Holt (>20 m) but smaller in Swindon (≈6 m). There is very little vegetation at the central London site; trees are mainly London plane (*Platanus hispanica*) and grass lawns are mainly confined to small public gardens. In Swindon, grass is the predominant surface cover and grows alongside roads as well as in residential gardens, recreational areas and on undeveloped land. Trees comprise a range of species but are mainly deciduous. At Alice Holt the predominant tree species is oak (*Quercus robur*) with hazel (*Corylus avellana*) and hawthorn (*Crataegus monogyna*) making up the understorey (Wilkinson et al., 2012). The above and below ground tree biomass is estimated to be 13.4 kg C m^{-2} (excluding shrubs and ground flora, based on 2009 data) and the mean peak leaf area index is 5.9 m^2 m^{-2} (1999–2010 data).

Table 1
Site characteristics (values are those given in the respective publications; surface cover is calculated at U for the average footprint climatology (Kotthaus and Grimmond, 2014b), at S for 500 m around the tower (Ward et al., 2013) and at W for the woodland area (Wilkinson et al., 2012)). z_H is the average building or tree height; z_d zero plane displacement height; z_0 roughness length.

	London (U)	Swindon (S)	Alice Holt (W)
Location	51°30′ N 0°07′ W	51°35′ N 1°48′ W	51°09′ N 0°51′ W
Classification	Urban	Suburban	Woodland
Description	High density central business district	Low-rise residential	Deciduous oak plantation
z_H [m]	22.0	5.5	21.0
z_d [m]	14.2	3.5	15.3
z_0 [m]	1.9	0.5	2.2
Surface cover [%]			
Impervious	43	33	0
Buildings	38	16	0
Vegetation (trees)	5 (2)	44 (9)	98 (97)
Open water	14	0	0.5
Bare soil	0	6	1.5

2.2. Instrumentation and data processing

Net fluxes of CO_2 between the surface and atmosphere were obtained for 30-min intervals using the eddy covariance (EC) technique at each site. The micrometeorological sign convention is used, i.e. negative flux indicates CO_2 uptake by the surface and positive flux indicates CO_2 release. The instrumental setup is summarised in Table 2. Equipment was mounted on towers (a square-section tower at Alice Holt, lattice towers in London and a pneumatic mast in Swindon) to ensure that measurements were made well above the mean height of the roughness elements (z_H) and above the roughness sub-layer (>2 z_H for U and S; > 1.3 z_H for W, Tables 1 and 2). Sites were carefully selected to ensure the measurements are representative of the local environment. Although the source areas vary with meteorological conditions, footprint models indicate that the majority of the flux usually originates from within a few hundred metres (approximately 200–400 m) of the towers; at night these distances increase (to around 600–700 m) as instability decreases. The variation in land cover around each tower is far smaller than the difference in land cover between the three sites. Full characterisation is provided in the individual site papers.

Raw data from the sonic and gas analyser were processed using LiCOR's EddyPro software (S, W) or ECPACK (van Dijk et al., 2004) (U). The quality control procedures applied were selected based on the requirements of each site, dependent on their different characteristics (see Kotthaus and Grimmond, 2012, Ward et al., 2013 and Wilkinson et al., 2012 for details). This was judged to be the most appropriate methodology, rather than attempting to apply a single set of tests across all sites which may not be suitable for each environment. All sites were subject to the following standard procedures: adjustment for the lag time between sonic anemometer and gas analyser; correction of sonic temperature for humidity; correction for spectral losses. The planar fit coordinate transformation was applied to the London data; double coordinate rotation was used for Swindon and Alice Holt. Data from all sites were despiked and subjected to physically-reasonable threshold checks and data were removed during times of instrument malfunction. In London the influence of micro-scale building emissions was removed from the local-scale fluxes using an algorithm based on the statistical characteristics of turbulent events (Kotthaus and Grimmond, 2012); this procedure is not required at the less urbanised sites. No friction velocity (u_*) threshold was used to reject CO_2 fluxes at the suburban or urban site because the rough