ENVIRONMENTAL POLLUTION

Environmental Pollution 116 (2002) S243–S254

www.elsevier.com/locate/envpol

Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago

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"Capsule": *The direct measurement and modeling of surface to atmosphere exchanges of carbon dioxide in urban landscapes are lacking to date but will be characterized in the future with continuous eddy covariance measurements.*

Abstract

Much attention is being directed to the measurement and modeling of surface–atmosphere exchanges of CO_2 for different surface types. However, as yet, few measurements have been conducted in cities, even though these environments are widely acknowledged to be major sources of anthropogenic CO_2. This paper highlights some of the challenges facing micrometeorologists attempting to use eddy covariance techniques to directly monitor CO_2 fluxes in urban environments, focusing on the inherent variability within and between urban areas, and the importance of scale and the appropriate height of measurements. Results from a very short-term study of CO_2 fluxes, undertaken in Chicago, Illinois in the summer of 1995, are presented. Mid-afternoon minimum CO_2 concentrations and negative fluxes are attributed to the strength of biospheric photosynthesis and strong mixing of local anthropogenic sources in a deep mixed layer. Poor night-time atmospheric mixing, lower mixed layer depths, biospheric respiration, and continued emissions from mobile and fixed anthropogenic sources, account for the night-time maxima in CO_2 concentrations. The need for more, longer-term, continuous eddy covariance measurements is stressed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Urban environment; Carbon dioxide fluxes; Eddy-covariance

1. Introduction

Urban areas represent a location where a large and ever increasing number of people live and where a disproportionate share of natural resources, including fossil fuels, are used. Attempts to quantify the role of urban areas on the global carbon budget have focused largely on inventories of emissions, from estimates of fossil fuel consumption, cement production, etc. (e.g. Mensink et al., 2000) and the amount of carbon sequestered in urban vegetation based on biomass estimates (Nowak, 1994a; Jo and McPherson, 1995), or short-term studies of CO_2 concentrations, documenting spatial patterns across cities or at single sites through time (see examples in Table 1). While these studies have documented that CO_2 concentrations are greater in urban environments, and isotopic analyses (Nakazawa et al., 1997; Kuc and Zimnoch, 1998) have attributed this difference to anthropogenic sources, none of the studies have documented the actual fluxes of CO_2 and their diffusive characteristics in urban environments, essential for assessing the potential impact on climate and biosphere at all scales (Dabberdt et al., 1993).

Surface–atmosphere exchanges of CO_2 can be measured directly using micrometeorological techniques, notably eddy covariance equipment mounted on tall towers. This approach has been employed for other ecosystems, notably grasslands, forests and wetlands, as part of the global FLUXNET program (Baldocchi et al., 2001a,b). Based on such measurements, important data are emerging on the role of these different ecosystems, spatial and temporal (daily, seasonal, and annual) variability and controls. However, enormous challenges face micrometeorologists trying to make meaningful flux observations using such technologies in urban environments. The spatial variability of surface cover and roughness is extreme, presenting special challenges to those wanting to make representative measurements, both in terms of siting equipment to appropriately measure sources and sinks, and subsequently when trying to generalize results to larger areas.

The purpose of this paper is two-fold: first, to highlight some of the key issues that need to be considered when making direct (micrometeorological) flux measurements of CO_2 in urban environments, drawing on

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PII: S0269-7491(01)00256-1

Table 1
Examples of studies measuring CO_2 concentrations in urban environments with summary details of measurements and key results (peak concentrations and diurnal fluctuations)[a]

Author City/Land use	Measurement conditions	Sampling	Range of CO_2 concentrations	Mauna Loa (ppmv)
Continuous measurements				
Woodwell et al. (1973) Brookhaven, Long Island, New York Research lab (2000 ha), with oak–pine forest	1965–1971: 159–24 h periods Sampling at: 3, 6, 12, 23, 46, 92, 108 and 125 m	Mine safety LIRA Model 200 IRGA Each level pumped to IRGA, sampled for 5 min (45 min for cycle) ±0.5–1 ppm	Fluctuations greatest closer to the ground diminish to 125 m; Local weather conditions very important; Winter peak (December–April). Wind direction influences impact of New York city; when inversion present, peak just before dawn Highest observed: > 500 ppmv Lowest: daylight, summer: 290–300 ppmv. Winter–summer difference at 125 m: 19 ppmv	1966/6: 323.59 1965–1971:323.16
Tanaka et al. (1985) Sendai, Japan Suburbs	December 1978–June 1981 30 m above ground (roof of building 20 m) 0.5 m above an unvegetated field	Hitachi-Horibia IRGA	Diurnal variations: up to 24 ppmv; greatest in the warm season—maximum June 1979 354 ppmv Minimum in afternoon; maximum in early morning Winter: 2 week maxima just after sunset and before noon. Means: 1–15 ppmv less at 30 m than 5 m	1978/12–1981/6: 339.2
Kuc (1991); Kuc and Zimnoch (1998) Krakow, Poland West of city bordering sports grounds	1983–1994 17 m above ground (roof of building)	Volumetric method (error < 5%) Sorption in a molecular sieve—biweekly interval	1983–1988 Mean: 374 ppmv 1983–1994 Mean: 373 ppmv Highest mean: 1991: 376 ppmv Decreasing values attributed to change in heating methods in the city	1983–1988: 346.6 1983–1994:351.17
Berry and Colls (1990a) Nottingham, UK City Center	Summer and winter 1984–1985 (8 months) Twice per day: just before dawn and mid-afternoon 4 m above a concrete pathway	ADC-225 IRGA At least 40 m from domestic, chimneys and traffic sources	Summer: no difference with paired rural site; winter: urban site 5 ppmv greater Urban—two peaks—morning and early evening; Diurnal range much reduced compared with rural site ~30 ppmv	1984: 344.25 1985: 345.74
Sigrist (1994) Biel, Switzerland Suburb	2–3 July 1986 Trailer system houses laser Height of observation not given	Tunable laser (Ultra Lasertech) Photosacoustic (PA)	Average 350 ppmv	1984/7:347.76
Ghauri et al. (1994) Karachi, Pakistan 13 sites	May 1990 (15 days): 06:00–21:00 h Height of observation not given	Technique not given	Busy urban streets exceeded 370 ppmv	1990/5:357.00
Aikawa et al. (1995) Nagoya, Japan	November 1990–December 1993		1991: 381 ppmv; 1992: 382 ppmv; 1993: 377 ppmv Summers lower than winter. Urban lower during the day, higher at night. Rush hour detected morning and afternoon	1991: 355.48 1992: 356.29 1993: 356.99

(*continued on next page*)

Table 1 (*continued*)

Author City/Land use	Measurement conditions	Sampling	Range of CO_2 concentrations	Mauna Loa (ppmv)
Derwent et al. (1995) London, UK	July 1991–June 1992 5 m above the ground 5 m from road Buildings 15 m tall	Technique not given	Weekdays: 1991/6–9: 384 ppmv; 1991/10–12: 427 ppmv 1992/1–3:418 ppmv; 1992/4–6:417 ppmv	1991/6–9: 354.01 1991/10–12: 353.55 1992/1: 356.74 1992/4–6: 359.27
Reid and Steyn (1997) Vancouver, Canada Suburban	22.5 and 5 m above ground June 1993	LI-COR 6262 1 s samples every 20 s	Mean: 375 ppmv Sample extremes: 351 and 445 ppmv Mean diurnal range: 27 ppmv	1993/6: 359.55
Day et al. (2000) Phoenix, Arizona	15 March–3 April 2000 (20 days) 2 m above ground over grass turf near urban center and edge of metropolitan area	LI-COR LI-800 Every 5 min	Urban turf: Mean 402 ppm Nocturnal highs: 481 ppm Midday lows: 374 ppm	2000/3: 370.2 2000/4: 371.4
Spatial patterns from vehicle traverses				
Berry and Colls (1990b) Nottingham, UK	Urban-rural transect: nine points (see authors Table 1) Dec 1984–July 1985 (125 sets) Just before dawn	ADC-225 IRGA Sample bags analyzed	Winter months: greater CO_2 towards city center at night and during the day Summer: trend reversed at night	1984/12–1985/7: 346.66
Clarke and Faoro (1966) Cincinnati, OH, USA	May–August 1963	Lura-Lift IRGA ± 5 ppm Sampling height: 3.7–4.6 m (Jutze and Tabor, 1963)	Maximum 411 ppmv in early morning (06:00) Minimum 323 ppmv afternoon (13:00–17:00) Urban enhancement at 03:00 67 ppmv	1963/5-8:320.15
Clarke and Faoro (1966) New Orleans LA, USA	16 September–16 December 1963		Maximum 377 ppmv 03:00–06:00 Minimum 320 ppmv 13:00–16:00 Urban enhancement at 03:00 51 ppmv	1963/9-12: 326.75
Clarke and Faoro (1966) St. Louis, MO, USA	March–May 1964		Maximum 346 ppmv at 07:00 Minimum 332 ppmv 12:00 14 00 Urban enhancement at 03:00 10 ppmv	1964/3–5: 321
Shorter et al. (1998) Manchester, NH, USA Whole city	Continuous sample on traverse November 1997: pre-rush hour (~16:00–17:00 pm); during rush hour (17:00–19:00 pm); post rush hour (19:00–20:00 pm). June 1998—time not given	LI-COR LI-6262 Air drawn in to mobile van used to traverse road. Sample rate: 1 Hz	November 1997: Build up of CO_2 was evident on the loop roads during rush hours. Range: 370–510 ppmv June 1998: Range June 19/1998: 375–725 ppmv. Samples from individual car's exhaust could be identified	1997/11: 362.49 1998/6: 368.94

(*continued on next page*)

Table 1 (*continued*)

Author City/Land use	Measurement conditions	Sampling	Range of CO_2 concentrations				Mauna Loa (ppmv)
Idso et al. (1998) Phoenix, AZ, USA Whole city	January 1998 at 05:00 and 14:00. Air collected in medical syringe.	ADC-225-MK3 IRGA	05:00 concentrations: up to 555 ppmv; Urban–rural difference: 185 ppmv; Rural surrounding: 370 ppmv				1998/1: 365.38
Idso et al. (2000) Phoenix, AZ, USA Whole city	Two times of day (05:00 and 14:00) July and January 1998: 4 days each 2 m height at 1.6 km intervals (within cities, mainly road intersections)	LI-COR LI-800 Air drawn in to traverse automobiles	(ppmv)	July	January		1998/1: 365.38 1998/7: 367.72
			Maximum	up to 532	up to 599		
			Peak pre-dawn urban–rural difference	156	231		
Vertical profiles from aircraft							
Nakazawa et al. (1997) Moscow, Russia	Aircraft samples to >6000 m 16 July 1992: 12:05–12:48 LT 10 August 1994: 16:36– 17:00 LT	Non dispersive IRGA with a precision of 0.01 ppmv (Tanaka et al. 1983)	Ht (m)	July ,1992 ppmv	Ht (m)	August 1994 ppmv	1992/7:356.94 1994/8: 357.49
		Air drawn into canisters in aircraft	500	356.26	680	353.59	
			1000	348.77	1130	350.23	
			1500	354.22	14.70	351.16	
			2000	349.97	2030	350.64	
			Values higher than from other locations (wetland, taiga, forest)				

[a] Average Mauna Loa data, from Keeling and Whorf (2000), presented as a reference, with months indicated where relevant.

results and experience from measuring other fluxes, notably the latent heat flux (evapotranspiration) in cities; and second, to present select results from a short-term flux measurement campaign conducted in Chicago, Illinois in the summer of 1995. These are amongst the first measurements of CO_2 fluxes made in urban environments, though it is important to stress that new initiatives to undertake long-term, continuous measurements in cities are now underway; see, for example, the Baltimore NSF-funded Urban Long Term Ecological research site.

1.1. Issues to consider when measuring CO_2 fluxes in urban environments

Whether considered in terms of roughness (the size, shape and separation of buildings and vegetation) or surface cover (the spatial arrangement and the range of radiative, thermal and moisture properties), the broad category "urban" and the land uses within (commercial, downtown, industrial, suburban, etc.) commonly incorporate a wider range of surface characteristics than forests, agricultural areas, or wetlands. Observations from many carefully selected sites with contrasting surface cover, energy use, and traffic regimes will be needed to characterize CO_2 fluxes in cities. In the context of CO_2 fluxes, of particular relevance are variations in vegetation cover and photosynthetic activity, and emissions from fixed (industrial, commercial, institutional) and mobile (traffic) sources. Grimmond and Oke (1999b) have documented that within urban areas evapotranspiration rates can be significant but are highly variable (Fig. 1). The area vegetated, and even more so the area irrigated, exerts an important control on turbulent heat partitioning (see results summarized on the lower right of Fig. 1). Given the importance of irrigation for evapotranspiration, the area irrigated also would be expected to be important in controlling photosynthesis, and thus carbon uptake.

It is widely accepted that the understanding of urban climates, and their observation and modeling, is critically tied to notions of scale (spatial and temporal) and boundary layer development. For urban areas, three spatial scales (micro-, local-, and meso-) are commonly recognized (based on Oke, 1984), and provide a basis for appropriately siting equipment and generalizing results. At the micro-scale (10^1–10^2 m), important spatial differences in processes occur in response to variability in building/canyon dimensions and orientations and proximity to localized CO_2 emissions (e.g. individual roads). At the local-scale (10^2–10^4 m), processes represent the integrated response of an array of buildings, vegetation, and paved surfaces. At this scale, spatial variability across a city reflects different neighborhoods, with various combinations of built and vegetated cover and morphometry. At the meso-scale (10^4–10^5 m), the city is considered in its entirety, and differentiated from its surroundings, areas of forest, agriculture, etc. Of those studies of CO_2 concentrations conducted in urban environments to date (Table 1), virtually all, with the notable exceptions of Kuc (1991), Nakazawa et al. (1997), Reid and Steyn (1997), and Kuc and Zimnoch (1998), focus on the micro-scale, considering processes and patterns in the urban canyon (below building height). Inadequate attention has as yet focused on how micro-scale results can be extrapolated to larger scales and their implications for documenting the effect of urban areas regionally.

A common approach to documenting urban effects is to conduct simultaneous urban–rural measurements, with differences attributed to the effects of urbanization. Oke and Grimmond (2000), in a study of surface energy balance fluxes, draw on Lowry (1977) to show that unless great care is taken the approach is flawed, as proximal rural sites are themselves subjected to anthropogenic influences and may also be affected by advection of urban influences. In the context of CO_2 fluxes and concentrations these influences may be significant; agriculture, for example, has a major effects on CO_2 concentrations (e.g. Berry and Colls, 1990a).

Advances in instrumentation (notably eddy covariance technology) have meant that representative flux data can be collected from urban areas, provided careful attention is paid to the siting and operation of equipment (Oke et al., 1989; Grimmond and Oke, 1999a; Roth, 2000). Instruments must be mounted at a height at least twice the mean height of the roughness elements (buildings and trees) to ensure that the instruments are above the influence of individual roughness elements and the measurements represent an integrated response at the local-scale (Grimmond and Oke, 1999a; Kastner-Klein et al., 2000; Rotach, 2000). Vertical profiles of CO_2 concentrations within the urban canopy are needed to account for storage changes between the surface and the flux measurement level. Fetch in dominant upwind directions ($\sim$1–2 km) must be fairly uniform (similar patterns of buildings, roads, vegetation, etc.) so that controls related to particular surface covers and emissions sources can be identified, and effects of advection are minimal, so that networks of stations are not needed to document horizontal gradients.

Although closed path sensors have been used in many studies, open path sensors have many advantages and also allow continuous measurements of the flux of CO_2. Closed path sensors require air to be sucked (pumped) to the ground for analysis with appropriate gas analyzers, and thus lag corrections (to account for the time lags between the measurements of the vertical velocity on the tower by a sonic anemometer and the gas concentration by the analyzer often at the ground) need to be made and pumps and flow controllers need to be maintained. Temporal lags may be greater in urban

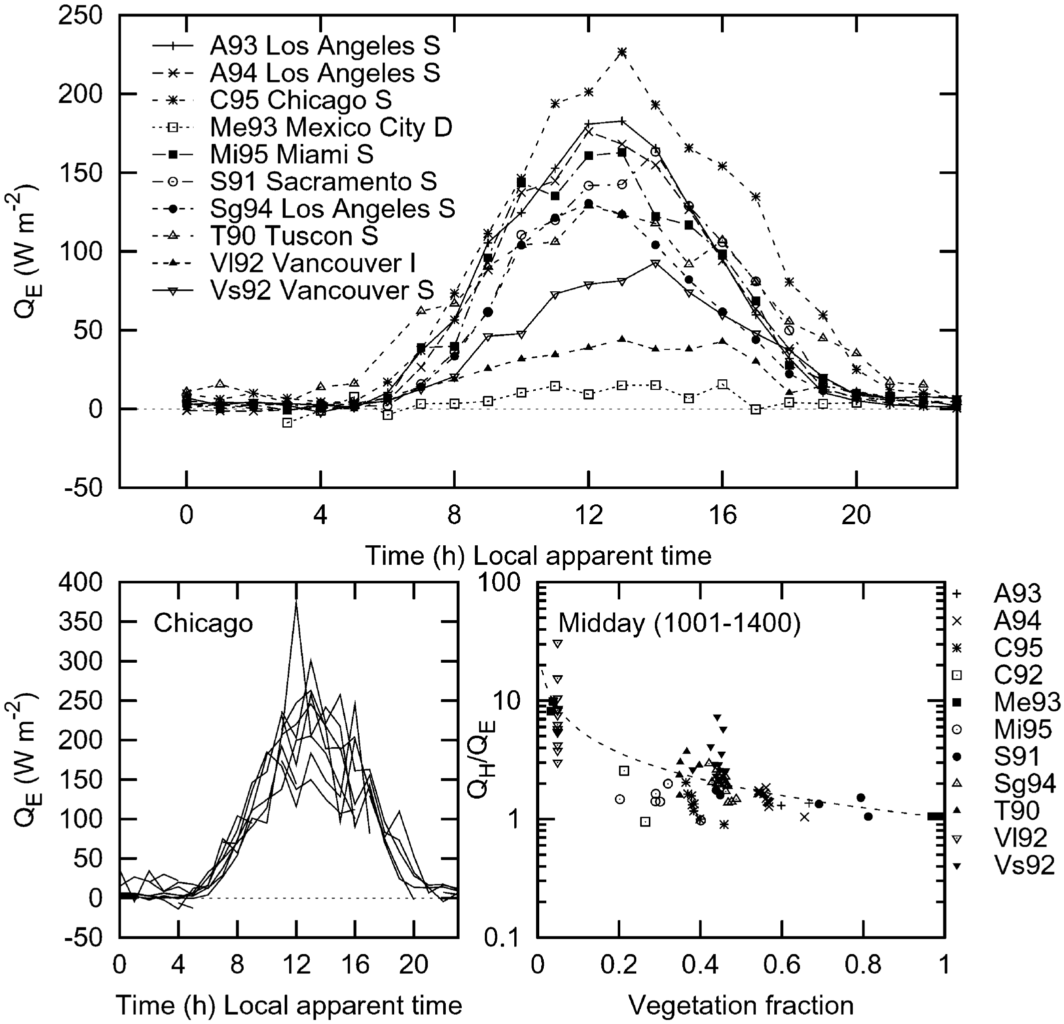

Fig. 1. Spatial and temporal variability of latent heat fluxes from 10 urban sites [residential (S), industrial (I) and downtown (D)] (adapted from Grimmond and Oke, 1999b). Top: average diurnal patterns for ten urban sites to show differences between sites; Bottom left: plots of hourly values for each day of measurements at the study site in Chicago in summer 1995; and Bottom right: relation of the midday (10:01–14:00) turbulent heat flux partitioning (the Bowen ratio: sensible heat flux/latent heat flux) for the urban study sites.

environments given the height needed to obtain representative measurements (although in mature forests the same issues are encountered, e.g. Schmid et al., 2000). As in other environments, issues related to the infilling of data, for periods with low friction velocity, will need to be addressed. If topographic variations occur in the vicinity of the site (common in many cities), the mean vertical wind velocity ($\overline{w}$) will be difficult to determine because of drainage flows. On an annual basis the number of hours with these types of conditions may become large, resulting in a large systematic error (Lee, 1998; Paw U et al., 1998; Finnigan, 1999). All these issues are receiving significant attention in micrometeorology today (e.g. Baldocchi et al., 2001a,b)

One of the few advantages of working in an urban environment is that detailed information on the surface (size, shape and spacing of roughness elements; fractional cover of different surface types—greenspace, roofs, impervious, etc.; emissions inventories of major CO_2 sources) often is available in spatially referenced databases (Geographic Information Systems). Such databases can be sampled, by overlying meteorological source area (footprint) models, for example, Schmid's (1997) FSAM—flux source area model, to describe key sources and sinks of CO_2. A general example of such an application, although not for CO_2, is presented in Grimmond and Souch (1994).

2. Material and methods

Measurements of surface–atmosphere exchanges of CO_2 were conducted in a northwest suburb of Chicago, Illinois (41° 57′ N 87° 48′ W) in the summer of 1995. Here we describe the site, equipment used, and details of the post-processing of the data.

2.1. The Chicago site

A 27 m tower (Aluma Tower Co., model TM-51-35-SS/T-100) was installed in the southwest corner of a cemetery down-wind of a fairly extensive, homogeneous suburban surface on Chicago's northwest side (Fig. 2). The instruments were mounted at sufficient height to be in the constant flux layer. Thus the measurements are representative of the local (10^2–10^4 m) scale.

The suburban area (Fig. 2) consists predominately of single-family houses, one and a half to two stories in height (mean height 6.3 m). Average surface cover is 36% building, 25% impervious, 7% trees and shrubs, and 32% grass (Grimmond and Oke, 1999b). The area has a large number of mature deciduous street trees (mean height 11.4 m). Street trees are a significant part of Chicago's landscape accounting for 10% of the city's trees and 24% of the total leaf-surface area (Nowak, 1994b). Most properties have a garden or green area around the house. The vegetation is generally healthy and well irrigated. The cemetery, which extends for nearly 800 m to the north and east of the tower site (Fig. 2), is characterized by an intermix of trees ($\sim$10 m in height) across an open grass surface.

2.2. The study period

Data were collected during the summer of 1995 (14 June–11 August, days 173–221). The period of observation includes the 1995 Chicago heatwave event (10–15 July), considered to be the most intense in 48 years (Changnon et al., 1996; Kunkel et al., 1996). Although brief, the heatwave resulted in hundreds of fatalities, and in many locations new record highs for dew point temperatures were established. Air quality in this period was poor. With respect to 8-h ozone concentrations, the city was in non-attainment for 11 days in the summer of 1995 (Illinois EPA, 1999).

2.3. The instrumentation

The main instruments used to directly measure the fluxes of CO_2 were a three-dimensional sonic anemometer [Applied Technology Instruments (ATI) model SAT-211/3k] and a closed path infrared gas analyzer (IRGA; LI-COR 6262). The ATI sonic was mounted on the tower at 27 m, with the tube intake for the IRGA. Wind velocity components and virtual temperature were sampled at 100 Hz. Corrections were made for transducer shadowing and sonic temperature (Kaimal, 1990). Data were block-averaged non-overlapping in real time to 10 Hz to minimize the effects of aliasing high frequency information back into the lower frequency portion of the turbulence spectrum. Post processing was conducted on 15-min intervals of raw data. In addition, three-dimensional coordinate rotation was applied to align the instrument coordinate system with the local mean streamline winds (McMillen, 1988; further details in Grimmond et al., 1998; Schmid et al., 2000).

Air was drawn down from the sample intake at the top of the tower, to the closed path IRGA at the tower base, through a 31 m Teflon tube with a 9.5 mm inside diameter, using a Gast (model 0323-1010-G582DX) vacuum pump. The average transit time was $\sim$8 s; average flow velocity 4.1 m s^{-1}. A traceable quality gas was used to perform calibrations. Fluxes of CO_2 were determined:

$$F_{CO_2} = \overline{w' \, CO_2'} \quad (1)$$

where, w is the vertical wind velocity, CO_2 the carbon dioxide concentration, and $'$ indicates the instantaneous departure from the mean. (Full details as applied to a forested site, where our group conducts such flux measurements, are presented in Schmid et al., 2000). In this study the vertical profile of CO_2 concentrations from the flux level to the surface were not measured.

Fig. 2. Aerial photograph of the Chicago measurements site. Location of the meteorological tower (C95u) is shown. North is to the top of the image. The distance west–east across the cemetery is approximately 750 m.

Additional measurements were made on the 27 m tower of wind speed and direction (R.M. Young model wind sentry 3001-5), temperature and relative humidity (Vaisala/CSI model HMP 35C), net all-wave radiation (Radiation and Energy Balance Systems (REBS) Q*6), incoming solar radiation (LICOR LI-200S), and sensible and latent heat fluxes [using a Campbell Scientific Inc. sonic anemometer and thermocouple system (model CA27) and krypton hygrometer (KH20), respectively]. At the ground surface, pressure (Vaisala model PTA-417), precipitation (Qualimetrics model 6011-B), soil heat flux (REBS model HFT1), soil temperature (CSI model TCAV), soil moisture (Watermark soil matric potential block 257 and gravimetric analysis), and surface wetness (Weiss type) were measured.

3. Results and discussion

Fig. 3a presents average concentrations of CO_2 for 13 days in the summer of 1995; plots for the individual days are shown in detail in Fig. 4. Rates of evapotranspiration (latent heat flux) for this period, measured using the krypton hygrometer, are shown in Fig. 1. In Chicago, the mean CO_2 concentration for these days was 384 ppmv; this compares with background Mauna Loa values of 361.60 ppmv (Keeling and Whorf, 2000). Although variations between days are evident, a marked and distinct diurnal cycle is apparent with an early morning peak attributable to anthropogenic (largely traffic), biospheric (nocturnal respiration), and meteorological (shallowest mixed layer heights at night) factors. The mean amplitude of the diurnal cycle is 35 ppmv. Peak nocturnal values average 405 ppmv (maximum value 441 ppmv), average daytime minima are 370 ppmv (the lowest is value 338 ppmv). This diurnal range is consistent with observations at other urban sites (Table 1). Although the diurnal variability of CO_2 concentrations is small at remote sites of the global CO_2 network, commonly less than 7 ppmv (Halter and Peterson, 1981), and often as low as 1 ppmv at Mauna Loa (Bacastow et al., 1985), in many terrestrial environments considerably greater variability has been documented. This is attributed primarily to the diurnal pattern of convective mixing. Reid and Steyn (1997), in the study most comparable with this one (local-scale measurements in a North American suburban area), document a summertime, average diurnal range 27 ppmv, with individual daily values up to 40 ppmv.

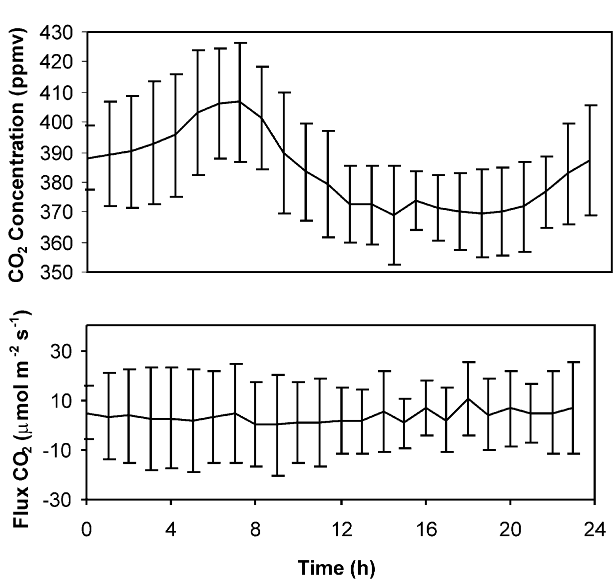

Fig. 3. Average diurnal pattern of CO_2 concentrations (ppmv) and CO_2 fluxes (µmol m^{-2} s^{-1}) for 13 days of measurement at the Chicago suburban site. Vertical bars represent ±1 standard deviation. Data for the individual days are shown in Fig. 4.

From the individual daily plots (Fig. 4) it is evident that superimposed on the diurnal pattern is considerable variability at much shorter time scales. The variability decreases under conditions of strong mixing in the middle of the day/late afternoon. Also evident on three of the days is a rise in CO_2 concentrations in the late afternoon, corresponding to the late afternoon traffic peak. In Chicago, the patterns of concentrations, as in other urban environments, reflect the complex set of controls related to temporal variations in source/sink strength (largely traffic at the suburban site), and boundary layer scale vertical mixing (also noted by Nakazawa et al., 1997; Reid and Steyn, 1997).

The average diurnal pattern of fluxes (net exchanges between the surface and atmosphere) is shown in Fig. 3b. Over forested sites in daylight in the growing season, a negative flux of CO_2 due to photosynthesis normally exists. Average midday fluxes for a midwestern forest site in July/August might be expected to be −20 to −25 µmol m^{-2} s^{-1} based on Schmid et al. (2000), and daily values are correlated strongly with photosynthetically active radiation, and influenced by water stress. Positive fluxes, up to ~5 µmol m^{-2} s^{-1} (Schmid et al., 2000) occur at night due to soil and plant respiration. The patterns of fluxes measured at the Chicago site show how anthropogenic sources of CO_2, mobile sources (traffic) and combustion of natural gas and oil (primarily for residential and commercial use at this site) complicate the diurnal flux pattern of forested sites (Figs. 3b and 4). Although negative fluxes are documented for specific hours (see minimum values up to ~16 µmol m^{-2} s^{-1} on Fig. 3b), on average for the period of observations fluxes at this urban site always remain positive; i.e. the urban surface is always a net source of CO_2. Urban vegetation clearly does have an effect during the day, but it is not enough to offset the significant anthropogenic sources (the morning and

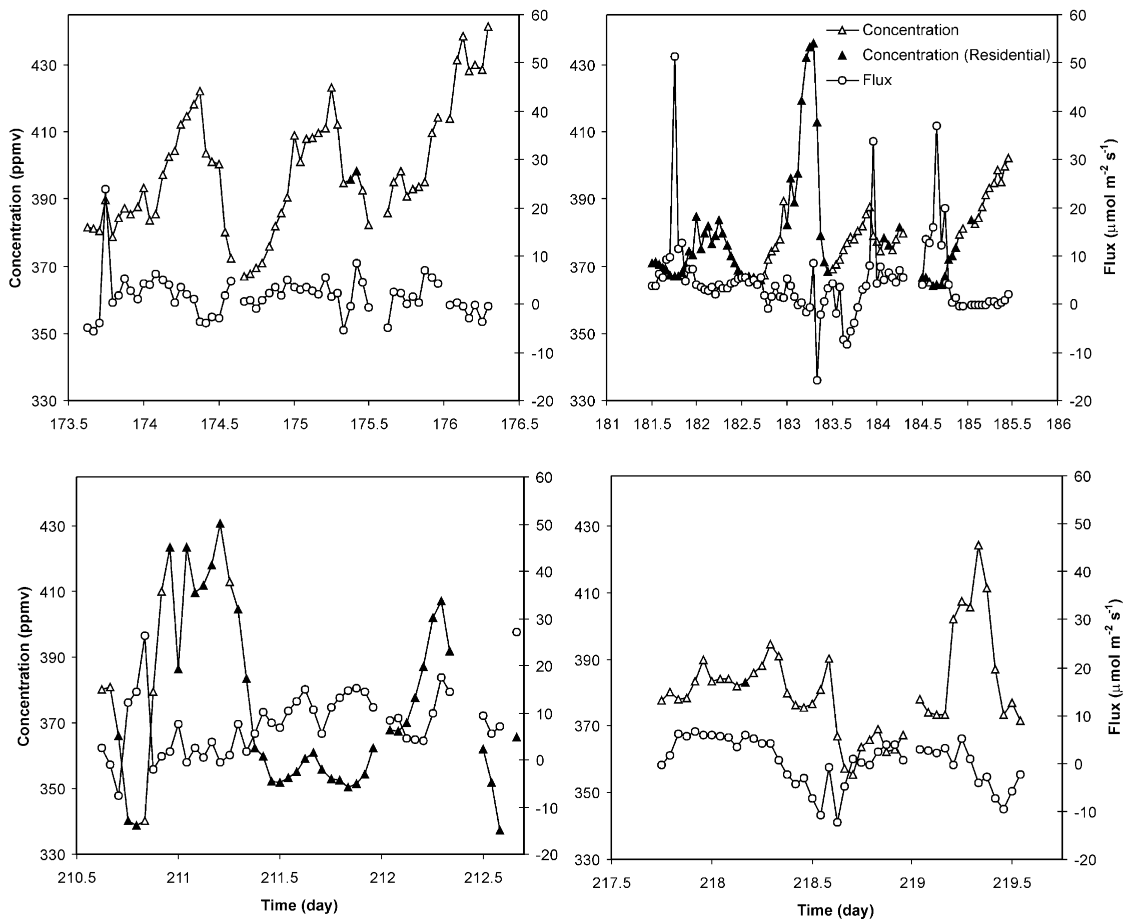

Fig. 4. CO_2 concentrations (ppmv) and fluxes F_{CO_2} (μmol m^{-2} s^{-1}) for four time periods in the summer of 1995: (a) days 174–176 (23–25 June); (b) 181–185 (30 June–4 July); (c) 210–212 (29–31 July); and (d) 217–219 (5–7 August). Note the scale of the *x*-axis varies between plots. When data for all four 15-min periods within an hour came from wind directions only influenced by residential surface cover (Fig. 2), a solid symbol is used for the concentration data points.

afternoon rush-hours are evident on this plot). This finding is independently supported by the calculations of Nowak (1994a) from his ecological inventory of 8996 trees from 652 randomly selected sites within the Chicago area. Nowak (1994a) estimated that in the Chicago area trees store 5.6 million t C, with most carbon stored in trees on residential land. Nowak estimated net annual carbon sequestration to be ~140,600 t, which is equivalent to transportation use in only 1 week (Citizens Fund, 1992).

Average nocturnal fluxes are ~10 μmol m^{-2} s^{-1}, peak hourly averages range up to 38 μmol m^{-2} s^{-1}. It is important to note that on many nights the urban atmosphere remains unstable (Grimmond and Oke, 2000), thus mixing and dispersion from the surface continues. When the individual daily data (Fig. 4) are considered, the temporal variability (hour to hour and day to day) is much more evident, as is the relation between fluxes and concentrations.

4. Conclusion

At the end of the twentieth century, approximately half of the world's population, over three billion people, lived in urban areas. By 2025, the United Nations (cited in Uitto and Biswas, 2000) predicts that this number will double, and the proportion of the global population who are urban residents will rise to two-thirds. Urban areas are important sources of CO_2, and locations where enhanced concentrations are amongst the most pronounced.

As yet, few measurements of concentrations or more importantly fluxes, needed to understand surface–atmosphere exchanges in cities, have been made. The nature of the urban surface makes identification of scales of measurement critical to ensure measurements are meaningful and representative. Results from studies of other fluxes in cities, notably measurements of latent heat flux (evapotranspiration) have demonstrated that spatially integrated results representative of the local-scale can be obtained by mounting micro-meteorological (eddy covariance) instruments in fairly uniform (both in terms of surface cover and roughness element height) neighborhoods, on tall towers (at a height at least twice the mean height of the roughness elements). Both across cities and between cities, significant spatial variability in CO_2 concentrations and fluxes can be expected as a consequence of the distribution of anthropogenic sources (mobile and fixed) and patterns of urban vegetation and irrigation. Clearly many sets of measurements will be needed to capture these patterns, and such measurements must be conducted for long periods to document temporal (diurnal, synoptic, seasonal, and annual) variability, known to be important for other ecosystems, patterns likely to be compounded by human activities and responses in cities. In some urban environments such measurements will be difficult to make given the topographic setting of many cities (near large water bodies or on hilly land), logistical issues related, for example, to vandalism, and ordinances that control the location of tower sites.

Our observations at a single suburban site in Chicago show significant diurnal variations in CO_2 concentrations. The CO_2 concentrations are elevated relative to global background values, but as expected, CO_2 concentrations measured at 27 m are lower than those documented closer to the ground (in micro-scale studies) in other cities. The Chicago results are consistent with other local-scale work. The CO_2 fluxes reported show exchanges on average are always positive; i.e. even in the summertime a fairly well vegetated, irrigated suburban environment is, on average, a carbon source. Although for individual hours negative fluxes may occur and urban vegetation clearly is sequestering carbon [substantiated independently by Nowak's (1994a) ecological inventory].

The observations reported here are for a very short period of time and limited range of conditions. Clearly many more studies of urban areas are needed to document the spatial and temporal variability of CO_2 concentrations and processes of uptake/release in cities.

Acknowledgements

The assistance of the people who provided permission to use sites, and the many who aided with the fieldwork and data analysis are greatly appreciated. In particular, we would like to thank Emily Freeman, Kevin Sayers, Neal Schroeder and Mark Hubble. Dr. Tilden Myers provided invaluable advice on instrumentation and software. John Chin provided the 2000 Mauna Loa data. Funding was provided by USDA Forest Service co-operative research grants No. 23-526 and No. 23-546. This paper was presented at the USDA Forest Service Southern Global Change Program sponsored Advances in Terrestrial Ecosystem: Carbon Inventory, Measurements, and Monitoring Conference held 3–5 October 2000 in Raleigh, North Carolina.

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