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Cities as Net Sources of CO_2: Review of Atmospheric CO_2 Exchange in Urban Environments Measured by Eddy Covariance Technique

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Abstract

Cities are main contributors to the CO_2 rise in the atmosphere. It is clear that accurate estimates of the magnitude of anthropogenic and natural urban emissions are needed to assess their influence on the carbon balance. Increasingly the eddy covariance (EC) method is applied in urban environments to quantify CO_2 fluxes. The technique has many advantages over other methods. It is a direct measure of the flux that includes all major and minor natural and anthropogenic sources and sinks, is *in situ*, non-intrusive, quasi-continuous and with proper selection of the footprint can represent a large upwind extent similar to the size of a complete urban neighborhood. This article reviews the basic principles and requirements of the EC technique, discusses its application in the urban context and summarizes observations from over 30 EC systems, primarily deployed in mid-latitude cities. The results show that the urban surface is a net source of CO_2, with vehicle exhaust and domestic heating as the major contributors while urban vegetation is not capable to completely offset the anthropogenic emissions. The largest CO_2 fluxes have been observed in densely built up locations in city centers, followed by sites within urban core, while the lowest fluxes are found in suburban neighborhoods. The daily net CO_2 exchange depicts a strong relationship with vegetation fraction, but not with population density.

Introduction

Cities are the most visible physical sign of anthropogenic global change. Due to their dense population, settlement structure, transportation networks, energy use and altered surface characteristics, they fundamentally change the carbon cycle, as well as the state of the atmosphere and climate (Mills 2007). Cities have an intensive metabolism requiring a significant inflow of artificial energy, and energy consumption per unit area is orders of magnitude higher than the same for rural, vegetated or less developed surfaces. Although cities take up only ~2% of the global land area, they release more than 70% of the total emissions of carbon dioxide (CO_2) of anthropogenic origin (Canadell et al. 2009). CO_2 is the greenhouse gas (GHG) of most concern due to its rapidly increasing concentration in the atmosphere (from ~280 ppm about 150 years ago to the present concentration of ~388 ppm). Fossil fuel combustion (including urban and non-urban sources) together with small contributions from cement manufacturing is responsible for 88% of the anthropogenic CO_2 emissions while land-use change, primarily deforestation, is accountable for the remaining 12% (Le Quéré et al. 2009). CO_2 emissions now represent 77% of the total anthropogenic GHG emissions and account for 63% of the direct radiative forcing responsible for global climate change (Hofmann et al. 2006).

In cities, CO_2 is emitted by the burning of fossil fuel associated with transport, energy use in households and public buildings, as well as manufacturing and industry. In the transport sector, the often dominant and fastest growing CO_2 sector, the burning of gasoline or diesel fuel results in direct emission of CO_2 [each liter of gasoline burned produces ~2.3 kg CO_2 (~1.3 m^3)]. CO_2 emissions from households, public buildings and industry have a direct local contribution from combustion processes (e.g. use of natural gas or biomass for cooking and heating), as well as an emission component at the site of the electricity generation (assuming electricity is generated from burning fossil fuel) which may be located some distance away from the city. Similarly, the emissions from incinerators, airports, maritime ports, etc. do not always occur within the urban boundaries, but contribute to the total emissions from cities.

The urban CO_2 flux is also influenced by natural sources and sinks. Vegetation (urban parks, scattered trees, vegetated rooftops) removes CO_2 from the atmosphere through photosynthesis during daytime and releases a fraction of it through respiration at night, with additional uptake from soils and corresponding belowground activity. Finally, the metabolic release of CO_2 by human respiration is an important and growing component that has not yet been considered in current strategies to mitigate GHG emissions (Prairie and Duarte 2007; West et al. 2009).

The relative strength of each of the aforementioned sources and sinks of the urban carbon flux varies widely as a function of population density, industrial activity, climatic region, local meteorology, amount of vegetation, land use distribution, and socioeconomic and cultural factors that vary from country to country. It is clear that accurate estimates of the CO_2 flux are needed to understand how urban emissions and land modifications are affecting the regional carbon exchange and explore how these impacts may change with urban growth and development patterns across the full range of city diversity. Figure 1 illustrates the range of city form and structure across a sample of cities from which direct CO_2 flux measurements are available.

This article presents a review of currently available results from urban CO_2 flux measurements using the eddy covariance (EC) technique, which is the only existing method to measure directly CO_2 fluxes that include all major and minor natural and anthropogenic sources and sinks. Given the relatively recent nature of such research this review also considers work not yet published in the peer-reviewed literature (e.g. conference proceedings, articles in newsletters and research reports) but which is original and meets a set of guidelines regarding, e.g. methodological rigor. A small number of studies were excluded because they clearly did not meet basic requirements for the application of the EC technique. An overview of the methods most commonly used to estimate CO_2 fluxes in urban environments and the basic principles and requirements of the EC technique in the urban context are introduced first. A summary of urban CO_2 flux measurements is used to assess the role of cities in the carbon exchange and provides the basis for some concluding remarks and suggestions for future research.

Measuring Urban CO_2 Exchange

A number of methods exist to estimate the carbon exchange from cities. The CO_2 released from the various emission sources is typically quantified by a bottom-up aggregation process that accounts for emission factors and fossil fuel consumption data. Since CO_2 emissions are primarily dependent on the carbon content of the fuel, the emissions are calculated by multiplying the amount of fuel burned by emission factors expressed as mass of CO_2 per unit of consumed fuel (e.g. IPCC 1997). However, this simple approach does not consider the heterogeneity and variability of the emission sources. Accurate estimations require specific emission rates for each type of source, as well as

Fig. 1. Sample of CO_2 flux measurement sites (indicated by purple dot) illustrating the possible diversity across cities in terms of morphology and vegetation fraction (North is top on all images). Source: Google-Maps© and IAUC Urban Flux Network (http://www.urban-climate.org/).

detailed information of fuel composition, operation conditions, technology, activity levels and emission regulations. Emission rates are often derived from laboratory or specific field measurements. Fossil fuel consumption and activity levels can be obtained from local authorities or specific surveys, such as traffic counts. Complete inventories must include emissions from mobile (e.g. vehicles), area (e.g. residences) and point (e.g. industries) sources plus the natural contributions from vegetation, soil and human breathing. A complete emissions inventory also needs to account for diurnal variations in activity levels and source distribution. The latter may be obtained from maps, aerial photographs or from population density estimates. The propagation of errors associated with this bottom-up process can result in large uncertainties (e.g. Marland 2008). In many cities, particularly in developing nations, the required data to quantify the CO_2 emissions are not always available, and the emission factors may not be representative.

Other attempts to quantify and characterize CO_2 emissions from urbanized land areas include measurements of ambient concentration of CO_2 describing spatial patterns across cities (e.g. Henninger and Kuttler 2007; Idso et al. 2001), downwind and upwind CO_2 concentration measurements which are directly assimilated into transport models to obtain regional surface fluxes (e.g. Geels et al. 2007; Mays et al. 2009; Rigby et al. 2008) and isotopic analysis to partition anthropogenic and biogenic contributions (e.g. Clark-Thorne and Yapp 2003; Pataki et al. 2003).

Large uncertainties are associated with estimating CO_2 emissions using the indirect methods above. Direct measurements of CO_2 fluxes that include all anthropogenic and natural sources and sinks from a specific region can be used to evaluate emission inventories.

Such direct flux measurements are now increasingly performed in cities using the EC technique and fast-response analytical sensors. The EC technique has been widely employed to investigate the surface–atmosphere exchange of CO_2 and other trace gases over natural ecosystems, including forests, grasslands and wetlands, often as part of long-term programs such as AmeriFlux (Baldocchi et al. 2001), AsiaFlux (Mizoguchi et al. 2009) and EuroFlux (Valentini et al. 2000). The application of this technique in the urban case, however, is particularly challenging.

Methodological Considerations when Using the Eddy Covariance Method in the Urban Environment

Eddy covariance has become the method of choice to measure CO_2 fluxes over a range of land covers, including urban environments. Its application, however, is complex and careful attention has to be given to the selection of measurement sites, positioning and operation of instruments as well as data processing to obtain meaningful and representative results. For an introduction to micrometeorological theory, the reader is referred to textbooks such as Arya (2001), Kaimal and Finnigan (1994) and Stull (1988). Information on measuring turbulence statistics and CO_2 fluxes in the urban environment is available in e.g. Roth (2000) and Grimmond et al. (2002a) and about the EC technique in Moncrieff et al. (1997), Aubinet et al. (2000), Baldocchi (2003), Lee et al. (2004) and Burba and Anderson (2007).

OVERVIEW OF THEORY

The vertical transport in the atmospheric layer near the ground, known as surface layer, is dominated by turbulent motions generated by surface friction or drag on the flow and surface heating due to absorption of energy from the sun. These turbulent motions (eddies or swirls of different sizes) are embedded in the mean flow and move air containing CO_2 (and other scalar entities such as heat, moisture and pollutants) upward and downward. Figure 2 is a conceptual diagram of the atmospheric eddy transport and its application to the EC technique. Choosing as a reference the top of an instrumented tower for example, at one moment one eddy will be moving an air parcel downward with a specific vertical velocity while at the next moment another eddy will be moving a new air parcel upward with a different vertical velocity. Knowing the CO_2 concentration of each air parcel and the speed of the vertical air movement, the vertical upward or downward flux of CO_2 can be calculated. The turbulent vertical flux (F) equals the covariance (product) between the instantaneous deviations or fluctuations of the vertical wind velocity (w_i') and CO_2 mass density (c_i') averaged over a specific time interval:

$$F = \overline{c'w'} = \frac{1}{N}\sum_{i=1}^{N} w_i' c_i', \tag{1}$$

where N is the number of samples during the averaging time, and the fluctuations are the differences between the instantaneous readings and their respective means (e.g. $c_i' = c_i - \bar{c}$). If the net flux is away from the surface, the surface is a source and the flux may be called *emission*. If the opposite is true, the surface is a sink and the flux may be called *deposition*.

From eqn (1), it follows that the CO_2 flux is expressed in units of mass per area and time (e.g. g m^{-2} s^{-1}). The mass can be given in micromoles (μmol), grams of CO_2 (g) or

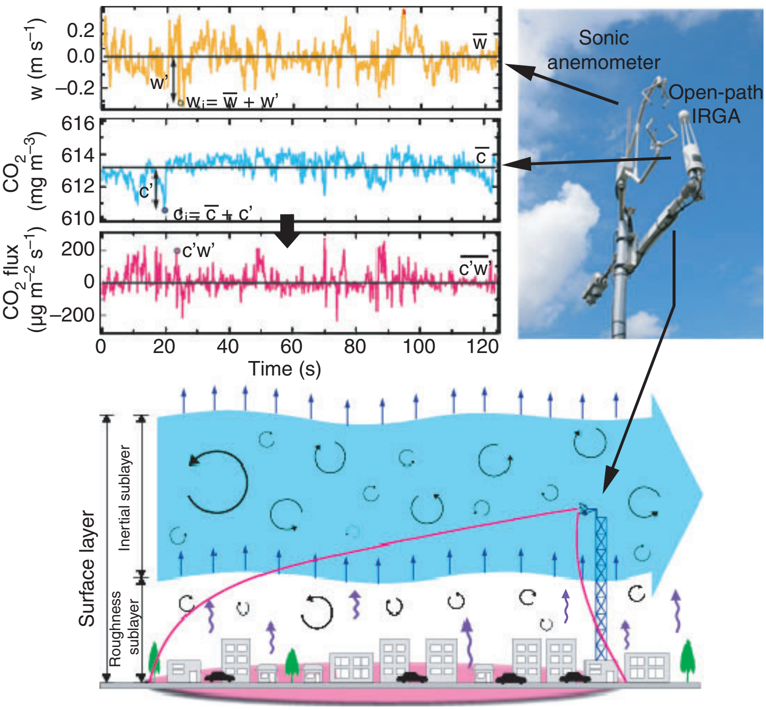

Fig. 2. Cross-section through the surface layer which forms the lowest part of the urban boundary layer (lower panel). Emissions from different sources (indicated by blue wavy and straight arrows) distributed across the three-dimensional city surface are blended by turbulent eddies (black circular arrows) to produce a net exchange (positive upward flux in this example) across the surface–atmosphere interface. The flux is measured by an EC system (top right; here consisting of a sonic anemometer and an open-path IRGA) which must be mounted within the inertial sublayer to produce values representative of the general characteristics of the underlying surface within the sensor footprint (pink ellipse). Reynolds decomposition is used to derive time series of vertical wind velocity and CO_2 concentration fluctuations which yield the flux (top left).

grams of carbon (gC), the area in m^2, ha or km^2, and the time in seconds, hours, days or years. To convert from moles to grams, the flux is multiplied by the molecular weight of CO_2 (44 g mol^{-1}). To convert from g to gC the flux is multiplied by 3/11 (the fraction of carbon in the CO_2 molecule). The units are selected depending on the study purpose, flux magnitude, and spatial and temporal scales.

INSTRUMENTATION AND FIELD IMPLEMENTATION

An EC system to measure fluxes of CO_2 consists of a sonic anemometer and a CO_2 analytical sensor (Figure 2). Fast-response CO_2 analyzers are based on the principle of absorption of infrared radiation by trace gases, and often measure CO_2 and water vapor at the same time. They are known as Infrared Gas Analyzers (IRGA) and the sensing path can be either closed or open. For urban setups, the open-path IRGA is usually chosen. It measures *in situ* next to the anemometer (Figure 2), and does not require a sampling line and external pump to collect samples as is the case for a closed-path IRGA. Both open- and closed-path sensors respond to changes in density ($mass_{gas}/volume_{air}$) rather than mixing ratio ($volume_{gas}/volume_{air}$) of CO_2 and H_2O with respect to dry air. The measured fluxes therefore need to be corrected for fluctuations in the air density produced by fluctuations of temperature and moisture in the air. This is usually done by applying the Webb–Pearman–Leuning (WPL) correction, which requires measurements of temperature and water vapor fluctuations (Webb et al. 1980).

Open-path IRGAs do not require frequent calibration for measuring fluxes but periodic setting of zero and span (e.g. every 15 days) using two standard concentrations below and above the monitored CO_2 range (e.g. at 350 and 500 ppm) are recommended to make accurate measurements of absolute values (Auble and Meyers 1992). The instrument response to water vapor can be verified using a dew point generator or by comparisons with data from a regular (slow-response) humidity sensor.

Turbulent motions responsible for the flux span across a wide range of eddy sizes. EC sensors have to be capable of measuring wind velocity and scalar concentration at very high sampling rates (10–20 Hz) and with high accuracy (low noise level) to capture the smallest eddies which occur very fast and are of small magnitude. The length of the averaging interval determines the size of the largest eddies that will be included in the calculation. For low measurement heights, 15 min may be adequate, but the averaging period has to be increased with increasing height because the proportion of large eddies contributing to the flux is also increasing with height above the surface (the peak of the energy spectrum is shifting toward lower frequencies, i.e. larger eddies) (Wyngaard 1973). An averaging period of 30 min or longer is therefore recommended for most applications.

To obtain representative and meaningful results, it is essential to conduct measurements at sufficient height above surfaces which are uniform in terms of topography (i.e. flat), urban morphology (i.e. buildings of similar height) and distribution of emission sources and sinks (i.e. no large factories, parking lots or urban parks). To avoid the microscale variability introduced by individual buildings, trees or emission sources and sinks characteristic of the roughness sublayer (RSL), the EC sensors need to be located above the blending height in the inertial sublayer (ISL) (also called constant flux layer). Here, flow divergence or convergence is reduced, emissions (of CO_2, H_2O, heat, etc.) have become completely blended (individual plumes have merged) by the turbulence generated at the surface and fluxes are expected to vary little with height and space and are considered representative of a well-defined neighborhood (Figure 2). The lower boundary of the ISL is about 15–40 m above ground for residential areas and higher for central city sites (Grimmond and Oke 1999); in practice, this works out to 2–4 times the mean height of buildings. The upper extent of the ISL layer is determined by the development of an internal boundary layer which responds to regional-scale land use changes in an upwind region 100–300 times the measurement height (Grimmond and Oke 1999). Bottema (1997) suggests that measurement heights should be <0.25 the height of the urban boundary layer. It is possible that under certain conditions, in particular when land-cover changes at scales of only a few kilometers, the depth of the RSL exceeds the potential depth of the ISL and no such layer exists (Oke et al. 1989). Fluxes obtained from very tall towers (>100 m) may therefore not be representative of the urban ecosystem. Tall towers may also reach above the top of the collapsing boundary layer at night, causing additional difficulties in interpreting such data.

Neither the instruments nor the tower should interfere with the turbulent motions carrying the flux, and their shape and installation must be as aerodynamic as possible. A large and solid structure as instrument platform for example will obstruct the flow and introduce additional turbulence upwind, which may be sensed by the instrument as a flux contribution (Griessbaum and Schmidt 2009; Mennen et al. 1996; Wyngaard 1988). The distance between the turbulence sensors should be small enough to allow the measurement of the smallest energy-carrying eddies but care has to be taken to prevent flow interference by the sensors themselves (Figure 2).

FOOTPRINT ANALYSIS

The height of the tower, together with the surface roughness length, turbulence intensity, wind speed and direction, and atmospheric thermal stability determine the footprint (also called source area) of the measured flux. The footprint is the fraction of the surface containing the sources and sinks that contribute to the vertical flux measured at the sensor platform (Figure 2). In the case of an extensive, homogeneous surface, the size or location of the footprint is not a major issue. However, over an inhomogeneous surface such as a city, it becomes imperative to ensure that the measured signal includes a representative sample of all sources and sinks of a certain neighborhood, without being biased toward unusual features such as e.g. a major traffic intersection or urban park.

An initial estimation of the source area of the flux measurements during daytime is to assume a footprint extending between 100 and 300 times the effective measurement height (Grimmond and Oke 1999). Since the early 1990s many footprint models have been developed using different approaches including analytical, Lagrangian stochastic particle dispersion, large-eddy and ensemble-averaged closure models. Vesala et al. (2008) review the advantages and disadvantages of these approaches. Analytical model such as those based on parameterization of Lagrangian dispersion modeling and dimensional analysis (e.g. Hsieh et al. 2000; Kljun et al. 2004; Schmid 1994) are often suitable to evaluate footprints. It is important to remember that none of these approaches have been developed exclusively for flux measurements over urbanized land areas and that their performance is still under evaluation.

The size of the footprint and location of the peak flux contribution strongly depend on atmospheric stability. With increasingly convective conditions, the former extends less in the upwind direction and the latter moves closer to the tower (Figure 3), i.e. during unstable conditions the upward transport of CO_2, or any other trace gas, originates from an area relatively close to the tower. The location of the footprint peak is typically

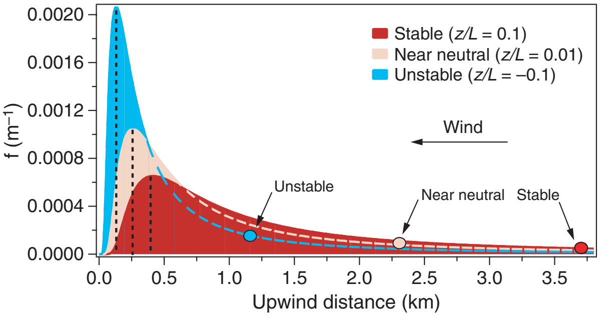

Fig. 3. Crosswind-integrated footprint evaluated for three different atmospheric stabilities (*z* and *L* are measurement height and Obukhov length, repsectively) for a hypothetical EC system mounted at 42 m above the surface in a residential neighborhood with average building height of 12 m. The area below the curve represents the flux proportion in the upwind direction (tower is located at 0.0). The upwind extent of the footprints encompassing 80% of the measured fluxes and locations of peak fluxes are indicated by filled circles and vertical dashed lines, respectively. Both move closer to the base of the tower with increasing instability (smaller *z/L*). Calculations are made with the analytical model of Hsieh et al. (2000) assuming a roughness height of 1 m which is a typical value for a suburban surface (Stull 1988).

between a few times the measurement height (unstable) to a few dozen times (stable) from the tower base. Mathematically, the surface area influencing the flux goes to infinity and it is necessary to define the fraction of the source area considered. Often a footprint encompassing from 70% to 90% of the total source area is acceptable (Vesala et al. 2008). The calculations in Figure 3 yield maximum footprints of ~3.7 km during stable conditions, which may prevail at nighttime, and ~1.2 km during unstable conditions. Lowering the sensor height will result in shorter footprints but increases the possibility that the observations are no longer located in the ISL (Figure 2). The footprint analysis is ideally carried out before the actual measurements to evaluate the micrometeorological suitability of a flux site and again afterwards to determine the exact location and characteristics of the sources and sinks contributing to the measurements within the monitored neighborhood to help in the interpretation of the results.

DATA PROCESSING AND QUALITY CONTROL

Data post-processing software is often included when buying turbulence sensors and a few open source codes are available on the web at no charge. However, they can only be used to compute on-line or preliminary estimates. It is necessary to adapt available software packages or design new ones to accommodate a specific sensor set-up and data acquisition systems and to calculate the turbulent fluxes of interest. Table 1 summarizes the steps that should be followed during the processing of EC data from an urban measurement program. A more in-depth discussion of each step in Table 1 is available in McMillen (1988) and Aubinet et al. (2000).

The quality of flux measurements is difficult to assess because there are various sources of possible errors, such as badly chosen sites, failure to satisfy the theoretical assumptions underlying the EC approach and inappropriate sensor installation. These effects cannot be quantified solely from the EC data and a classical error analysis and propagation will remain incomplete. Instead, Aubinet et al. (2000) suggest an empirical approach to determine whether the fluxes meet certain plausibility criteria. Besides the statistical and stationarity characteristics of the raw measurements, the frequency resolution of the EC system needs to be verified through inspection of the (co)spectra of the measured variables. An EC system attenuates the true turbulent signal at low and high frequencies, which correspond to large and small eddy sizes, respectively. This can occur due to limitations imposed by the physical size of the instruments, finite distance between co-located sensors, inherent time response limitations and any signal processing associated with de-trending or removal of the mean (Massman and Lee 2002). Inspection of the (co)spectra of the measured variables helps to determine the influence of these attenuations. For example, a logarithmic plot of the power density (co)spectra should be free of distortions (such as e.g. a -1 slope) at the low-frequency end (Chapter 2 in Kaimal and Finnigan 1994) and exhibit the characteristic $-5/3$ ($-7/3$) slope in the inertial subrange at the high-frequency end.

Applicability of the EC method and the derivation of the fluxes requires stationary conditions, i.e. statistical properties of the flow do not change with time, which permits the introduction of time averages and hence Reynolds decomposition (Kaimal and Finnigan 1994). Non-stationary conditions may occur during sunrise and sunset, during periods with changing wind direction or those affected by short-term horizontal advection of plumes from unusual local sources. Periods that do not fulfill the stationarity requirements also do not meet the (co)spectral low-frequency criteria mentioned above. They can therefore be discarded from further analysis based on the stationarity test, which is easier

Table 1. Guidelines for processing eddy covariance flux data measured in urban environment.

Step	Action	References
1	Conversion of raw data to scientific units by applying calibration factors; removal of hard spikes (i.e. unreasonable values; e.g. CO_2 > 800 ppm, T > 60 °C); identification and flagging of data gaps – if gaps represent >25% of readings in a period, then calculated fluxes need to be treated with suspicion	
2	Computation of mean values and standard deviations. Removal of soft spikes (large, short-lived, e.g. <0.4-s departures from the mean values)	Schmid et al. (2000)
3	Three-dimensional coordinate rotation for alignment of axes to the local mean streamlines. Removes the vertical advective from the total flux and eliminates errors due to sensor tilt relative to the terrain surface or aerodynamic shadow due to sensor or tower structure	Aubinet et al. (2000), Lee et al. (2004)
4	Apply Reynolds decomposition to remove mean values and obtain turbulent fluctuations ('primed' quantities). Apply a filter to remove trends (recursive digital filter is recommended for complex terrains and places where rapid changes in CO_2 concentrations are expected as is the case in a city)	McMillen (1988), Kaimal and Finnigan (1994)
5	Calculate vertical fluxes (e.g. CO_2, momentum, sensible heat, latent heat) and other turbulence statistics over chosen averaging interval. If the CO_2 and H_2O densities were measured by a closed-path IRGA, lag time correction needs to be applied first. The lag time may be determined empirically by running a circular correlation and shifting the delay scan-by-scan until a maximum flux is found	Schmid et al. (2000)
6	Account for the effects of air density fluctuations (due to fluctuations in temperature and water vapor) on the CO_2 and H_2O fluxes by applying the Webb–Pearman–Leuning (WPL) correction. This is particularly important for impervious and dry surfaces which can generate large heat but small CO_2 and H_2O fluxes	Webb et al. (1980), Ham and Heilman (2003), Kondo and Tsukamoto (2008)
7	Flux correction for high-frequency loss due to sensor separation. If a closed-path IRGA was used, correction for loss due to damping of fluctuations within the sampling tube and limited instrument response time is necessary	Massman and Lee (2002)
8	Check for stationarity. If the difference between the flux obtained from an averaging period (i.e. 30 min) and the average of fluxes from six continuous sub-periods (i.e. 5 min) during the same averaging period is <60%, the data are acceptable	Aubinet et al. (2000)
9	Apply second phase of quality control to see if calculated turbulence statistics are reasonable and within pre-defined limits, otherwise they will have to be rejected. Inspect shape of (co)spectra	

to apply in an objective manner than (co)spectral shape criteria. Nevertheless, it is always recommended to evaluate (co)spectra of a number of sampling periods to verify the capability of the EC system to measure the entire range of energy-carrying eddies.

Eddy Covariance Flux Measurements of CO_2 in Urban Environments

The first urban CO_2 flux measurements by EC were carried out over a residential district of Chicago in 1995 (Grimmond et al. 2002a). Since then, the number of EC sites has grown and now includes locations representing a wide range of urban land uses (Figure 4 and Table 2). The earliest observations were restricted to short campaigns (e.g.

Table 2. Chronological summary of urban EC CO_2 flux measurements reported in the peer-reviewed literature.

City, country	Observation period	Sensor height (z) and z/z_H	LCZ[1]	Land use	LCF (%)[2]	Pop. density (km^{-2})	Sonic, IRGA[3]	References
Chicago – Dunning, USA	June–August 1995	27 m 4.29	House and garden	Residential	Bldg: 36 Veg: 39 IG: 25	4342	ATI SAT-211/3k, LICOR-6262[c]	Grimmond et al. (2002a)
Edinburgh – Calton Hill, UK	November 2000	65 m 6	Old core	Commercial Residential Recreational	Bldg: NA Veg: NA IG: NA	1724	Gill Solent R1012, LICOR-6262[c]	Nemitz et al. (2002)
Copenhagen – Frederiksberg, Denmark	2001	40 m 1.78	NA	Residential Commercial	Bldg: NA Veg: 9 IG: NA	10,923	Gill Solent, LICOR-6262[c]	Soegaard and Møller-Jensen (2003)[4]
Marseille – CAA, France	June–July 2001	43.9 m 2.81	Old core	Residential Commercial	Bldg: 59 Veg: 14 IG: 27	NA	RM Young-81000, LICOR-7500[o]	Grimmond et al. (2004)
Tokyo – Kugahara, Japan	2001–2007	29 m 3.97	Compact housing	Residential	Bldg: 33 Veg: 29 IG: 38	11,800	Metek USA-1, LICOR-7500[o]	Moriwaki and Kanda (2004)
Basel – Sperrstrasse, Switzerland	June–July 2002	31 m 2.07	Old core	Residential Commercial	Bldg: 54 Veg: 16 IG: 30	25,000	Gill R2, LICOR-7500[o]	Vogt et al. (2006a)
Mexico City – Iztapalapa, Mexico	April 2003	37 m 3.08	Compact housing	Institutional Residential Industrial	Bldg: 50 Veg: 12 IG: 38	12,000	ATI SATI-3K, NOAA-IRGA[o]	Velasco et al. (2005a)
Melbourne – Preston, Australia	February 2004–June 2005	40 m 3.33	House and garden	Residential	Bldg: 45 Veg: 37 IG: 18	2939	CS CSAT3, LICOR-7500[o]	Coutts et al. (2007)
Melbourne – Surrey Hill, Australia	February–July 2004	40 m 2	House and garden	Residential	Bldg: NA Veg: 47 IG: NA	NA	CS CSAT3, LICOR-7500[o]	Coutts et al. (2007)
Firenze – Ximeniano, Italy	September 2005–	33 m 1.32	Old core	Residential Commercial	Bldg: 69 Veg: 2 IG: 29	3561	RM Young-81000V, LICOR-7500[o]	Matese et al. (2009)
Helsinki – SMEAR III, Finland	December 2005–	31 m 1.55	NA	Institutional	Bldg: 10 Veg: 30 IG: 60	NA	Metek USA-1, LICOR-7500[o]	Vesala et al. (2007)

Table 2. (*Continued*)

City, country	Observation period	Sensor height (z) and z/z_H	LCZ[1]	Land use	LCF (%)[2]	Pop. density (km^{-2})	Sonic, IRGA[3]	References
Mexico City – Escandon, Mexico	March 2006, February 2009–	42 m 3.5	Compact housing	Residential Commercial	Bldg: 57 Veg: 6 IG: 37	7412	ATI SATI-3K, ADC OP2°	Velasco et al. (2009)
Münster – near city center, Germany	August 2006–	65 m 4.33	House and garden	Residential Commercial Recreational	Bldg: 40 Veg: 35 IG: 23[5]	NA	RM Young-81000V, LICOR-7500°	Schmidt et al. (2008)

z_H, average building height.
[1] Local climate zone classification proposed by Stewart and Oke (2009).
[2] Land-cover fraction: Bldg., buildings; Veg., vegetation; IG, impervious ground. Data from original references and IAUC Urban Flux Network (http://www.urban-climate.org).
[3] (c) – Closed-path IRGA, (o) – open-path IRGA.
[4] Study included additional short-term measurements with a mobile 10-m tower in six urban sites.
[5] The remaining 2% correspond to open water.

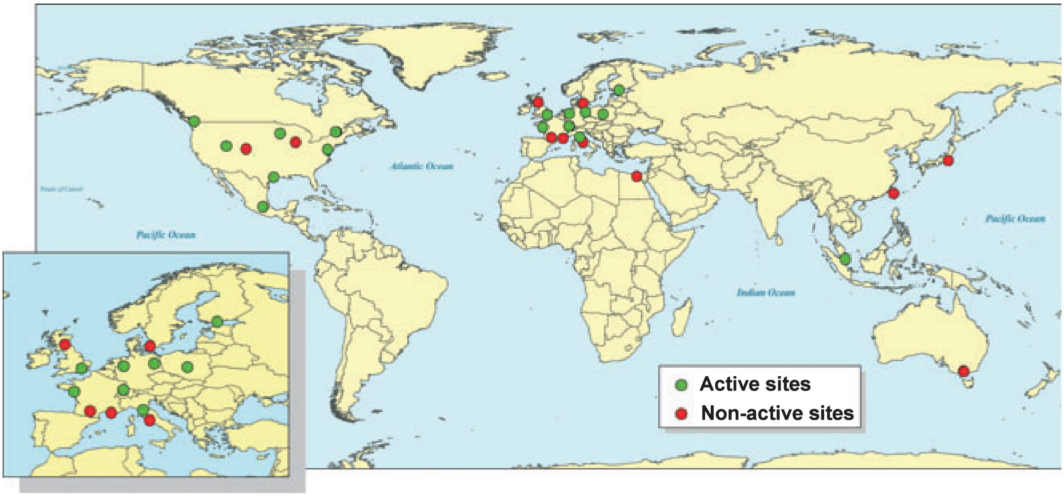

Fig. 4. Cities with current (active) or past (non-active) EC CO_2 flux measurement sites. An updated list of urban flux sites and bibliography is available at the Urban Flux Network website (http://www.urban-climate.org).

Grimmond et al. 2002a; Nemitz et al. 2002) and even more recent research published in peer-reviewed literature often lacks long-term (>1 year) measurements with the notable exceptions of Copenhagen-Frederiksberg (Soegaard and Møller-Jensen 2003), Tokyo-Kugahara (Moriwaki and Kanda 2004) and Melbourne-Preston (Coutts et al. 2007). Another long-term program has recently been initiated in Vancouver and Montréal (Canada) by the Environmental Prediction in Canadian Cities program (http://www.epicc.uwo.ca).

The majority of CO_2 flux measurements by EC in urban environments have been carried out in residential and commercial neighborhoods. Some sites have been located in city core areas, e.g. in Edinburgh-Calton Hill (Nemitz et al. 2002), Marseille-CCA (Grimmond et al. 2004) and Firenze-Ximeniano (Matese et al. 2009) or densely populated districts in Tokyo-Kugahara (Moriwaki and Kanda 2004), Basel-Sperrstrasse (Vogt et al. 2006a) and Mexico City-Escandon (Velasco et al. 2009). Both types of sites are characterized by high population density, compact housing, intense vehicular traffic and scarce vegetation. Other flux systems have been deployed in residential suburbs of Chicago-Dunning (Grimmond et al. 2002a) and Melbourne-Preston (Coutts et al. 2007), where population density is relatively low, vehicular traffic is reduced and vegetation cover is quite extensive. A fourth category of sites represents university environments, e.g. Mexico City-Iztapalapa (Velasco et al. 2005a) and Helsinki-SMEAR III (Vesala et al. 2007). Table 2 summarizes experimental and site information of EC CO_2 flux measurement projects reported in the peer-reviewed literature.

To date, more than 30 EC systems have been deployed with the majority in mid-latitude cities of Europe and North America. Only one tropical (Singapore: Roth and Jansson 2008) and four subtropical sites (two in Mexico City: Velasco et al. 2005a, 2009; Houston: Schade 2009; Cairo: Burri et al. 2009) have been studied to date. Similar to investigations into other aspects of the urban climate most studies have been carried out in developed countries with the exception of Mexico City and Cairo. This is unfortunate because much of the current and projected urban growth is occurring in countries with developing economies.

DIURNAL AND SEASONAL PATTERNS

The most striking feature reported is the positive (i.e. directed away from the surface) flux values observed during most hours of the day at the vast majority of sites (Figures 5 and 6). This indicates that cities are generally a source of CO_2. The diurnal patterns reveal the importance of vehicular traffic as the main emission source in urban environments. In most locations, the CO_2 flux and the traffic volume increase during the morning

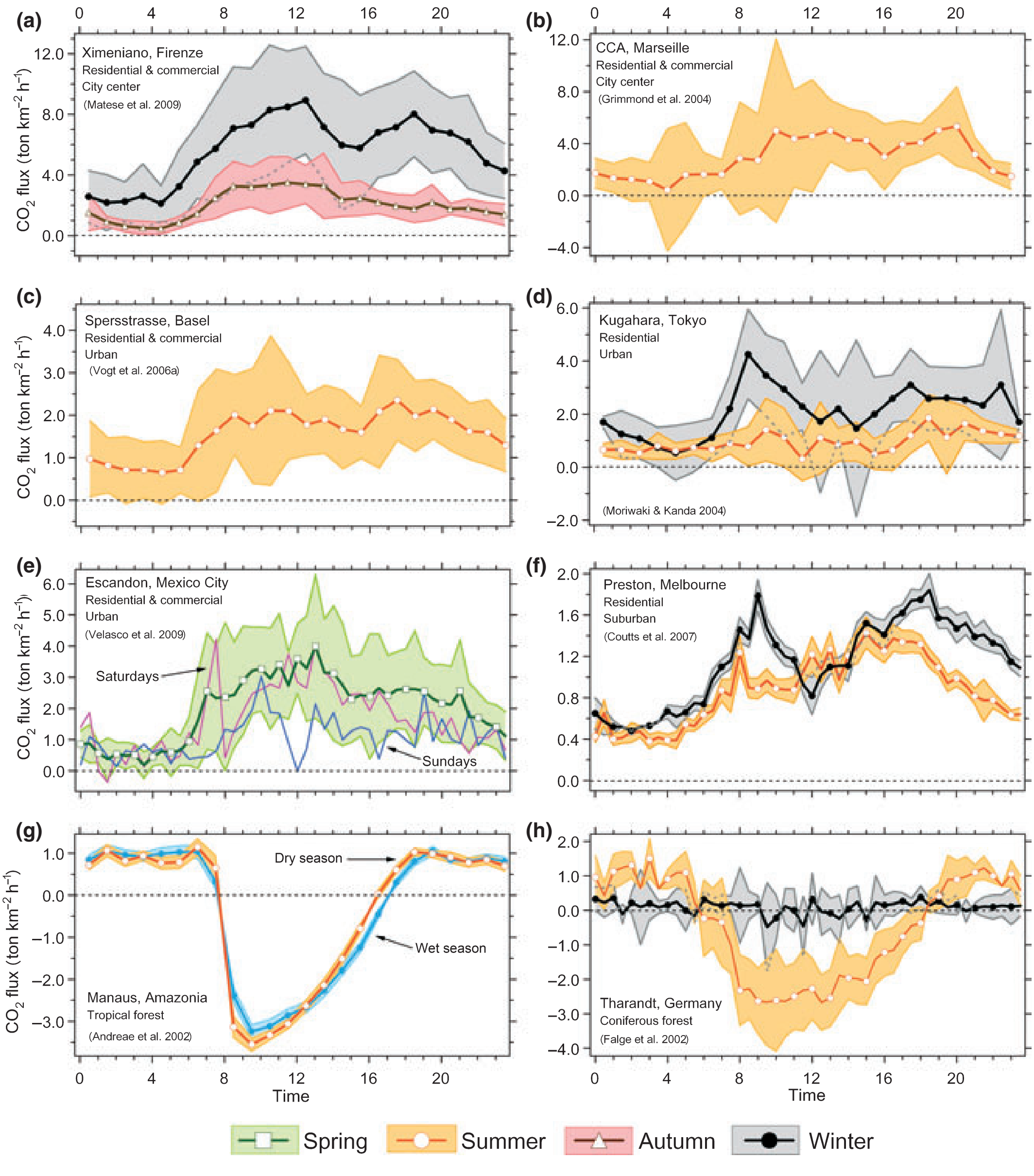

Fig. 5. Average diurnal variation of CO_2 fluxes from selected urban and forested sites for different seasons. The shaded regions are ±1 standard deviation and give an indication of the day-to-day variability at every hour of the day. Note different flux scales for individual panels.

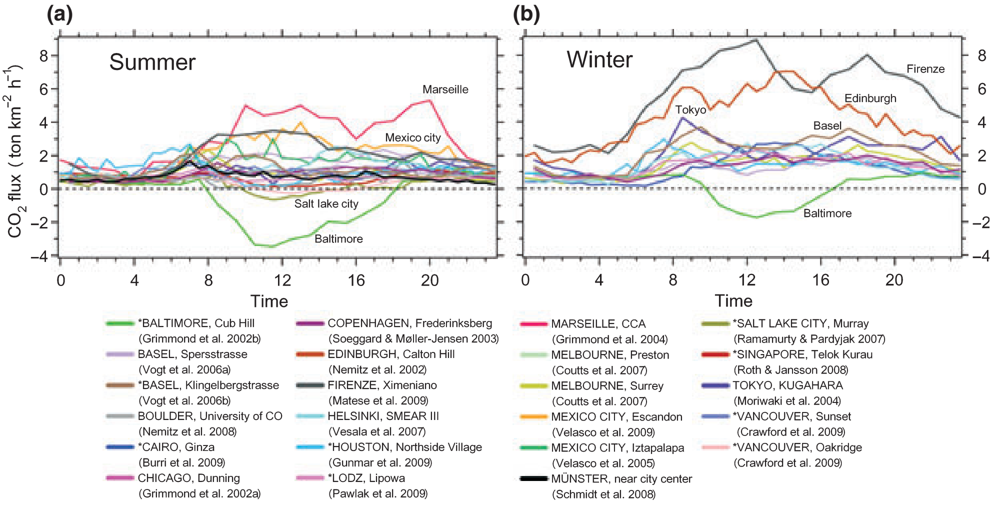

Fig. 6. Average diurnal variation of CO_2 fluxes from a range of urban sites during (a) summer and (b) winter. Sites marked with * have not been reported in the peer-reviewed literature. Sites reported in peer-reviewed literature are also listed in Table 2.

rush hour. In busy districts with heavy traffic and scarce vegetation, the CO_2 flux tends to stay constant and high throughout the day, decreasing in phase with the traffic load in the evening (e.g. Mexico City-Escandon, Figure 5e). Many places exhibit strong early morning and late afternoon traffic peaks (e.g. Basel-Sperrstrasse and Melbourne-Preston, Figure 5c and f, respectively), whereas at other sites only minor peaks are observed during the rush hours (e.g. Marseille-CCA; Figure 5b). Usually, the correlation coefficient obtained from linear regression between traffic volume and CO_2 flux for busy districts is high ($r > 0.7$) (e.g. Nemitz et al. 2002; Soegaard and Møller-Jensen 2003; Velasco et al. 2009). In suburban neighborhoods, the magnitude of the fluxes in the middle of the day is modulated by the amount of vegetation, particularly during the summer growing season. For example, the measurement site Cub Hill in Baltimore is heavily treed and hence capable of significant daytime uptake exceeding the anthropogenic emissions (Figures 1 and 6).

The morning and late afternoon peaks are also related to domestic activities such as cooking and household heating or cooling. The impact of domestic heating on the CO_2 flux increases as the ambient temperature drops in winter as demonstrated by Firenze-Ximeniano where the CO_2 flux correlates negatively with ambient temperature (Matese et al. 2009). They found that household heating increases the wintertime CO_2 flux by 2.8 times compared to that measured in autumn (Figure 5a). In Tokyo-Kugahara, Moriwaki and Kanda (2004) found that domestic heating contributes 62% to the total CO_2 flux in winter. In contrast to vegetated areas, the lowest CO_2 fluxes in urban locations occur at night when human activities are at a minimum. The positive fluxes are supported by the remaining traffic, plant respiration mainly during summer and heating in winter.

The diurnal variability of the fluxes shown in Figure 5 is primarily the result of the flux strengths of the anthropogenic and natural sources and sinks but modulated by other factors. The vegetation uptake depends on meteorological variables as well as on the plants' phenology and environmental stress conditions (e.g. pollution, dryness).

Some anthropogenic emissions, such as household heating, also depend on meteorological variables, but others merely on social patterns. For example, the traffic emissions on weekends are usually lower than on weekdays as shown in Figure 5e for the Escandon site in Mexico City. Similarly, in Cairo, the *Jumu'ah* (Muslim prayer day) is held on Friday, and because it is a rest day the traffic emissions are much reduced (Burri et al. 2009).

The generally large urban fluxes during daytime, with the exceptions of Baltimore-Calton Hill, Salt Lake City-Murray and Vancouver-Oakridge (all sites with surface vegetation fractions >50%), illustrate the anthropogenic contribution cities have on the atmospheric CO_2 exchange. Forested ecosystems, in contrast, have negative fluxes during daytime (Figure 5g,h) due to photosynthesis, while at night plant respiration produces positive fluxes of similar magnitude to those observed in urban environments. Hourly average fluxes from densely built-up sites in Marseille-CCA and Mexico City-Escandon, which have surface vegetation fractions <14% exceed 4 tons km^{-2} h^{-1} (Figure 6a) during summer and spring, respectively. In wintertime, the average fluxes from sites in city centers such as Firenze-Ximeniano and Edinburgh-Calton Hill exceed 6 tons km^{-2} h^{-1} (Figure 6b). In general, daytime CO_2 fluxes shown in Figure 6 range from about 0 to 1.5 tons km^{-2} h^{-1} in summer and from 1 to 3 tons km^{-2} h^{-1} in winter. In comparison CO_2 fluxes observed in the rainforest of Manaus (Brazil) and the coniferous forest of Tharandt (Germany) reach daytime values below −3 tons km^{-2} h^{-1} (i.e. uptake) during the entire year and summer, respectively (Figure 5g,h).

Figure 7 summarizes the daily net CO_2 exchanges in winter and summer for urban sites with available flux data. In mid-latitude locations wintertime fluxes can be more than two times those measured during the summer (e.g. Firenze-Ximeniano, Tokyo-Kugahara, Lodz-Lipowa, Copenhagen-Frederiksberg). In cities with mild winters, such as Houston and Melbourne, the cold season increase is 1.2–2 times. Such seasonal differences are primarily due to space heating patterns and reductions in vegetation and biological activity during the cold season which constrain the CO_2 uptake. In sites like SMEAR III in Helsinki where the heating is provided by a central station and emissions are therefore non-local and produced outside the measurement footprint, the seasonal difference is only due to reduction in vegetation. Traffic load has little influence on seasonal differences since it is nearly constant throughout the year as shown by data from Copenhagen-Frederiksberg, Tokyo-Kugahara and Firenze-Ximeniano. Little seasonal variation is observed in low-latitude cities based on preliminary results from Singapore (Roth and Jansson 2008) where temperature, cooling needs and vegetation cover (growing season) are relatively constant throughout the year. In case of tropical locations with substantial green-spaces and dense vegetation, small variations may be expected in the carbon uptake between the dry and wet seasons, similar to the small variations observed in the tropical forest of Manaus, Brazil (Figure 5g).

IMPACT OF URBAN CHARACTERISTICS ON THE CO_2 FLUX

The largest CO_2 fluxes are found in densely built-up locations and city centers (Figure 7). Their CO_2 emissions are two to five times larger compared to residential sites in suburban districts, where vehicular traffic is usually lower and vegetation fraction is larger. There is a strong relationship between the daily net CO_2 exchange and vegetation fraction during summer (Figure 8). Including autumn and spring fluxes from Firenze and Mexico City where vegetation influence is negligible, a correlation coefficient of 0.70 is obtained. Removing the two more distant points from the correlation line (Copenhagen-

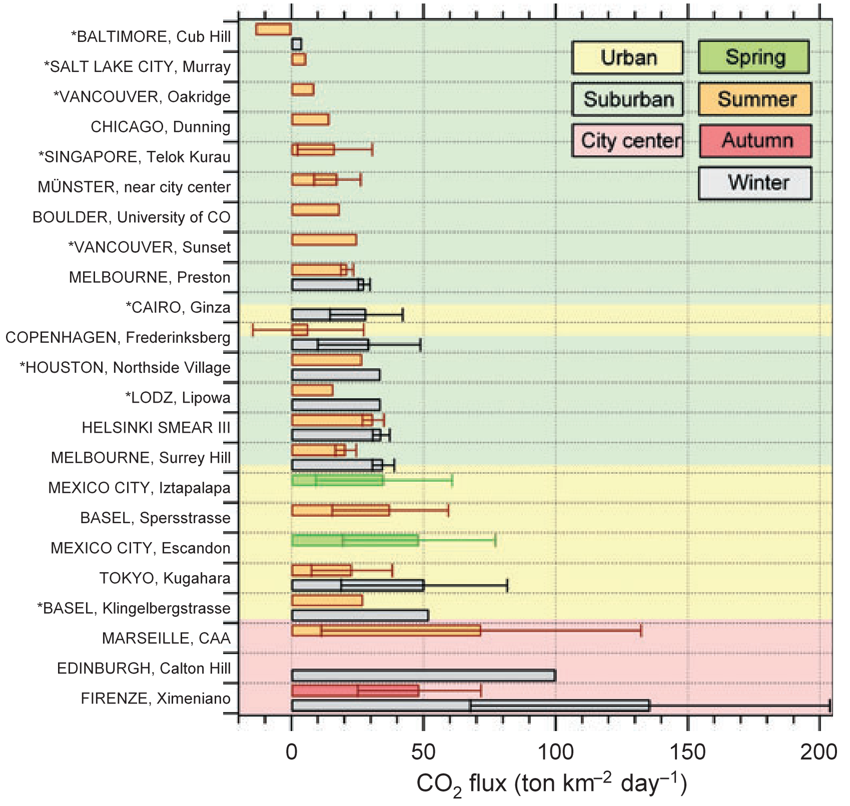

Fig. 7. Net daily CO_2 fluxes for a range of urban sites for different seasons and land uses. Length of solid bars correspond to the seasonal average, thin lines indicate ±1 standard deviation. Sites marked with * have not been reported in peer-reviewed literature. The flux for Singapore–Telok Kurau is the annual average.

Frederiksberg and Marseille-CCA), the correlation coefficient improves to 0.87. No correlation was found between population density and daily CO_2 flux, as well as vegetation fraction and CO_2 flux per capita. Urban cores generally have higher daily CO_2 emissions compared to suburban neighborhoods, but not in terms of per capita emissions. Comparing daily fluxes with population density, it is found that many suburban sites have higher per capita emissions despite the larger abundance of vegetation and lower population densities. This surprising result may be due to differences in traffic patterns, domestic activities and contributions from suburban vegetation. However, these results may not be fully representative given the limited sample available and parameters considered. For example, the fraction of area covered by vegetation is not a good indicator of available biomass and density of trees by species may be more representative. Additional environmental factors such as atmospheric pollution and water availability may also bias the relationship between CO_2 flux and vegetation, and explain some of the variability seen in Figure 8. Further, population density values given usually only consider permanent residents, neglecting the daytime working population which can be significant in downtown and commercial districts. It is obvious that the large diversity of urban morphology, climatology, level of activity, and economic and social factors complicate a comprehensive comparison between urban areas.

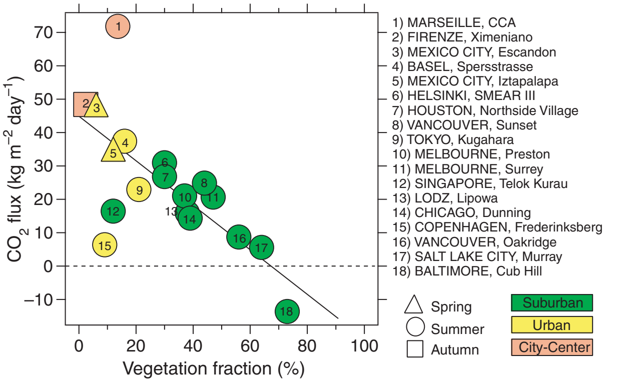

Fig. 8. Net daily CO_2 flux versus vegetation fraction for different urban land covers. Black line is regression through all data points.

ANNUAL CO_2 EXCHANGE

The few available long-term studies provide a first indication of annual CO_2 budgets. Moriwaki and Kanda (2004) measured an annual CO_2 emission of 12.3 kg m^{-2} for the densely populated residential neighborhood of Kugahara in Tokyo. Coutts et al. (2007) obtained an annual emission of 8.5 kg m^{-2} for the residential district of Preston in Melbourne. Combining remote sensing and EC flux measurements from various neighborhoods, Soegaard and Møller-Jensen (2003) computed an average annual CO_2 flux of 12.8 kg m^{-2}, representative of the entire metropolitan area of Copenhagen. Finally, based on short-term studies assuming little seasonal variation, Velasco et al. (2005a, 2009) determined annual fluxes of 12.8 and 17.6 kg m^{-2} for two different districts in Mexico City. These annual fluxes can be compared to typical net CO_2 ecosystem exchanges in nearby forests. For example, the average CO_2 emission per unit area from Copenhagen is 20–28 times the total CO_2 sequestered by a Danish beech forest (Pilegaard et al. 2001). Similarly, the CO_2 emission from Kugahara in Tokyo is ~27 times the CO_2 absorbed by a broadleaf deciduous forest in Japan (Yamamoto et al. 1999). Comparing the two districts in Mexico City with the absorption rate from an evergreen oak forest (Baldocchi et al. 2001), forest areas which are five to seven times larger than those neighborhoods are needed to absorb their emissions. Tropical and subtropical forests are usually evergreen and therefore have a larger potential for CO_2 assimilation than boreal and temperate forests (Falge et al. 2002). Considering two hypothetical urban neighborhoods of equal size and CO_2 emission rate, one in a mid-latitude location and the other in the tropics, a larger temperate forest is needed to counterbalance the CO_2 emissions from the former neighborhood in comparison to a tropical forest to counterbalance the emissions from the second neighborhood.

EVALUATION OF EMISSION INVENTORIES BY EC FLUX MEASUREMENTS

An important purpose of the EC flux measurements of CO_2 in urban environments is to evaluate the accuracy of local emission inventories which are usually based on the indirect methods described earlier. The CO_2 fluxes measured by EC can be compared directly to the estimated emissions within the monitored neighborhood if these are available. Only few such comparisons have been carried out to date (Matese et al. 2009; Moriwaki and Kanda 2004; Nemitz et al. 2002; Soegaard and Møller-Jensen 2003; Velasco et al. 2009).

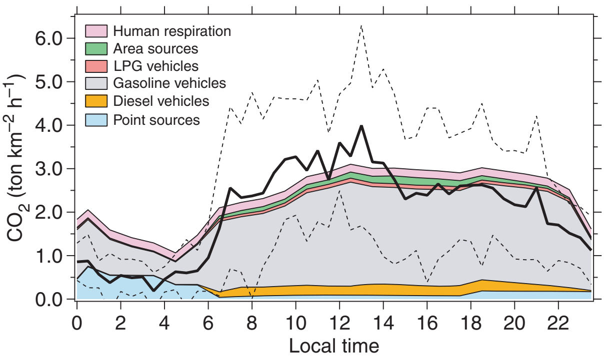

Fig. 9. Diurnal CO_2 emission profiles by source types for the Escandon district in Mexico City extracted from a local CO_2 emissions inventory (SMAGDF 2008). The CO_2 released by human breathing was estimated as the product of per capita rate of respiration, average CO_2 concentration of the air expired and population density (West et al. 2009). Under normal breathing conditions and considering the average weight of Mexico City inhabitants, a per capita metabolic emission of 0.6 kg day^{-1} was determined. The solid black line corresponds to the average flux measured by EC, while the dashed lines indicate ±1 standard deviation from the measured flux (Velasco et al. 2009).

In general, the agreement between directly measured fluxes and indirectly estimated emissions has been good. An example is shown in Figure 9, which includes CO_2 emissions from anthropogenic sources, including human respiration, together with the measured CO_2 flux for the Escandon district in Mexico City. With the exception of the early morning period, the indirect estimates were generally within 10% of the measured flux. In this particular example, the transport sector contributes 87% to the total CO_2 emissions. The benign weather eliminates the need for household heating or cooling, but the high population density makes human respiration a significant source of CO_2 (~6%). In contrast, the biogenic CO_2 uptake or release is negligible due to the scarce presence of trees (25 ha^{-1}) and soils for respiration, respectively.

Summary and Conclusion

The majority of the monitored urban sites exhibit clear diurnal patterns with significant contributions from vehicular traffic and domestic heating, particularly in winter in the northern hemisphere. During daytime, the CO_2 uptake by urban vegetation is generally not strong enough to offset the anthropogenic CO_2 emissions. The maximum daily CO_2 fluxes are observed during winter. Summer values show a distinct minimum due to the benign weather which reduces emissions associated with fossil fuel consumption for heating and trees are in full leaf which increases the potential for CO_2 sequestration. In spring, the flux gradually changes from winter to summer levels and the opposite is found in autumn.

The CO_2 flux data presented in this review indicate that it is possible to obtain meaningful and representative results from city surfaces if careful attention is given to the selection of measurement sites, positioning and operation of instruments as well as data processing. EC observations provide an integrated measurement from all potential anthropogenic and natural CO_2 sources and sinks, including those not usually accounted for in typical emission inventories, such as emissions from food street sellers, human respiration and CO_2 uptake by photosynthesis. EC observations can also be used to evaluate CO_2 emissions inventories, whose spatial resolution is similar to the size of flux footprints (10^2–10^4 m).

The number of measurement sites is still insufficient to assess the potential spatial and temporal variability of the CO_2 exchange produced by the full diversity (in terms of economic development, transport, amount of vegetation, heat/cooling needs, etc.) of cities. Many more studies of urban areas are needed to produce reliable city-wide emission budgets. Since the analytical sensors to measure CO_2 require only limited maintenance and calibration, permanent CO_2 flux monitoring programs using the EC technique may become part of meteorological and air quality networks in cities. EC observations provide continuous CO_2 flux data that may be used in the development of environmental policies intended to reduce GHG emissions.

The EC technique has also been used to measure urban fluxes of other species of concern for climate change and public health, such as volatile organic compounds (e.g. Langford et al. 2009, 2010; Velasco et al. 2005b, 2009) and aerosols (e.g. Dorsey et al. 2002; Mårtensson et al. 2006; Nemitz et al. 2008). Results of these measurements have contributed to improve emission inventories used for air quality and GHG assessment. Simultaneous EC flux measurements of selected trace gases strongly associated with particular emission sources and CO_2 fluxes may be conducted to determine the CO_2 apportionment from individual sources. For example, benzene is a good tracer of vehicle exhaust and knowing the ratio of benzene emitted per mass of CO_2 by traffic (Zavala et al. 2006) the vehicular contribution to the observed CO_2 fluxes may be found. Similarly, acetonitrile and hydrogen cyanide may be used as indicators of biomass burning (Crounse et al. 2009; de Gouw et al. 2009). Further, analysis of CO_2 isotopes in conjunction with EC measurements can be used to separate the anthropogenic and biogenic contributions to the total CO_2 flux (Pataki et al. 2003).

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Short Biographies

Erik Velasco is an environmental engineer involved in research concerning urban air pollution and climatology. His research focus is on the evaluation of emission inventories by direct and indirect methods (i.e. micrometeorological techniques and modeling comparison). He is also interested in the interactions between the urban surface and the low boundary layer in terms of mass and energy exchange and pollution dispersion. He is currently a postdoctoral fellow at the National University of Singapore. He holds BS and MS degrees from the National Autonomous University of Mexico, and a PhD from Washington State University.

Matthias Roth is an Associate Professor in the Department of Geography at the National University of Singapore. He holds a PhD degree from the University of British Columbia in Vancouver (Canada) and is the immediate Past-President of the *International Association for Urban Climate* (IAUC). His main academic interest is to understand how land-cover changes affect local climates with a particular focus on the climate of cities and the role they play in climate change. As an experimental researcher he has conducted observations of the energy balance, carbon dioxide fluxes and fundamental turbulence properties in North American, European and Asian cities.

Note

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