Carbon Dioxide Emissions of the City Center of Firenze, Italy: Measurement, Evaluation, and Source Partitioning

A. MATESE, B. GIOLI, F. P. VACCARI, A. ZALDEI, AND F. MIGLIETTA

Istituto di Biometeorologia, Consiglio Nazionale delle Ricerche, Florence, Italy

ABSTRACT

An eddy covariance station was installed in the city center of Firenze, Italy, to measure carbon fluxes at half-hourly intervals over a mostly homogeneous urban area. Carbon dioxide (CO_2) emission observations made over an initial period of 3.5 months were compared with indirect estimates of CO_2 emissions based on inventory data sources of vehicle circulation and natural gas consumption for domestic heating and cooking. Such a comparison provided proper evaluation of the measurements. Using seasonal dynamics of observed fluxes, the overall CO_2 source of the city center was partitioned into its major components (i.e., road traffic and domestic heating). Results were directly compared with CO_2 source estimates based on inventory sources.

1. Introduction

An increasing part of the world's population is living in urban areas, where a disproportionate share of natural resources, including fossil fuels, is used. Carbon dioxide (CO_2) emissions of cities are an important term of the global carbon budget, but its estimation is mainly based on inventories of fossil fuel consumption and road traffic (Mensink et al. 2000). The amount of carbon sequestered in urban vegetation is, with a few exceptions (Nowak and Crane 2002), largely unknown. The actual fluxes of CO_2 have been only rarely measured in urban environments, although micrometeorological techniques, notably eddy covariance, can be applied as is done, for instance, with natural and cultivated ecosystems (Baldocchi et al. 2001a; Baldocchi 2003). The few observations that were made include Chicago, Illinois (Grimmond et al. 2002); the center of Edinburgh, United Kingdom (Nemitz et al. 2002); the metropolitan region of Copenhagen, Denmark (Soegaard and Møller-Jensen 2003); a Mexico City, Mexico, urban landscape (Velasco et al. 2005); Basel, Switzerland (Rotach et al. 2005; Vogt et al. 2006); and Marseille, France (Grimmond et al. 2004).

In general, those studies have shown that the complex morphological nature of urban surfaces and the inho-

mogeneous distribution of CO_2 sources and sinks are a challenge for micrometeorological flux measurement techniques: the spatial variability of surface cover and roughness of cities is often high, leading to serious limitations in the generalization of the results that are obtained (Grimmond 2006). On the other hand, proper estimation of urban fluxes is becoming increasingly important (Grimmond 2006) because they determine the thermodynamic properties of the urban boundary layer as well as turbulence statistics and mixing properties (Salmond et al. 2005). Flux measurements in cities also offer the possibility of separating carbon sources and sinks (Soegaard and Møller-Jensen 2003) and provide relevant information on how urban and suburban areas function as integrated, ecological systems. In a longer perspective, urban flux measurements made on a continuous basis can also provide useful information that can be used to monitor changes in carbon emission in response to local, national, and global policies aimed at the reduction of greenhouse gas emission from anthropogenic sources.

This paper illustrates some preliminary results of urban observations in the city of Firenze (Florence), Italy. The aim of this study is twofold: it provides a detailed evaluation of the measured fluxes that is based on a comparison with inventory data sources, and then it shows that flux data can actually be partitioned into their major components, road traffic and domestic heating, simply using their seasonal dynamics.

Corresponding author address: Alessandro Matese, IBIMET-CNR, Via Caproni, 8 50145 Florence, Italy.
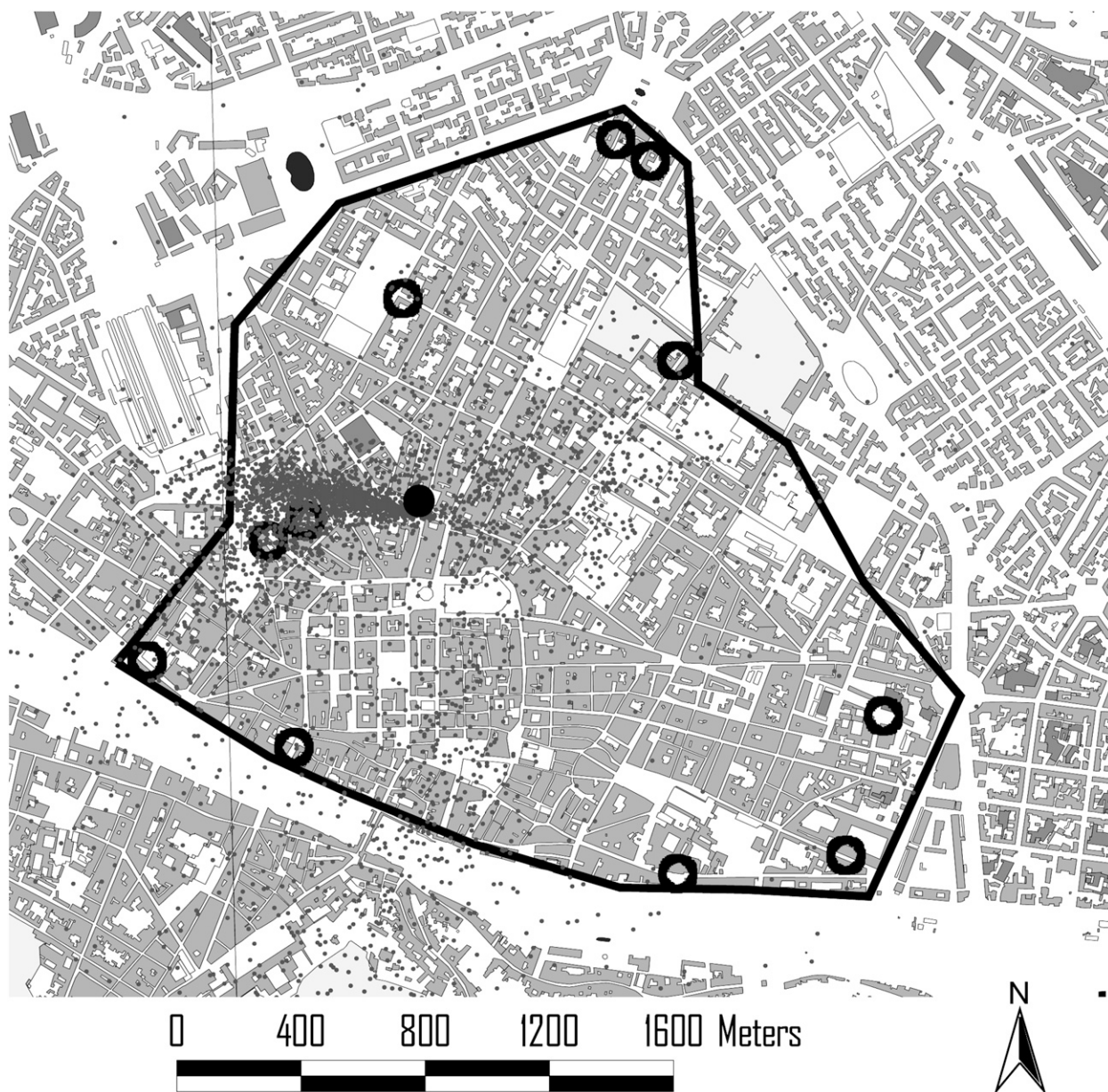E-mail: a.matese@ibimet.cnr.it

FIG. 1. Map of the city center of Firenze (source: Carta Topografica Regionale, Regione Toscana). The position of the flux station is indicated by a filled circle, and traffic checkpoints are indicated by open circles. The dots superimposed on the map denote the lengths of upwind segments (connecting each dot to the tower), which contain 90% of the observed flux (see text for explanation).

2. Materials and methods

a. Flux measurements

An eddy covariance (EC) flux station was installed in Firenze (43°47′N, 11°15′E) in September of 2005 at the Osservatorio Ximeniano, in the center of the city (Fig. 1), and was operated from 14 September to 31 December 2005. A mast of 3 m was mounted on a typical tile roof of an ancient building of the observatory at 33 m above the street level. Turbulent fluxes of CO_2,

momentum, and sensible heat were collected using a sonic anemometer (R. M. Young Co. model 81000V) and an open-path CO_2/H_2O infrared gas analyzer (IRGA; Li-Cor, Inc., Model 7500). The distance between the two sensors was approximatively 0.4 m. The IRGA was inclined toward the north by an angle of 30° to minimize solar radiation interference (Li-Cor recommendation) and to facilitate the shedding of water droplets from the sensor lenses. It was calibrated every month using reference gas tanks and a portable dewpoint generator

(Li-Cor Model 610). Raw data were acquired at the frequency of 20 Hz. Half-hourly fluxes were derived using the following processing tasks:

1) a despiking procedure specifically tuned to remove erroneous IRGA data, especially under rainy and foggy conditions,
2) a high-pass filtering with linear detrending (Aubinet et al. 2000),
3) coordinate axis rotations as described in Aubinet et al. (2000), and
4) corrections of CO_2 and water (H_2O) fluxes applied for air density fluctuations (Webb et al. 1980).

Quality-control procedures, including stationarity analysis and integral turbulence tests, were applied as described in Foken and Wichura (1996). Half-hourly integration time of eddy covariance measurements is commonly accepted as a good compromise between the need of accounting for proper statistics and that of reducing nonstationary problems. Appropriateness of such a time interval is also confirmed by cospectral analysis in which relevant flux-carrying time scales are well within the averaging interval both in stable and unstable conditions. In this study, a threshold friction velocity u_c^*, equal to 0.15 m s^{-1}, was used to identify acceptable turbulence conditions. The value was determined by analyzing the dependence of nighttime eddy flux on u^* and choosing a u_c^* as the value beyond which the flux leveled off (Aubinet et al. 2000). Missing data were reconstructed using a gap-filling procedure based on a mean diurnal variation. In such a method, a missing observation at a certain time is replaced by the mean for that time (half hour) based on adjacent days. A number of 10 adjacent days has been chosen during the first period (P0) ranging from 14 September to 8 October when flux temporal variability is lower while a number of six adjacent days has been used during the second period (P1) from 2 November to 31 December. This method is only able to reproduce mean flux magnitudes; it cannot reproduce deviations from means in any statistically defensible manner (Falge et al. 2001). In the presence of nonbiogenic fluxes like those analyzed here that do not respond directly to environmental forcing, no lookup tables or regression analysis against one or more external meteorological variables can be applied (Falge et al. 2001).

Footprint calculations were made using an approximate analytical model based on stochastic Lagrangian dispersion combined with dimensional analysis that explicitly describes the relationship among footprint, atmospheric stability, observation height, and surface roughness within the surface layer (Hsieh et al. 2000). This model was chosen because it provides a non-ecosystem-specific approach that is likely more applicable than others to an urban area. Atmospheric stability information required by the model was derived directly from sensible heat flux and friction velocity data. Zero plane displacement height Z_d was estimated on the basis of the surface characteristics of the study area; the average heights of surrounding buildings Z_h and of the building hosting the installation are 25 and 30 m, respectively. The height of the instruments Z_m is equal to 33 m from the street level, and Z_d was calculated as $0.8Z_h$ as done elsewhere (Grimmond and Oke 1999; Velasco et al. 2005). Roughness length Z_0 was calculated directly from observations by assuming similarity-theory relations for the surface layer:

$$\overline{u}_z = \left(\frac{u^*}{k}\right)\left\{\ln\left[\frac{(Z - Z_d)}{Z_0}\right] + \psi_m\left(Z - \frac{Z_d}{L}\right)\right\}; \quad (1)$$

Z_0 was explicitly resolved from Eq. (1), where k is von Kármán's constant, L is the Obukhov stability length, and ψ_m is a dimensionless function that accounts for the wind profile curvature based on atmospheric stability. For more information on L and the form of the ψ_m function, refer to Kaimal and Finnigan (1994). The mean value of Z_0 calculated in this way was equal to 1.08 m. Sensitivity of the footprint analysis to these input parameters was assessed, calculating the propagation of uncertainty of Z_d to Z_0 and then to footprint model results. Cospectral source area analysis was also implemented to study relevant temporal and spatial scales associated with the fluxes. Cospectra of vertical wind velocity and CO_2 mixing ratio in representative stable and unstable conditions showed that CO_2 fluxes are mostly related to time scales ranging from 30 to 500 s, with a peak located on average around 260 s. These figures, when converted to the spatial domain by invoking Taylor's hypothesis (Cooper et al. 2003), correspond to spatial scales between 150 and 1200 m. Such measurement conditions are beyond the influence of roughness elements, thus representing an integrated response at local scale.

b. CO_2 source from traffic

The city center of Firenze is characterized by small squares surrounded by a network of narrow streets linked to the ancient gates. According to the reconstruction plan of 1885, the city walls were demolished and were replaced by a ring of avenues surrounding the city center that are the most busy streets. There is almost no vegetation in the city-center area.

Traffic data are routinely collected at 15-min time intervals by optical systems measuring the number of passing vehicles at several locations (checkpoints; Fig. 1) within the city center (Direzione Mobilità Comune di Firenze). The estimation of CO_2 emission associated with road traffic was made using the method recommended by

the Handbook on Emission Factors for Road Transport (INFRAS 2001), which defines basic emission models associated with "real world" driving cycles. Those models include the "urban slow" pattern associated with a mean emission factor of 203 gCO_2 km^{-1} per vehicle, the "stop-and-go A" pattern associated with a mean emission factor of 460 gCO_2 km^{-1} per vehicle, and the "stop-and-go B" pattern with an emission factor of 738 gCO_2 km^{-1} per vehicle. Those driving cycles were arbitrarily related to the number of circulating vehicles, assuming that when the number of cars is at a minimum there is no traffic congestion and the urban slow pattern can be used, when the traffic corresponds to the mean observed value the stop-and-go A model applies, and when the traffic reaches its maximum the highest emission factor corresponding to the stop-and-go B pattern can be used. The total hourly emission associated with traffic was calculated also assuming that the average distance traveled by each vehicle is equal to the mean distance between checkpoints (2.5 km). Such distance was assumed to correspond to a mean "typical path" driven by vehicles circulating the central area of the city. The CO_2 source due to the traffic per unit land area was then calculated on the basis of the total surface area of the city center, equivalent to 2.4 km^2 (Fig. 1). In this way, the simplifying assumption was made that the traffic is evenly distributed over that area.

c. CO_2 source from domestic heating and cooking

Hourly distribution data of natural gas used for domestic heating and cooking were provided by two pumping stations, Ugnano and Rifredi, of Società Fiorentina Gas, S.p.A., which controls the gas supply in the city. The conversion of natural gas release into emitted CO_2 from combustion was made using CO_2 emission-factor data from the literature (Houghton et al. 1996; Aubè 2001). The values used are 37.23 MJ m^{-3} for the energy content of natural gas and 49.68 tCO_2 TJ^{-1} for the CO_2 emission factor. Hourly CO_2 emission generated by natural gas use per unit land area was calculated by dividing the overall CO_2 emission by natural gas combustion by the city area served by the nodal points of the gas distribution network (20.8 km^2). Also in this case, a simplifying assumption was made of an even spatial distribution of CO_2 emission.

d. Flux partitioning

Partitioning of turbulent CO_2 flux data measured at the eddy covariance station into their major components (road traffic and domestic heating plus cooking) was done considering two different periods P0 and P1 within the temporal limits of our study (Fig. 2). During P0, the contribution from domestic heating was assumed to be
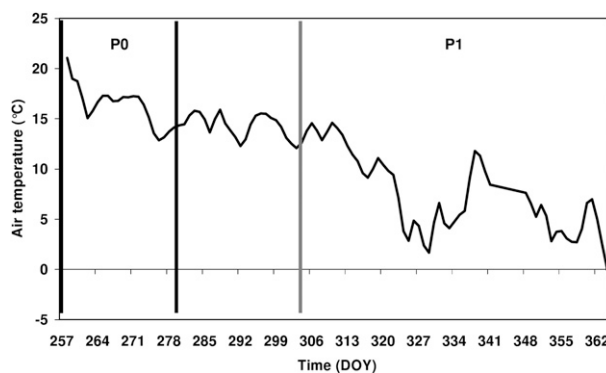

FIG. 2. Temporal trends of the daily mean air temperature measured at the flux station during the study period. The x axis is day of year (DOY). The distinction between periods P0 and P1 is indicated—P0 is the period during which the domestic heating is assumed to be off [14 Sep (DOY 257)–8 Oct (DOY 281)], and P1 is the period during which domestic heating is assumed to be operating [2 Nov (DOY 306)–31 Dec (DOY 365)].

zero as a consequence of the relatively warm air temperature (mean = 15.7°C) and because the municipal authorities of the city of Firenze only allow domestic heating after 1 November (Presidential Decree 412/93). During P1, domestic heating was assumed to be turned on as a consequence of cooler air temperature (mean = 6.7°C). Nonheating natural gas sources were considered to be constant throughout both periods P0 and P1. Considering that road traffic has no seasonality and does not significantly change between P0 and P1 (Fig. 5, described below), it may be assumed that the difference in the CO_2 flux observed between P1 and P0 can be entirely ascribed to domestic heating.

3. Results

The eddy covariance station at Osservatorio Ximeniano operated for almost 90% of the time during the study period, and interruptions were due mainly to maintenance operations. Sensitivity of the footprint analysis to model input parameters was assessed: assuming an uncertainty on the value of Z_d of ±20%, its propagation to Z_0 through Eq. (1) and then to footprint model outputs was calculated. Results are shown in Table 1 for footprint distance containing 90% of the flux. For the "central" case (i.e., Z_d = 20 m and Z_0 = 1.08 m), individual footprint data are reported in Fig. 1, which illustrates how most of the measured fluxes originate from the city center. Because of prevalent wind directions, the western section of the area was more densely sampled. This result does not change significantly for the other combinations of Z_d and Z_0 reported in Table 1. The footprint of the flux tower and the inventory data source have an obvious mismatch. This is expected to be

TABLE 1. Sensitivity of the footprint analysis to model input parameters: Z_d (zero plane displacement height), Z_0 (roughness length), and X90 (footprint distance containing 90% of the flux).

Z_d (m)	Z_0 (m)	X90 (m)
20	1.08	521 ($\pm$432)
18	1.28	568 ($\pm$478)
22	0.98	447 ($\pm$365)

TABLE 2. Daily means and standard deviation of variables during P0 (14 Sep–8 Oct) and P1 (2 Nov–31 Dec).

	P0	P1
NEE (μmol m^{-2} s^{-1})	13.37 ($\pm$2.9)	35.40 ($\pm$10.4)
CO_2 concentration (ppm)	388.83 ($\pm$10.3)	424.30 ($\pm$39.7)
$u*$ (m s^{-1})	0.28 ($\pm$0.1)	0.27 ($\pm$0.2)
Sensible heat flux (W m^{-2})	41.87 ($\pm$18.0)	25.52 ($\pm$13.3)
Wind velocity (m s^{-1})	1.96 ($\pm$1.1)	1.82 ($\pm$1.2)

smaller for traffic data and larger for natural gas sources because those data are related to the entire city area and not only to the city center. Therefore, a direct comparison between flux data obtained in the two different ways assumes, with a simplification, that source patterns are evenly distributed over those footprints.

During the study period, the daily mean air temperature decreased from 21° to 0°C (Fig. 2). Daily net ecosystem exchange (NEE) was always a positive term, corresponding, on average, to 25.8 μmol m^{-2} s^{-1}, but NEE varied from 12.7 μmol m^{-2} s^{-1} during P0 up to 35.9 μmol m^{-2} s^{-1} during P1. NEE correlated negatively with air temperature (Fig. 3). Sensible heat flux also decreased over the study period following seasonal reduction in irradiance (Table 2). The mean diurnal course of NEE followed typical patterns. A rapid increase was observed after 0400 central European time (CET), and a maximum was observed around noon. In the afternoon, the flux decreased until 1800 CET when a second increase was observed, after which the CO_2 flux decreased to remain almost constant at a minimum level during the night (Fig. 4).

Traffic and natural gas inventory data provided reliable information to calculate the actual CO_2 emission of the city. The pattern of daily and diurnal city traffic did not vary substantially over the study period (Figs. 5a–c), but it differed among the different days of the week, with a minimum on Sundays (16.6% less than average) and a

maximum on Fridays (10.5% more than average). An exception to this is represented by the period around Christmas and New Year's Eve, when the highest traffic intensity was recorded on Friday 23 December and a minimum was recorded between 24 and 31 December. Such a peculiar traffic pattern reflects the typical behavior of the local population over the Christmas period.

Natural gas use increased substantially over time (Fig. 6), mainly because domestic heating started when the air temperature dropped below a certain threshold.

Road traffic can be assumed to be the prevailing source of CO_2 during P0, whereas domestic heating increasingly contributes to the overall flux during P1. Other CO_2 sources during both P0 and P1 were "nonheating" natural gas combustion and human respiration, two terms that may be assumed to remain constant over both P0 and P1. The city center of Firenze is the commercial core of the city and is characterized by shopping areas, institutional buildings, and offices. The city center is surrounded by residential neighborhoods. Human respiration, which is not a negligible term in a densely populated city, may be calculated on the basis of a population density of approximately 3470 inhabitants per kilometer squared (Istat 2001) and an estimated unit emission of approximately 3.5 gCO$_2$ m^{-2} day^{-1} (estimate obtained online on 5 December 2008 from the Carbon Dioxide Information Analysis Center Web site: http://cdiac.ornl.gov/faq.html).
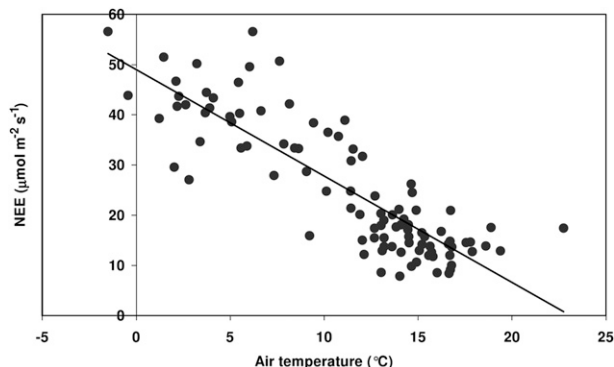

FIG. 3. Relationship between mean daily NEE measured by the flux tower and air temperature in the study period. The line fitted to the data was calculated by regression ($R^2 = 0.729$).
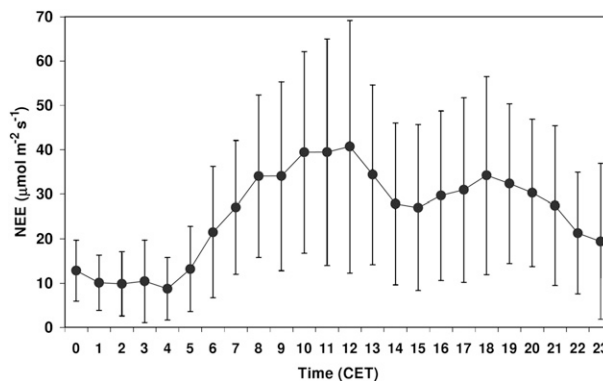

FIG. 4. Mean diurnal course of NEE of the whole study period (14 Sep–31 Dec), calculated over a total of 100 days.
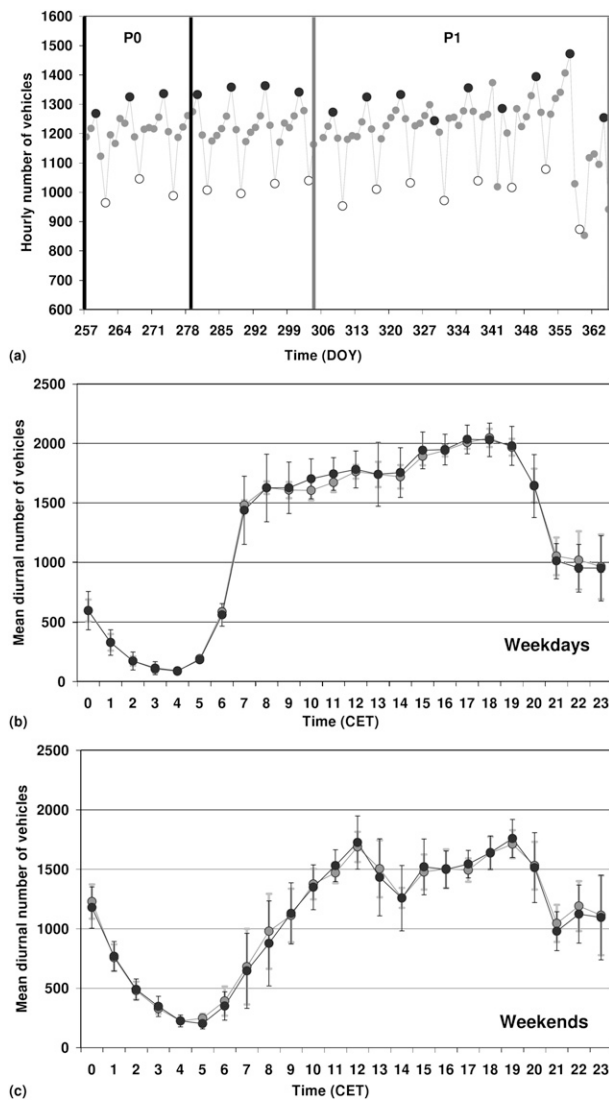
FIG. 5. (a) Daily average of hourly sums of vehicles at the traffic checkpoints shown in Fig. 1. Black, gray, and white symbols refer to Friday, weekdays, and Sunday, respectively. Average diurnal course of hourly sums of vehicles for (b) weekdays and (c) weekends. Black and gray symbols refer to P0 and P1, respectively.

By summing all of these contributions, the CO_2 source of the city was reconstructed for each day of both P0 and P1 (Fig. 7), and those daily means compared very well to the corresponding NEE measured by eddy covariance (Fig. 8). A clear distinction was apparent between data collected during P0 (high air temperature; low NEE) and during P1 (low air temperature; high NEE). The ''average diurnal day'' calculated respectively for P0 (nonheating contribution only) and P1 (all contributions) showed a good match with the corresponding NEE measured by eddy covariance over the two periods (Figs. 9a,b).
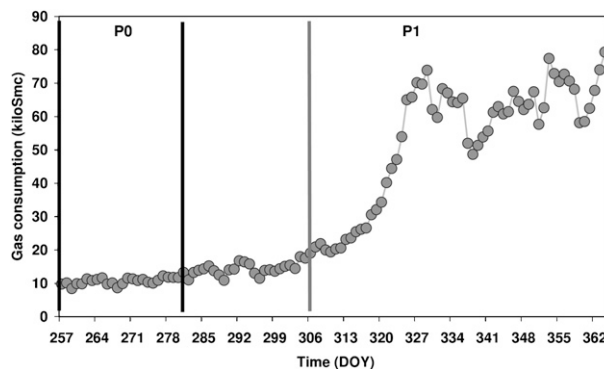

FIG. 6. Daily means of the hourly rate of gas consumption, expressed as standard cubic meters (kiloSmc) per hour over P0 and P1 (Società Fiorentina Gas, S.p.A.).

4. Discussion and conclusions

The good match between urban CO_2 fluxes directly measured by eddy covariance and those estimated using detailed inventory sources of city traffic and natural gas use indicated that the eddy covariance technique is well suited to monitor CO_2 emission of the central part of the city of Firenze. This implies that the basic micrometeorological requirements and assumptions are adequately met (Baldocchi et al. 2001a,b; Baldocchi 2003) and confirms previous attempts that pioneered the application of this technique in urban areas (Grimmond et al. 2002; Soegaard and Møller-Jensen 2003; Vogt et al. 2006).

Average diurnal courses of CO_2 emission were comparable, with some discrepancy during the central part of the day when the tower data were consistently higher than inventory data both during P0 and P1. Such discrepancy cannot be easily interpreted. The occurrence of unknown CO_2 sources in the central part of the day that are not accounted for by inventory data seems very unlikely, because autonomous power generators or
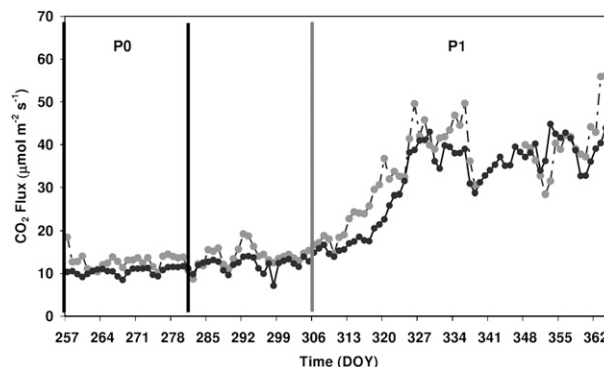

FIG. 7. Daily averages of CO_2 fluxes (NEE; gray symbols) and daily averages of CO_2 emissions calculated from inventory sources (black symbols).
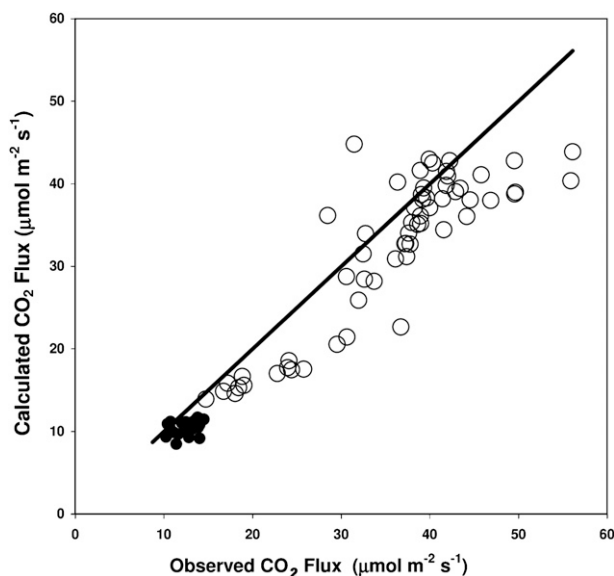
FIG. 8. Relationship between observed eddy covariance CO_2 fluxes (x axis) and daily fluxes calculated from inventory sources (y axis). Filled circles denote the period P0, and open circles denote P1. The solid line is the 1:1 line.

propane cylinders that may be eventually responsible for additional CO_2 emissions are very rarely used in private households or in businesses in Firenze.

The hypothesis of an uneven temporal and spatial distribution of the traffic within the city center could also explain the observed discrepancy, but such a hypothesis contradicts the fact that the difference among P1 is higher than among P0. A third hypothesis, that the variable footprint area of the tower is contributing to the observed difference, cannot be ruled out. As expected, footprint analysis revealed that the tower footprint tends to be smaller with the occurrence of higher turbulence, and it is known that atmospheric turbulence is generally higher during the central part of the day, when convection reaches a maximum value of the day. It is therefore possible that under those circumstances the tower footprint becomes more affected by microscale positive contributions to the flux than during other times of the day. It must be considered, however, that differences between average diurnal tower and inventory data are typically within 10% both during P0 and P1 (Figs. 9a,b).

The overall results are of relevance in view of operational applications involving the use of eddy covariance for CO_2 flux monitoring in cities. Flux measurements made with this technique can now be made on a routine basis, because human intervention is only required for periodic calibration and limited instrument maintenance. The obvious advantage of using eddy covariance in urban applications is that it may provide a rapid and direct monitoring tool that does not require inventory data,
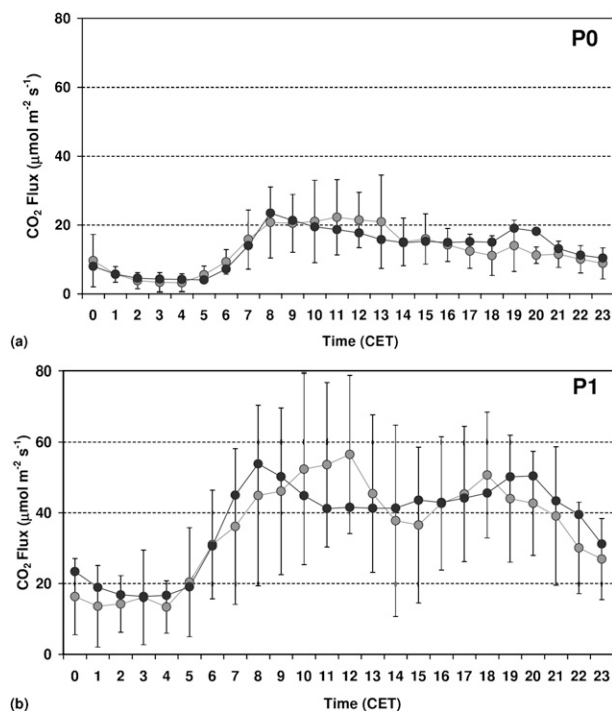

FIG. 9. Average diurnal courses of hourly CO_2 fluxes observed by the flux tower (gray symbols; $N = 25$ for P0 and $N = 51$ for P1) in comparison with corresponding hourly values calculated from inventory sources (black symbols) for (a) P0 and (b) P1. Vertical bars are standard deviation of the eddy flux data.

which may not be readily available in many situations. In addition, the deployment of multiple EC stations over the urbanized area may further strengthen the value of direct measurements, because this may provide relevant information to detect the relative contribution of different sections of a city to the overall NEE. Those contributions may in fact vary in response to different road traffic intensities, domestic heating efficiency, population density, and the ratio between urbanized land and green areas acting as CO_2 sinks at the annual scale (Grimmond and Oke 1999)—something that can hardly be assessed on the basis of inventory sources only.

Our results also demonstrated that seasonal changes in NEE can provide a clue to partitioning the overall CO_2 flux into its major source components. This may enhance the value of the measurements for urban monitoring applications, because it allows detection of short- to long-term changes in the overall NEE that can be obtained by emission-limitation policies being implemented at the local scale.

In a wider perspective, flux measurements made by EC can provide novel information on the correlation existing between meteorological data and urban CO_2 emission, with the regression between air temperature and NEE being a typical example as shown in Fig. 3.

Robust relationships of this kind are certainly of value while trying to create reliable inventories of regional or national CO_2 emission budgets. So far, estimations of greenhouse gas emissions of urban territories have been mostly based on indirect methods that often lack independent validation.

In conclusion, the data presented in this paper confirm that EC can be successfully used in cities as a long-term monitoring tool of CO_2 emissions, thus opening new opportunities to obtain rapid and reliable information of CO_2 emission data of urbanized territories and to evaluate the effect of emission reduction policies that we feel must be adopted, without any further delay, by our society.

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