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Comparison of net CO_2 fluxes measured with open- and closed-path infrared gas analyzers in urban complex environment

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Simultaneous eddy covariance (EC) measurements of CO_2 fluxes made with open-path and closed-path analyzers were done in urban area of Helsinki, Finland, in July 2007–June 2008. Our purpose was to study the differences between the two analyzers, the necessary correction procedures and their suitability to accurately measure CO_2 exchange in such non-ideal landscape. In addition, this study examined the effect of open-path sensor heating on measured fluxes in urban terrain, and these results were compared with similar measurements made above a temperate beech forest in Denmark. The correlation between the two fluxes was good ($R^2 = 0.93$) at the urban site, but during the measurement period the open-path net surface exchange (NSE) was 17% smaller than the closed-path NSE, indicating apparent additional uptake of CO_2 by open-path measurements. At both sites, sensor heating corrections evidently improved the performance of the open-path analyzer by reducing discrepancies in NSE at the urban site to 2% and decreasing the difference in NSE from 67% to 7% at the forest site. Overall, the site-specific approach gave the best results at both sites and, if possible, it should be preferred in the sensor heating correction.

Introduction

Due to the growing concern about changing climate, there has been an increasing interest to measure the exchange of carbon dioxide (CO_2) between terrestrial ecosystems and the atmosphere. For this purpose, direct measurements of CO_2 exchange with the eddy covariance (EC) technique have been widely used (e.g. Aubinet *et al*. 2000, Baldocchi 2003). Traditionally, EC measurements have been made above vegetated surfaces, but were recently extended to urban areas, which play an important role as a source of CO_2 (e.g. Grimmond *et al*. 2002, Nemitz *et*

al. 2002, Moriwaki and Kanda 2004, Vogt *et al*. 2006, Vesala *et al*. 2008). The urban environment brings its own challenges to EC measurements due to the complexity of the surface, which may not always provide homogeneous and stationary conditions.

Most commonly, CO_2 fluxes are being measured with either open- or closed-path CO_2/H_2O infrared gas analyzers in combination with fast response sonic anemometers. The measurement principles of these two types of analyzers are rather different, and they may not be equally suitable for measurements in urban environments. An open-path analyzer measures partial CO_2 densities (μmol m^{-3}) *in situ* in ambient air, which can be directly used for computing fluxes (in unit μmol m^{-2} s^{-1}) via the covariance approach. This apparent advantage is, however, hampered by the fact that any variation in the density of air (caused e.g. temperature or humidity fluctuations) in the sampled air volume that is not perfectly uncorrelated with the variations in partial CO_2 densities leads to apparent fluxes that need a special correction (*see* below). In contrast, closed-path analyzer uses a controlled sample air volume with highly reduced temperature fluctuations at a stabilized temperature and known pressure. Depending on whether the air was dried or water vapour concentrations were measured simultaneously, such instruments could measure dry air mole fractions (or mixing ratios) in ppm. Measuring dry mole fraction requires, however, the density of air in eddy covariance flux computations to yield flux densities in μmol m^{-2} s^{-1}. This is usually not measured with a very high accuracy.

Fluxes measured with both systems need to be corrected for inadequate system response, which has an especially large effect on closed-path measurements. Often these frequency response corrections are based on a model co-spectra obtained above a flat terrain (e.g. Kaimal *et al*. 1972, Eugster and Senn 1995). The usage of these model co-spectra may cause an error in the frequency response corrections especially in complex terrains, where co-spectra may have a different shape. Spectral studies made in urban areas have so far reported similar co-spectral shapes as those by Kaimal *et al*. (1972) at several specific locations (e.g. Roth and Oke 1993, Roth 2000, Vesala *et al*. 2008). The CO_2 fluxes measured with open-path analyzers need also to be corrected for the density fluctuations caused by correlated heat and water vapour fluctuations (WPL correction, Webb *et al*. 1980). The unresolved energy budget closure observed in many flux sites is likely to affect the accuracy of the WPL correction (e.g. Liu *et al*. 2006). The energy imbalance can originate from advection of both heat and moisture which are assumed to be higher in urban areas due to the heterogeneity of the surface. There is also a concern about pressure variance term in the WPL correction which is usually assumed to be negligible, but which might have significant bias at the sites having frequently high wind speeds and strong turbulence (Kramm *et al*. 1995, Massman and Lee 2002). Lately, there has also been a discussion about the heat flux produced by the open-path sensor itself, which should be taken into account when correcting CO_2 fluxes (Burba *et al*. 2006, Grelle and Burba 2007, Burba *et al*. 2008). Previous studies have reported the surface heating causing an apparent CO_2 flux outside the growing season (Grelle and Burba 2007, Burba *et al*. 2008, Ono *et al*. 2008).

The main purpose of this study is to compare CO_2 fluxes measured with open-path and closed-path CO_2/H_2O infrared gas analyzers (LI-7500 and LI-7000, respectively) in a complex urban environment in Helsinki, Finland. The measurement location creates rather different ground for the CO_2 exchange, with high emissions through the year covering all the four seasons. So far, comparisons between these two analyzers have been made under controlled conditions or above vegetated surfaces (Leuning and King 1992, Suyker and Verma 1993, Grelle and Burba 2007, Burba *et al*. 2008, Ono *et al*. 2008). Comparisons are lacking in urban areas, in which also errors concerning the technique itself are expected to be larger. The secondary purpose is to examine the sensor heating correction of the open-path analyzer, and correction methods proposed by Burba *et al*. (2006 and 2008) in an urban environment alongside the measurements made above forest located in Lille Bøgeskov, Denmark, are tested.

Materials and methods

Measurement sites and instrumentation

The measurements were carried out at the SMEAR III (Station for Measuring Ecosystem–Atmosphere Relationships) station in Helsinki, Finland, located about 5 km to the north-east from the centre of Helsinki. EC measurements were made on the top of a 31-meter-high lattice tower (60°12.17´N, 24°57.671´E in WGS84) situated on a rocky hill 26 meters above sea level. A maximum slope of 12° is present in the direction 120°–180° (Vesala *et al*. 2008). Besides the tower, meteorological measurements were placed on the roof of the University of Helsinki buildings located next to the measurement tower. The surrounding area is heterogeneous consisting of buildings, paved areas, patchy forest and cultivated area, and it can be divided into three land use sectors (urban 320°–40°, road 40°–180° and vegetation 180°–320°), each representing typical land use in the area. A more detailed description about the station can be found from Järvi *et al*. (2009) and Vesala *et al*. (2008).

The EC setup at the SMEAR III station to measure CO_2 fluxes consisted of a Metek ultrasonic anemometer (USA-1, Metek GmbH, Germany) to measure all three wind components and sonic temperature, as well as open- and closed-path infrared gas analyzers (LI-7500 and LI-7000, respectively, LI-COR, Lincoln, Nebraska, USA) to give CO_2 and water vapour densities and mixing ratios, respectively. The EC setup was situated on a boom, with a distance of 1.3 meters to the south-west of the tower. The open-path analyzer was mounted 0.2 m away from the anemometer and it was tilted 30° in the north-west direction to allow rainwater to drip off. In case of the closed-path analyzer, air sample was taken 13 cm below the anemometer and it was drawn to the analyzer through a 40-meter-long steel tube with an inner diameter of 8 mm. The flow rate in the tube was 17 l min^{-1} to ensure turbulent flow, and the sampling line was heated with a power of 4 W m^{-1} to avoid condensation of water vapour. The open-path gas analyzer was connected to the analogue input channels of the anemometer, whereas closed-path analyzer data were recorded separately using the RS-232 output. The frequency of the EC measurements was 10 Hz and the raw data were stored for later post-processing.

Besides the EC measurements, the air temperature was measured with a Pt-100 resistance ("home-made", ventilated and shielded from rain and solar radiation) thermometer, and incoming and outgoing shortwave and longwave radiation with a net radiometer (CNR1, Kipp&Zonen, Delft, Netherlands) at the height of 31 meters. The measurement interval for these was 1 minute. Air pressure was measured with a barometer (Vaisala DPA500, Vaisala Oyj., Vantaa, Finland) on the top of the University of Helsinki building at the height of 50 meters with a measurement interval of 4 minutes.

Similar open-path and closed-path CO_2 flux measurements were also conducted over natural ecosystem for comparison with the urban environment. The measurements were made above a beech forest in Lille Bøgeskov (55°29´N, 11°38´E, 40 m a.s.l.) near Sorø in Zealand, Denmark (Pilegaard *et al*. 2003). The EC measurements were made at the height of 43 meters and the setup consisted of a Solent ultrasonic anemometer (R2, Gill Instruments, Lymington, UK), and LI-7500 and LI-7000 infrared gas analyzers. The open-path analyzer was tilted 10–15 degrees. In the case of the closed-path analyzer, air was sampled 0.6 m distance below the anemometer and was drawn through a 50 meters long sampling tube to the analyzer with inner diameter of 8 mm and flow rate of 20 l min^{-1}. The sampling frequency was 10 Hz.

Basic equations and data processing

The 30-min turbulent flux of scalar *s* was calculated as a co-variance between the vertical wind speed and *s* according to e.g. Aubinet *et al*. (2000). Before the flux calculation, the linear trend was removed from the time series and two-dimensional coordinate rotation was applied. Flux values were calculated with a maximum covariance method (*see* McMillen 1988, Moncrieff *et al*. 1997) which also gave a time lag of 7.3 s for closed-path CO_2 caused by the tube.

Below we go through the other necessary corrections in a more detail.

Co-spectral corrections

The atmospheric fluxes measured with both open-path and closed-path sensors have flux losses at both high and low-frequency ends. At low frequencies, the losses are caused by the averaging time and linear de-trending used in the flux calculations, while at the high frequency end losses are due to the imperfect frequency response of the EC system (e.g. Moore 1986, Eugster and Senn 1995, Aubinet *et al*. 2000, Rannik *et al*. 2004). The underestimation of the measured flux can be determined with the following equation:

$$\frac{F_{\mathrm{m}}}{F}=\frac{\int_0^\infty \mathrm{TF_H}(f)\,\mathrm{TF_L}(f)\,C_{\mathrm{ws}}(f)\,df}{\int_0^\infty C_{\mathrm{ws}}(f)\,df}, \quad (1)$$

where f is the natural frequency (in Hz), F_{m} and F are the measured and un-attenuated scalar fluxes, $\mathrm{TF_L}(f)$ and $\mathrm{TF_H}(f)$ are the transfer functions accounting for the low- and high-frequency losses, and $C_{\mathrm{ws}}(f)$ is the co-spectral density describing the frequency behaviour of the turbulent flux (Horst 1997, Moore 1986, Massman 2000).

At the urban site, the co-spectral corrections were calculated by integrating numerically Eq. 1. By assuming a scalar similarity, co-spectral models for sensible heat by Kaimal *et al*. (1972) were used as $C_{\mathrm{ws}}(f)$, and the normalized frequency n_{m} in which the co-spectrum of sensible heat attains its maximum value was determined separately for each land use sector (e.g. Kaimal *et al*. 1972, Horst 1997). In an unstable case, n_{m} was independent from wind direction and stability with an average value of 0.10 ± 0.04 (SE). In stable cases, the stability dependence of n_{m} differed among the land-use sectors with the best approximations determined by nonlinear fitting in a least-square sense (Rannik *et al*. 2004):

$$n_{\mathrm{m}}=\begin{cases}0.1\left(1+2.54\zeta^{0.28}\right), \text{urban}\\ 0.1\left(1+0.96\zeta^{0.02}\right), \text{road}\\ 0.1\left(1+2.00\zeta^{0.27}\right), \text{vegetation}\end{cases}, \quad (2)$$

In Eq. 2, $\zeta = (z - d)/L$ is the stability parameter, where z is the measurement height, L is the Monin-Obukhov length and d is the displacement height (13, 8 and 6 m for urban, road and vegetation sectors, respectively) approximated to be 2/3 of the mean canopy height.

For the open-path EC system, $\mathrm{TF_H}(f)$ was calculated as the product of the appropriate theoretical transfer functions associated with the high-frequency attenuation according to Moncrieff *et al*. (1997). The co-spectral transfer function $\mathrm{TF_H}(f)$ for the closed-path EC system was experimentally calculated according to

$$\mathrm{TF_H}(f)=\frac{1}{1+\left(2\pi\tau_{\mathrm{c}}f\right)^2}, \quad (3)$$

where τ_{c} is the first order response time (s) defined from the measured co-spectra of sensible heat and CO_2 fluxes. For the low frequency loss, the functional form of the co-spectral transfer function $\mathrm{TF_L}(f)$ associated with linear detrending was used for both systems (Rannik and Vesala 1999).

The detailed spectral corrections used at the forest site are presented in Ibrom *et al*. (2007).

WPL correction

The fluxes measured with the open-path analyzer were corrected for temperature and water vapour fluctuations according to Webb *et al*. (1980):

$$F_{\mathrm{OP}}=F_0+\mu\frac{\bar{\rho}_{\mathrm{c}}}{\bar{\rho}_{\mathrm{dry}}}\overline{w'\rho_{\mathrm{v}}'}+\left(1+\mu\frac{\bar{\rho}_{\mathrm{v}}}{\bar{\rho}_{\mathrm{dry}}}\right)\bar{\rho}_{\mathrm{c}}\frac{\overline{w'T'}}{\bar{T}_{\mathrm{a}}}, \quad (4)$$

where F_{c} and F_0 are the WPL-corrected and co-spectrally corrected open-path CO_2 fluxes, respectively, (in kg m^{-2} s^{-1}), μ is the ratio of molar masses of air and water vapour (μ = 1.6077), ρ_{c}, ρ_{v} and ρ_{dry} are the densities of CO_2, water vapour and dry air (in kg m^{-3}), respectively, T_{a} is the air temperature, $\overline{w'\rho_v'}$ is the water vapour flux (in kg m^{-2} s^{-1}) and $\overline{w'T'}$ is the sensible heat flux (in K m s^{-1}) corrected for cross wind and humidity effects as proposed by Schotanus *et al*. (1983). In Eq. 4, ρ_{c} and ρ_{v} obtained from closed-path analyzer were used, since density measurements made with open-path analyzers may be more inaccurate due to e.g. lens contamination (Serrano-Ortiz *et al*. 2008).

Effect of open-path sensor heating on WPL correction

The effect of the density fluctuations generated by the open-path analyzer itself should be taken into account in the traditional WPL correction. Burba *et al*. (2006, 2008) proposed three slightly different correction procedures for this sensor heating and all these procedures are tested in practice here.

In Burba *et al*. (2006), an additional term is added to F_{OP} calculated with Eq. 4, so that the final corrected flux, F_{Fit}, can be presented as

$$F_{Fit} = F_{OP} + \delta \frac{(T_s - T_a)\rho_c}{r_a(T_a + 273.15)}\left(1 + \mu \frac{\bar{\rho}_v}{\bar{\rho}_{dry}}\right), (5)$$

where δ is that fraction of heat produced by the analyzer which stays in the thermal boundary layer of the analyzer and is relevant for the correction, T_s is the instrument surface temperature (°C) and $r_a = U u_*^{-2}$ is the aerodynamic transfer resistance (s m^{-1}) (Jones 1992). Here the unit for density of CO_2 is μmol m^{-3}. By assuming a linear relationship ($T_s = a_0 + a_1 T_a$) between T_s and T_a, and that the closed-path CO_2 flux is the true flux F_{Fit}, Eq. 5 can be solved as a least-square regression to obtain parameters δ, a_0 and a_1. In the fitting, initial guesses for all the unknown variables were used. For δ, a value of 0.05 suggested by Rogiers *et al*. (2008) was used, while for a_0 and a_1, the bottom window values separately for day and night from the body heating experiment from Burba *et al*. (2008) were used. We used bootstrapping to obtain more generalized correction parameters separately for daytime and nighttime at both urban and forest sites. In bootstrapping, the data were divided into 100 subsamples, each including arbitrary 5/6 of the data. The parameters δ, a_0 and a_1 were solved for each subset and the final ones to correct the open-path data were calculated as arithmetic means from the subset parameters (Table 1). The sensitivity of the parameters was tested by choosing only 2/6 of the data for each 100 subsample. This affected less than 3% to the parameters δ, a_0 and a_1 at both sites. F_{Fit} was then calculated with the fitted parameters. Henceforth this method is referred to as the fitting method (Fit).

The fitted value of T_s describes the combined surface temperature of the different parts of the analyzer, which are influenced by the instrument electronic and prevailing meteorology (especially solar radiation). Heating caused by the electronics increases with decreasing T_a, while that caused by the sun increases with increasing T_a. In a daytime forest, T_s decreases with increasing T_a similarly as was observed by Burba *et al*. (2008), and thus the heating by the electronics dominated T_s (Table 1). However, T_s increases with increasing T_a at the urban site probably due to heating by the sun. The larger effect from solar heating is likely related to the position of the analyzer, since tilting affects how much different parts of the analyzer are subjected to solar radiation. Also the shorter measurement period in the forest with different radiation conditions possibly affects the observed difference between the forest and urban sites.

In Burba *et al*. (2008), the sensor heating correction is done by adding the heat flux generated by the sensor to the heat flux measured with the sonic anemometer, and the sensor heating corrected flux is calculated with Eq. 4. The sensible heat flux caused by the analyzer itself can be calculated via modified resistance approach following Nobel (1983) when the surface temperatures of the open-path analyzer are known. If the surface temperatures are not measured, Burba *et al*. (2008) proposed two methods to calculate the surface temperatures of different parts (bottom window, upper window and spar) of the LI-7500. In the first method, the difference between T_s and T_a is calculated using the following equation:

$$(T_{s,x} - T_a) = \begin{cases} b_{0,x} + b_{1,x}T_a + b_{2,x}R_g + b_{4,x}U, \text{ day} \\ b_{0,x} + b_{1,x}T_a + b_{2,x}R_{IR} + b_{4,x}U, \text{ night} \end{cases}, (6)$$

where x stands for bottom window, upper window and spar, R_g is the global radiation (W m^{-2}), R_{IR} is the incoming long-wave radiation (W m^{-2}), U is the wind speed (m s^{-1})

Table 1. Parameters (± SD) δ, a_0 and a_1 obtained with the fitting method.

		Urban	Forest
	δ	0.060 ± 0.011	0.085 ± 0.003
Daytime	a_0	1.77 ± 0.07	3.17 ± 0.17
	a_1	1.14 ± 0.01	0.93 ± 0.01
Nighttime	a_0	–0.38 ± 0.04	1.52 ± 0.14
	a_1	1.13 ± 0.01	1.05 ± 0.02

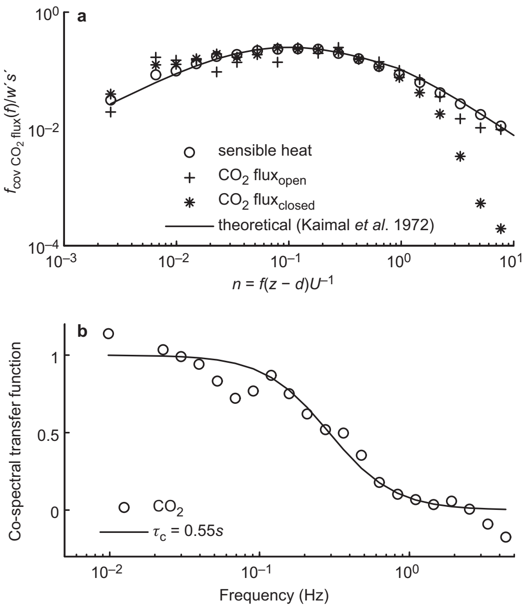

Fig. 1. (**a**) Normalized logarithmic co-spectra of the sensible heat flux and CO_2 fluxes obtained from open-path and closed-path systems as a function of normalized frequency *n*. (**b**) effective transfer function of closed path CO_2 *versus* natural frequency *f*. τ_c is the first order response time determined from effective transfer function. Co-spectra are calculated as an average from 270 half-hour unstable co-spectra between March 2008 and June 2008.

and $b_{0,x}$ … $b_{4,x}$ are parameters obtained with the multiple linear regression analysis made for hourly surface temperature measurements (*see* table 2 in Burba *et al*. 2008). In the second method, the surface temperatures of the bottom window, upper window and spar are calculated linearly from T_a using parameters obtained from hourly measurements in the body heating experiment (*see* table 3 in Burba *et al*. 2008). Below, these two methods utilizing a modified resistance approach to correct for the sensor heating are called the multiple linear regression method (MLR) and the linear method (Lin), and the open-path CO_2 fluxes obtained with these methods are denoted by F_{MLR} and F_{Lin}, respectively.

Analyzed periods and data removal

We analyzed the data over one year from the urban site during July 2007–June 2008. During this period, data gaps due to maintenance and power outages affected 12% of all the flux measurements. In the quality control step, clear spikes identified by visual inspection were removed, and half-hour fluxes with a friction velocity u_* < 0.1 m s^{-1} were omitted. To ensure stationary conditions, a stationary test according to Foken and Wichura (1996) was applied. In the test, 30-minute intervals used in the flux calculation were divided into six five-minute sub-intervals, and if the difference between the 30-minute covariance and the mean covariance of the sub-intervals was greater than 30%, the flux value was removed. Overall, the quality analysis removed 31% and 44% of closed-path and open-path CO_2 flux data, respectively. The higher rejection of the open-path data was due to the larger amount of the data spikes caused by rain or fog. Comparisons between the CO_2 fluxes obtained with open-path and closed-path analyzers were made only when the data from both analyzers were available after the quality control procedure. This reduced the data to 7060 half-hour data records, covering 40% of the whole year.

The data from the beech forest in Denmark were collected between October and December 2006. After quality control procedures similar to those used for the urban site, the remaining forest data covered 41% from the three month period.

Results and discussion

Results below concern the measurements made at the urban site in Helsinki, except in the last section where the effect of different surface heating corrections on F_{OP} are presented for urban and forest sites.

Frequency response corrections

The average normalized co-spectrum of sensible heat (Fig. 1a) follows the Kaimal *et al*. (1972) co-spectra, suggesting that the standard co-spectral model was applicable at our urban measurement site. The open-path CO_2 flux had only a slight effect due to the inadequate frequency response, whereas the effect of high-frequency attenuation was distinct in the normal-

ized co-spectrum of the closed-path CO_2 flux. The first-order response time τ_c to be used in Eq. 3 was determined experimentally from the ratio of co-spectral density of CO_2 and sensible heat (Rannik *et al*. 2004), which was assumed to be free from attenuation. From the effective co-spectral transfer function of the closed-path system, a value of $\tau_c = 0.55$ s was found for the response time (Fig. 1b).

On average, the co-spectral flux losses were 11% ± 3% (SD) and 3% ± 2% (SD) for closed- and open-path CO_2 fluxes, respectively. The flux loss of both measurement systems depended on stability and wind speed similarly as reported by Massman (2000) and Moore (1986).

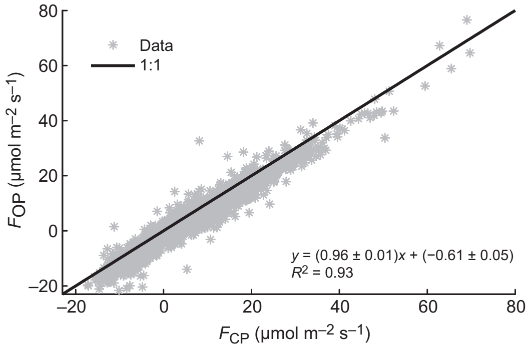

Fig. 2. Correlation ($p < 0.05$) between the urban CO_2 fluxes measured with closed-path (F_{CP}) and open-path (F_{OP}) analyzers between July 2007 and June 2008. The equation gives a least-square linear regression and 95% CIs.

Correlation between the open- and closed-path CO_2 fluxes

The CO_2 flux obtained with the closed-path analyzer (F_{CP}) was correlated with F_{OP} for the period July 2007–June 2008 (Fig. 2). A correlation analysis yielded $R^2 = 0.93$, showing that the two setups were measuring the same signal. The slope using a linear least square fit was slightly lower than one. From the offset (0.61 μmol m^{-2} s^{-1}) it can be seen that the open-path analyzer gave smaller CO_2 fluxes than the closed-path analyzer, which corresponds to an apparent additional uptake of CO_2. This was mainly due to the daytime situations ($F_{CP} = 0.97F_{OP} - 1.39$). The nocturnal fit ($F_{CP} = 0.90F_{OP} + 0.40$) gave a slightly positive offset, showing that the open-path analyzer was measuring larger fluxes than the closed-path analyzer. In general, the daytime correlation was better than the nocturnal one. With the correlation between the two fluxes being so high, even a small difference of the regression slope from 1.0 and the offset from 0.0 will have a large effect on the annual carbon budgets.

The correlation found in this study is better than the observed correlations of $R^2 = 0.79$ and $R^2 = 0.70$ between two closed-path systems with separate anemometers above arctic tundra and forest, respectively (Eugster *et al*. 1997, Rannik *et al*. 2006). Burba *et al*. (2008) found a weaker correlation ($R^2 = 0.86$) between the two sensors with the same anemometer above grassland during winter with the slope of 0.82 and the offset of –0.45 μmol m^{-2} s^{-1}. A better correlation ($R^2 = 0.98$) was found by Ibrom *et al*. (2007) above a beech forest in summer (slope 1.00, offset 0.44).

Diurnal cycle of F_{CP} and F_{OP}

The diurnal behaviours of F_{OP} and F_{CP} were plotted separately for different temperature ranges (Fig. 3) due to the dependence of the difference $\Delta F_C = F_{CP} - F_{OP}$ on T_a (Fig. 4). The diurnal pattern was calculated as medians from half-hour flux points.

The diurnal patterns of F_{CP} and F_{OP} followed closely each other. The surroundings acted as a source of CO_2, except in the highest temperature range of 12–28 °C when downward (negative) fluxes were observed during daytime. The highest downward fluxes (–8 μmol m^{-2} s^{-1}) were due to the direction of prevailing winds (SW) which was also the direction of the highest vegetation cover. As suggested already by the correlation analysis, the closed-path analyzer measured higher upward and lower downward (depending on T_a) fluxes than the open-path analyzer during daytime. Below 5 °C, the difference between the two fluxes was around 0.8 μmol m^{-2} s^{-1} (10% difference), increasing to 3.5 μmol m^{-2} s^{-1} (25% difference) in the temperature range of 12–28 °C. This indicates that the underestimation of the WPL correction increases with the increasing

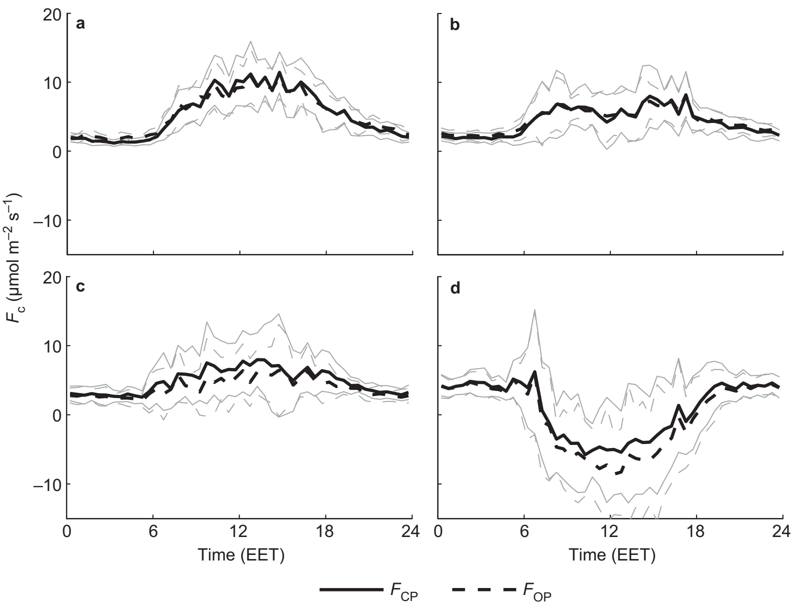

Fig. 3. Median diurnal variation of urban CO_2 fluxes obtained with closed-path (F_{CP}) and open-path (F_{OP}) analyzers for temperature ranges (**a**) –12 to 0 °C (**b**) 0 to 5 °C, (**c**) 5 to 12 °C, and (**d**) 12 to 28 °C. Values were calculated from the half-hour flux points and grey lines show the respective ±1 quartiles.

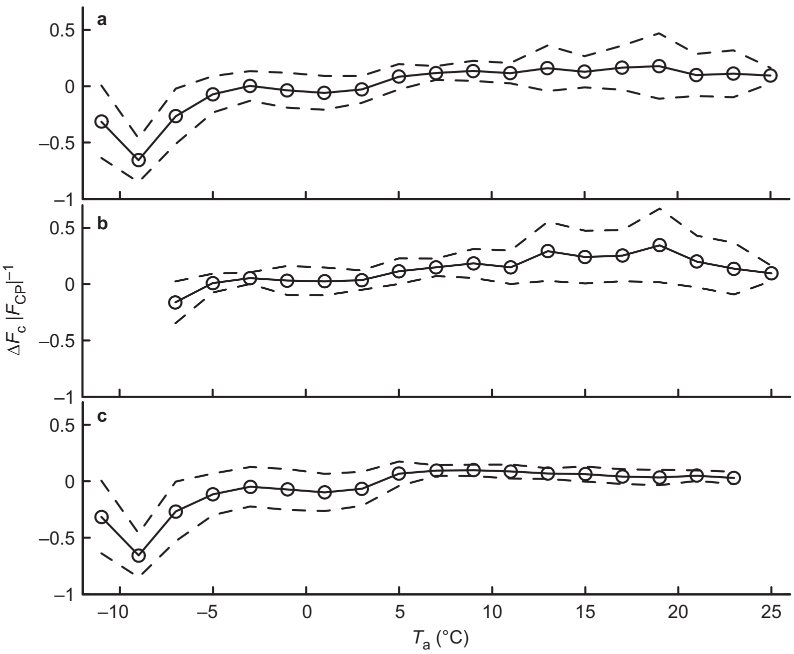

Fig. 4. Temperature dependence of the difference ($\Delta F_C = F_{CP} - F_{OP}$) between CO_2 fluxes measured with open-path (F_{OP}) and closed-path (F_{CP}) analyzers normalized with F_{CP} in the urban area (**a**) for the whole measurement period between July 2007 and June 2008, and separately for (**b**) daytime and (**c**) nighttime fluxes. Values are medians calculated from half-hour data.

temperature. The most likely reason for this was the heating of the open-path sensor surface caused by stronger solar radiation at higher temperatures. Previous studies have also found that the open-path analyzer is measuring 10%–20% lower upward/higher downward CO_2 fluxes than the closed-path analyzer (e.g. Leuning and King 1992, Liu *et al*. 2006, Ono *et al*. 2008). The reason for this has been reported to be underestimation of the WPL correction due to an unbalanced energy closure (Ham and Heilman 2003, Liu *et al*. 2006). Some studies have found the heating of the open-path sensor to be the reason for the apparent ecosystem uptake outside the growing season (Grelle and Burba 2007, Burba *et al*. 2008, Ono *et al*. 2008).

The closed-path analyzer measured most of the time higher fluxes than the open-path analyzer when upward fluxes were observed. Nevertheless, during cold nights (below 5 °C), F_{CP} reached 0.7 μmol m^{-2} s^{-1} lower values than $F_{OP,}$ corresponding to a difference of 10%–30%. This is propably related to different meteorological conditions when outgoing long-wave radiation is able to cool the surface of the analyzer below the ambient temperature. However, also cold nocturnal fluxes include several possible error sources and thus should be considered with caution. First of all, the open-path analyzer may be facing problems at cold temperatures because no external heater was used. On the other hand, the anemometer heater turns on at 5 °C, which might cause an overestimation of the WPL correction. Problems may also be related to the nocturnal functionality of the closed-path system, such as inadequate frequency response corrections due to the deviations from model co-spectrum. More generally, Ono *et al*. (2008) stated that the conventional WPL correction might be inappropriate in situations when this corrections is of same order or greater than the raw F_{OP}.

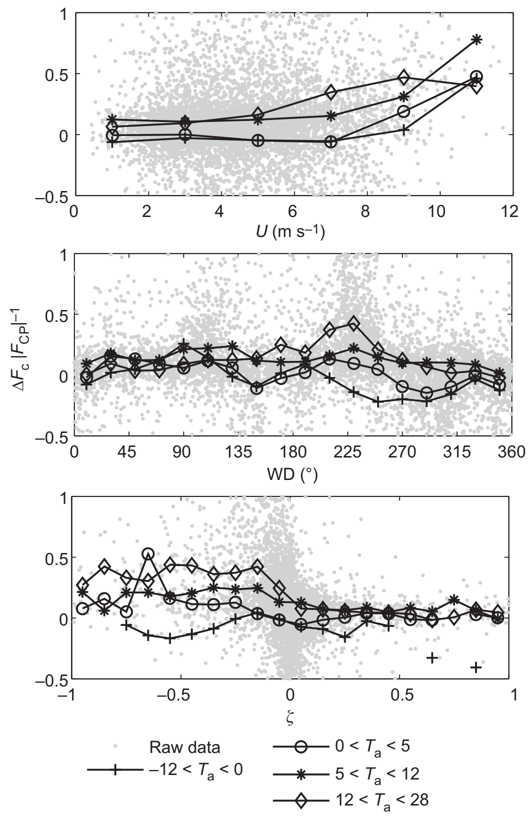

Fig. 5. The median dependence of ΔF_C normalized with F_{CP} on (**a**) wind speed U (m s^{-1}), (**b**) wind direction WD (°) and (**c**) stability ζ in different temperature ranges at urban site from July 2007 to June 2008. Grey points show the half-hour ratios. The limits of different land-use sectors (urban, road and vegetation) are also plotted.

Systematic differences between F_{CP} and F_{OP} due to meteorological variables

Beside temperature, the difference between the two fluxes had systematic dependence on the wind speed (U), wind direction (WD) and the variable ζ (Fig. 5). In all temperature ranges, the normalized ΔF_C increased from near zero to 0.8 with an increasing wind speed, especially at $U >$ 8 m s^{-1} (Fig. 5a). The data points with $U >$ 10 m s^{-1} should be interpreted with caution due to their low number (fewer than 12) in the bin $U =$ 10–12 m s^{-1}. At strong wind speeds, the pressure term in the WPL correction might become important (Massman and Lee 2002), and ignoring it should lead to an underestimation of F_{OP} as was found in our case. This, however, disagrees with Ono *et al*. (2008) who found that ignoring the pressure variance term could not explain the difference between CO_2 fluxes measured with open- and closed-path analyzers above a rice paddy. An alternative interpretation for this U dependence could be errors in sonic temperature measurements at high wind speeds, causing an underestimation of the sensible heat flux (Grelle and Lindroth 1996), which affects the WPL correction and further F_{OP}.

The effect of complex measurement surroundings can be seen in a highly variable WD dependence of the normalized difference (Fig. 5b). The most distinguishable feature is the peak of normalized ΔF_C that reached the value of 0.4 in the direction 190°–250° that corresponds to the vegetation sector. At the same time, the normalized ΔF_C decreased to –0.25 with a decreasing temperature. This suggests that the peak was related to the vegetation cover, which caused an underestimation of the WPL term. The measure-

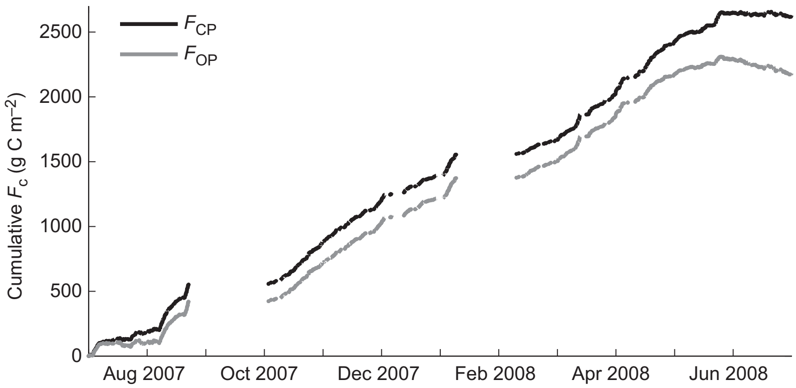

Fig. 6. Cumulative urban CO_2 fluxes (g C m^{-2}) obtained with closed-path (F_{CP}) and open-path (F_{OP}) analyzers from July 2007 to June 2008. No gap filling was made.

ment tower located in the direction 10°–50° did not have any distinct effect on the normalized ΔF_C. Tilting of the analyzer could have the effect that flows coming from certain directions relative to the analyzer would remove the heat more efficiently from the optical path of the analyzer than flows coming from some other directions. This kind of phenomenon was, however, not observed. Normalized ΔF_C was larger under unstable conditions than under stable conditions, except in the temperature range of –12 to 0 °C (Fig. 5c) where the small positive daytime and negative nighttime normalized ΔF_C cancelled each other out. Larger differences observed under unstable conditions support the observed diurnal behaviour.

Annual net surface exchange (NSE)

Despite the close relation between the CO_2 fluxes measured with the closed-path and open-path analyzers during July 2007–June 2008 (Fig. 2), the analyzers gave a substantially different net surface exchange (NSE), with values of 2630 and 2180 g C m^{-2} measured with closed-path and open-path analyzers, respectively (Fig. 6). Thus, measurements made with the open-path analyzer would underestimate the total carbon emission by 450 g C m^{-2}, corresponding to a difference of 17% between the analyzers. Burba *et al*. (2008) reported a yearly difference of 14% to 16% in the NSE measured above maize and soybean, which is comparable to our result, even though the measurement environments were rather different.

The effect of open-path sensor heating on CO_2 fluxes

The effect of open-path sensor heating on the measured CO_2 fluxes was studied at both urban and forest sites. Comparisons between the different CO_2 fluxes were made when all five fluxes (F_{CP}, F_{OP}, F_{Fit}, F_{MLR} and F_{Lin}) were available, giving a total of 5641 and 1806 half-hour data points at urban and forest sites, respectively.

Diurnal behaviour of the corrected CO_2 fluxes

Below 5 °C, the linear method overcorrected the open-path flux over the whole diurnal course, while the fitting and MLR methods removed most of the difference in daytime (Fig. 7). At night, however, also the MLR method failed to correct F_{OP} by overcorrecting it. The fitting method did not notably affect nocturnal ΔF_C in the temperature range 0–5 °C (Fig. 7b), but lowered nocturnal F_{OP} in the coldest temperature range of –12 to 0 °C, and ΔF_C approached 0 (Fig. 7a). The fitting method is the only method that takes into account the magnitude of nocturnal cooling well enough (*see* also Table 1), while with the MLR and linear methods this high surface cooling is not possible. In temperature range 5–12 °C, all correction methods improved the open-path flux, but the best results were obtained with the linear method especially at night (Fig. 7c). The fitting and linear methods corrected the nocturnal open-path fluxes well in the temperature range 12–28 °C (Fig. 7d), whereas the fitting

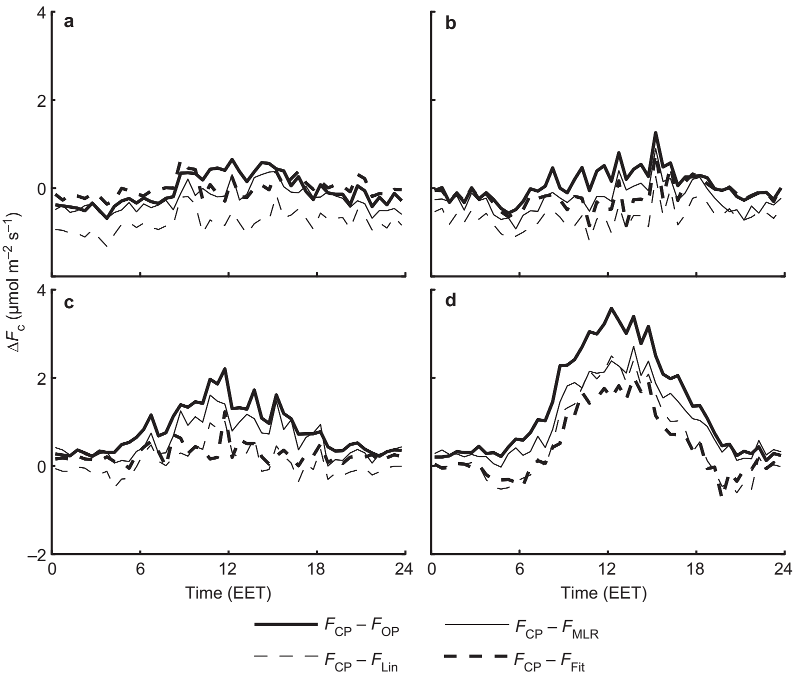

Fig. 7. Median diurnal behaviour of the differences (ΔF_C) between CO_2 fluxes (μmol m^{-2} s^{-1}) obtained with closed-path and open-path analyzers at the urban site for different temperature ranges. F_{CP} is the closed-path flux, F_{OP} is the traditionally corrected open-path flux, and F_{MLR}, F_{Lin} and F_{Fit} are the open-path fluxes corrected with the MLR, linear and fitting method, respectively (*see* text for details).

method was best in daytime between 08:00–17:00. In early morning and evening, the fitting and linear methods overestimated the open-path flux because the linear estimation of T_s from T_a yielded too high values of T_s. During the transitions from night to day and day to night, the surface of the analyzer likely heats and cools, respectively, slower than the ambient air due to the solar radiation. This was observed only in the highest temperature range when there is strong enough solar radiation in Helsinki.

The diurnal behaviour of closed-path and open-path CO_2 fluxes corrected in the traditional way were plotted for temperature ranges 0–12 °C and 12–18 °C above forest (*see* Fig. 8). There were only few data points below 5 °C, so the temperature range 0–5 °C was not separated. Similarly to urban site, F_{CP} was larger/smaller than F_{OP} when the flux was upward/downward. The apparent net ecosystem uptake was visible in the colder temperature range when F_{CP} was zero but F_{OP} was –2 μmol m^{-2} s^{-1} in daytime similarly to previous studies made above vegetation outside the growing season (Grelle and Burba 2007, Burba *et al*. 2008, Ono *et al*. 2008). All the three correction methods improved the CO_2 flux measured with the open-path analyzer,

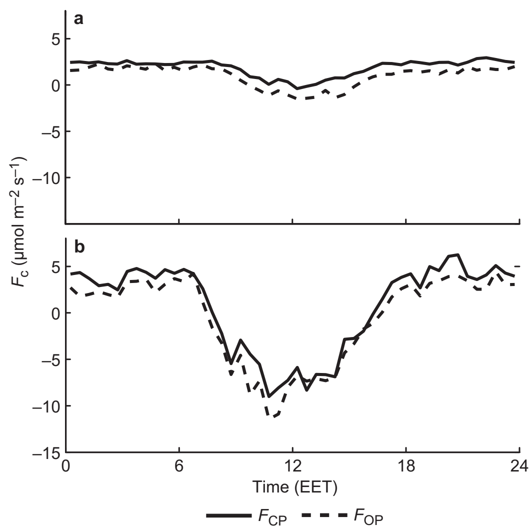

Fig. 8. Median diurnal variation of CO_2 fluxes measured with closed-path (F_{CP}) and open-path analyzers (F_{OP}) above beech forest in Denmark for temperature ranges (**a**) 0–12 °C, and (**b**) 12–28 °C in October–December 2006.

but the best results were obtained with the fitting method especially in the temperature range 0–12 °C (Fig. 9). ΔF_C did not exhibit a distinct diurnal pattern above forest (Fig. 9) contrary to the urban site where the diurnal pattern was

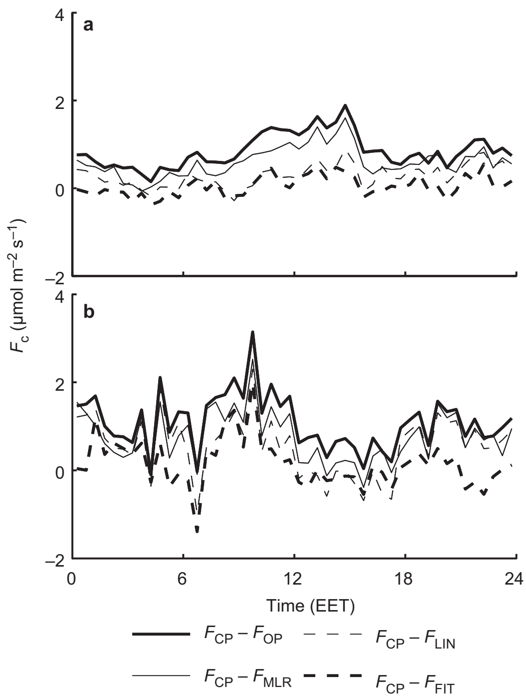

Fig. 9. Median diurnal behaviour of the differences (ΔF_C) between CO_2 fluxes (μmol m^{-2} s^{-1}) obtained with the closed-path and open-path analyzers above the forest for different temperature ranges [(**a**) 0–12 °C, and (**b**) 12–28 °C] in October–December 2006. F_{CP} is the closed-path flux, F_{OP} is the traditionally corrected open-path flux, and F_{MLR}, F_{Lin} and F_{Fit} are the open-path fluxes corrected with the MLR, linear and fitting method, respectively (*see* text for details).

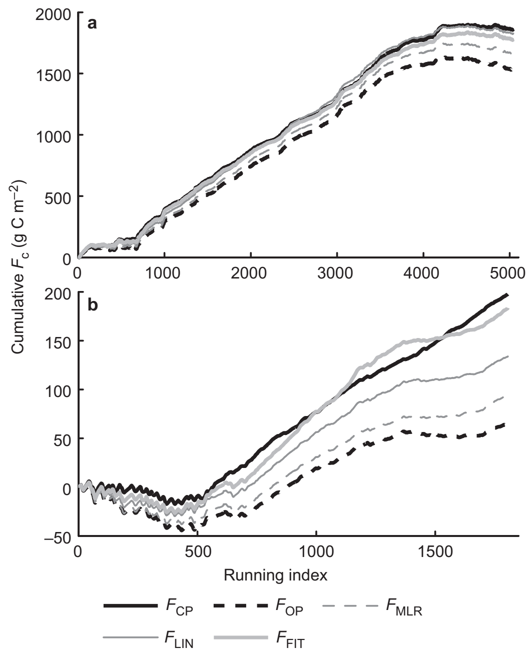

Fig. 10. Cumulative CO_2 fluxes (g C m^{-2}) measured with closed-path and open-path analyzers (**a**) at urban site from July 2007 to June 2008, and (**b**) above forest in October–December 2006. F_{CP} is the closed-path flux, F_{OP} is the traditionally corrected open-path flux, and F_{MLR}, F_{Lin} and F_{Fit} are the open-path fluxes corrected with the MLR, linear method and fitting method, respectively (*see* text for details). No gap filling was made.

pronounced even after the surface heating corrections. This is likely due to the shorter measurement period at the forest when the radiation conditions were rather different than those at the urban site over the whole summer.

Cumulative CO_2 fluxes

We calculated cumulative CO_2 fluxes with different methods for both urban and forest sites (no gap filling was made) (Fig. 10). At the urban site, the total carbon budgets (Table 2) of F_{CP} and F_{OP} were slightly different from those presented in Fig. 6 due to the smaller amount of the data.

Table 2. The cumulative (non-gap filled) carbon budgets measured with closed-path (F_{CP}) and open-path (F_{OP}) analyzers corrected traditional way, with the MLR (F_{MLR}), linear (F_{Lin}) and fitting methods (F_{Fit}) for urban and forest sites. Differences between the closed-path and open-path fluxes expressed as percentages have also been listed. For urban site, 5042 half-hour data between July 2007 and June 2008 while for forest site 1806 data points between October and December 2006 were analyzed.

		F_{CP}	F_{OP}	F_{MLR}	F_{Lin}	F_{Fit}
Urban	g C m^{-2}	1860	1530	1660	1830	1780
	Percentage	–	–18	–11	–2	–4
Forest	g C m^{-2}	200	60	90	130	180
	Percentage	–	–67	–52	–30	–7

At both sites, all heating corrections decreased the difference between the cumulative CO_2 fluxes measured with closed-path and open-path analyzers. At the urban site, both the linear and fitting methods corrected the NSE estimates well by decreasing the difference between the analyzers to 30 g C m^{-2} (2%) and 80 g C m^{-2} (4%), respectively (Fig. 10a). The MLR method failed to correct the fluxes this well by decreasing the difference to 200 g C m^{-2} (11%). For the forest site, the best results were evidently obtained with the fitting method, which decreased the difference in NSE from 140 to 20 g C m^{-2}, corresponding to a decrease from 67% to 7% (Fig. 10b). The linear and MLR methods decreased the difference to 70 g C m^{-2} (30%) and 110 g C m^{-2} (50%), respectively. The difference between F_{CP} and F_{OP} for the forest was large but comparable to differences reported in other studies. Burba *et al.* (2008) found a difference of 75%–81% between the two analyzers outside the growing season. Grelle and Burba (2007) showed a cumulative plot for October in Sweden and got a difference of 25% between the analyzers. We made the cumulative plot for November only, presenting similar weather conditions as in Sweden during their measurement period, and found a difference of 22% between F_{CP} and F_{OP}. Ono *et al.* (2008) found that with near-zero closed-path flux, open-path showed 0 to –5.9 μmol m^{-2} s^{-1} above a paddy field. Over long periods, this would cause high difference between F_{CP} and F_{OP}.

Preferred surface heating correction

We calculated regressions between F_{CP} and open-path CO_2 fluxes corrected with different methods for both urban and forest sites (*see* Table 3). All heating correction methods improved the relationships for both sites, but the fitting method gave the best results with $R^2 = 0.94$, slope of 0.98 and offset of –0.25 at the urban site and $R^2 = 0.81$, slope of 0.97 and offset of –0.06 at the forest site. Again, the linear method gave better results than the MLR method by increasing the offset closer to zero at both sites. The fitting method was the only method removing most of the systematic dependence of ΔF_C on stability and wind direction at the urban site (not shown). Also the peak seen in the vegetation sector was lowered, implying an underestimation of WPL partly due to the sensor heating. However, the effect of vegetation cover could not entirely be ruled out in the WPL underestimation. None of the correction methods removed dependence of ΔF_C on the wind speed, being suggestive of other reasons for the observed dependence as already discussed.

Besides the linear relationships and systematic dependencies, the fitting method corrected most efficiently the fluxes on a diurnal scale for both sites. Thus, we recommend that the fitting method will be used in the surface heating correction despite the fact that the linear method most efficiently corrected NSE for the urban site. This can be a pure coincidence because for the forest site the correction with the linear trend was poor. The better functionality of the fitting method as such is not surprising, since the MLR and linear methods are based on equations derived for a setup in which the open-path analyzer is mounted vertically. Sloping of the analyzer affects how much analyzers windows and spars gain solar radiation, and how the thermal boundary layer inside the optical volume develops. These have large effects on the surface tem-

Table 3. Linear regressions ($p < 0.05$) between closed-path and open-path CO_2 fluxes corrected with different methods for urban and beech forest sites in July 2007–June 2008 and October–December 2006, respectively. F_{OP} stands for traditionally corrected open-path CO_2 flux, F_{MLR}, F_{Lin} and F_{Fit} are the corrected open-path fluxes calculated with the MLR, linear and fitting methods (*see* text for details).

		F_{OP}	F_{MLR}	F_{Lin}	F_{Fit}
Urban	Slope ± 95% CI	0.98 ± 0.01	0.98 ± 0.01	0.98 ± 0.01	0.98 ± 0.01
	Offset ± 95% CI	–1.40 ± 0.06	–0.89 ± 0.06	–0.38 ± 0.06	–0.25 ± 0.06
	R^2	0.94	0.95	0.94	0.94
Forest	Slope ± 95% CI	0.98 ± 0.02	0.96 ± 0.02	0.93 ± 0.02	0.97 ± 0.02
	Offset ± 95% CI	–0.99 ± 0.08	–0.67 ± 0.08	–0.35 ± 0.08	–0.06 ± 0.08
	R^2	0.80	0.80	0.79	0.81

perature equations, and equations derived for the vertical sensor do not work so well either. The fitting method, on the other hand, does not have any assumptions on the position of the analyzer and provides a site-specific approach to correct for the effect of sensor heating. The downside of the fitting method is that it requires some period of simultaneous measurements with open-and closed-path analyzers. If there is no possibility to use the fitting method, the linear method should be used rather than the MLR method. Already Burba *et al*. (2008) suggested the linear method to be better in correcting long-term measurements.

Conclusions

The purpose of this study was to investigate the differences between simultaneously-measured CO_2 fluxes with the open- and closed-path infrared gas analyzers (LI-7500 and LI-7000, respectively) in an urban area of Helsinki over one year from July 2007 to June 2008. The suitability of the analyzers to accurately measure CO_2 fluxes in such a complex environment and the necessary correction procedures were studied. Besides, three different methods proposed by Burba *et al*. (2006 and 2008) to calculate the effect of open-path surface heating were tested, and comparisons were made with similar measurements made above beech forest in Denmark between October and December 2006.

The co-spectra obtained from the Kaimal *et al*. (1972) model were found to apply well to our complex measurement site, even though originally the model was established for homogeneous surfaces and flat terrain. The frequency response corrections based on the model spectrum were found to be 11% and 3% for closed-path and open-path CO_2 fluxes, respectively. The correlation between F_{CP} and traditionally corrected F_{OP} was good with $R^2 = 0.94$, slope of 0.96 and offset of –0.61 μmol m^{-2} s^{-1}, and showed the analyzers to clearly measure the same signals. Despite the apparent good correlation, the total carbon budgets for the studied year were 17% lower when measured with the open-path analyser. Most of the difference between the analyzers was caused by warm (over 12 °C) daytime situations when the difference reached 25%, probably due to the intense solar radiation. Beside the air temperature, the difference was systematically dependent on the wind speed, wind direction and stability.

All tested surface heating corrections lowered the difference between the closed-path and open-path CO_2 fluxes at both urban and forest sites. However, the best results were obtained with the fitting method, for which a linear relationship between the surface and air temperature was derived with the bootstrapping method from the measurements. The differences in total carbon budgets measured with the closed-path and open-path analyzers were reduced to 4% and 7% at the urban and forest sites, respectively. The fitting method also removed most efficiently the systematic dependencies of ΔF_C. The linear method gave the best results in carbon budgets at the urban site by reducing the difference between F_{CP} and F_{OP} to 2%. However, for forest it produced a difference of 30%, and failed to correct for the diurnal pattern as efficient as the fitting method for both sites. The MLR method produced a difference of 11% and 50% at the urban and forest sites, respectively. The MLR and linear methods are based on surface temperature equations which were derived for measurement setups where the open-path analyzer was mounted vertically. Thus, they may not work as well with sloping analyzers like in our case. The fitting method, on the other hand, provides a site-specific approach to correct the effect of sensor heating, but the downside is the need for simultaneous open-path and closed-path measurements. If simultaneous measurements do not exist (e.g. when correcting fluxes which date back), the linear method should be preferred over the MLR method.

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