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# Spatial variability of carbon dioxide in the urban canopy layer and implications for flux measurements

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## HIGHLIGHTS

- The micro-scale variability of carbon dioxide was mapped in an urban environment.
- During day, carbon dioxide was mainly a function of proximity to traffic.
- At night, the distribution was controlled by accumulation due to cold-air pooling.
- Hourly changes of carbon dioxide storage in the urban canopy layer were calculated.
- Changes affected measured eddy covariance fluxes on average by 5%, but up to 123%.

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## ABSTRACT

This contribution reports $CO_2$ mixing ratios measured in the urban canopy layer (UCL) of a residential neighborhood in Vancouver, BC, Canada and discusses the relevance of UCL $CO_2$ temporal and spatial variability to local-scale eddy covariance (EC) fluxes measured above the UCL. Measurements were conducted from a mobile vehicle-mounted platform over a continuous, 26-h period in the longterm turbulent flux source area of an urban EC tower. Daytime mixing ratios were highest along arterial roads and largely a function of proximity to vehicle traffic $CO_2$ sources. At night, there was a distinct negative correlation between potential air temperature and $CO_2$ mixing ratios. The spatial distribution of $CO_2$ was controlled by topography and micro-scale advective processes (i.e. cold-air pooling). Mobile $CO_2$ measurements were then used to calculate $CO_2$ storage changes ($F_S$) in the UCL volume and compared to single-layer $F_S$ estimates calculated from the EC system. In total, five variations of $F_S$ were calculated. On average, the choice of $F_S$ calculation method affected net measured hourly emissions ($F_C$) by 5.2%. Analysis of $F_S$ using a four-year dataset measured at the EC tower show $F_S$ was 2.8% of hourly $F_C$ for this site on average. At this urban EC location, $F_S$ was relatively minor compared to $F_C$ and calculation of $F_S$ using a single-layer method was adequate, though $F_S$ still represents a potentially large uncertainty during individual hours.



## 1. Introduction

Eddy covariance (EC) has been established as a robust technique to directly measure net carbon dioxide ($CO_2$) surface–atmosphere exchange, or flux density, in urban areas in recent decades (Christen, 2014). The first published flux measurements of $CO_2$ by means of EC were from Chicago in 1996 (Grimmond et al., 2002), and there are currently at least 30 urban $CO_2$ flux sites in operation worldwide (Velasco and Roth, 2010). While measurements of the net vertical turbulent $CO_2$ flux have been reported for a range of urban sites worldwide, relatively little attention in these studies has been given to determination of non-turbulent advective fluxes and how changing mean $CO_2$ mixing ratios within the air volume between ground and measurement level affect measured fluxes (i.e. storage change terms). These terms have long been recognized as sources of uncertainty in EC measurements above forest ecosystems on timescales of typical flux-averaging periods (30–60 min) (e.g. Goulden et al., 1996) and storage has been shown to account for up to 60% of individual hourly net ecosystem change (NEE) values (Yang et al., 1999). Given the application of EC methods in urban neighborhoods to measure $CO_2$ emissions and validate emission inventories and models at high spatial and temporal resolution, a better quantitative understanding of storage and advective fluxes in urban ecosystems and evaluation of

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measurement techniques is needed. The focus of this work is on storage changes of $CO_2$ within and above the urban canopy layer (UCL).

To measure the storage term ($F_S$), researchers at forest or agricultural sites often use vertical profile systems to measure and integrate changes in mean $CO_2$ partial density ($\Delta\overline{c_\rho}$) at several heights ($z$) across the flux averaging period ($t$) (e.g. Aubinet et al. (2005)):

$$F_S = \frac{1}{t}\sum_{i=0}^{n}\Delta\overline{c_\rho}z_i \quad (1)$$

A vertical profile is used because of different rates of $CO_2$ buildup (or depletion) at different heights within and above a canopy. When a profile system is unavailable, researchers have used the change in $CO_2$ concentration at a single height (usually the same height where EC system is operated) to calculate $F_S$, with the assumption that $\Delta\overline{c_\rho}/\Delta t$ is constant throughout the depth of the measurement volume (e.g. Hollinger et al., 1994; Black et al., 1996). This assumption has been tested in a Douglas-fir forest ecosystem and was found to produce equivalent $F_S$ compared to calculations using four measurement levels at different heights, except for differences of about 10% during mid-morning and mid-afternoon (Morgenstern et al., 2004). However, this approach is complicated by differences between the source areas of scalar concentrations and turbulent fluxes. At typical 30-min flux-averaging timescales, concentration scalar source areas can be larger than turbulent flux source areas by an order of magnitude (Schmid, 1994).

Researchers in forest ecosystems have found $F_S$ to be an important factor on flux-averaging timescales, particularly at night during stable conditions. A comparison of six forest flux sites in Europe found that 20–80% of carbon released by nocturnal respiration sources is stored in the air volume below measurement height, depending on the slope surrounding the measurement site (Aubinet et al., 2005). Slope can be important because of removal of stored carbon due to horizontal advection by slope drainage flows (e.g. Froelich and Schmid, 2006; Feigenwinter et al., 2008; Leitch, 2010). $F_S$ has also been found to vary according to friction velocity ($u_*$), as a variable representing turbulent mixing, with negligible storage at higher $u_*$ values. As a result, researchers in forest ecosystems often use a visually determined $u_*$ threshold to filter out periods of low turbulence and high storage that can be gap-filled using a variety of methods (e.g. Falge et al., 2002). This procedure however has potential to introduce bias to long-term estimates of NEE through subjective choice of $u_*$ threshold and potential double-counting of $CO_2$ stored in the measurement volume during gap-filling when that $CO_2$ is eventually vented from the canopy and measured by the EC system (Gu et al., 2005).

In an urban environment, the physical form of the canopy and the distribution of heat sources are expected to alter the atmospheric processes affecting $F_S$. The presence of anthropogenic heat sources and relatively large heat storage releases during night are likely to contribute to more frequent periods of instability and in denser urban areas result in a shallow, weakly unstable surface layer overnight (Christen and Vogt, 2004). Similarly, the increased roughness of the urban surface is hypothesized to result in greater mechanically produced turbulence and mixing compared to porous vegetation canopies. The relatively open urban canopy structure compared to forests could result in greater vertical coupling between canopy and above-canopy conditions, but at the same time urban form can cause horizontal de-coupling (e.g. between different streets and between backyards and streets (Weber and Weber, 2008)). Additionally, the greater overall strength and spatial variability of surface emission sources (e.g. vehicles, buildings) will affect the magnitude and relative strength of $F_S$ relative to net $CO_2$ flux ($F_C$).

Several studies have documented observational evidence of $CO_2$ storage and venting (i.e. negative storage) from the urban canopy layer (UCL). In Tokyo, Japan, vertical profile measurements of $CO_2$ concentrations within a street canyon show an increase in UCL $CO_2$ of over 40 ppm relative to above-canopy measurements during stable, wintertime conditions. Similarly, in Basel, Switzerland, UCL accumulation of $CO_2$ and differences between a street canyon and above-canopy measurements up to 15 ppm are observed during late afternoon and overnight periods during summer (Vogt et al., 2006). Venting between the UCL and the surface layer above the canopy is also observed in Marseille, France (Salmond et al., 2005). Here, discontinuous overnight 'bursts' of $CO_2$ from within a canyon are shown to be related to intermittent convective plumes of relatively warm canopy-layer air buoyantly escaping the UCL. Together, these results indicate that the mechanisms for $CO_2$ buildup and venting are dynamic and vary according to a combination of site-specific atmospheric conditions (stability, energy balance, wind speed, wind direction), built form (canyon depth and orientation), and timing and magnitude of local emissions processes.

Despite these findings, consideration of storage in the urban $CO_2$ flux literature is relatively rare. In Edinburgh, Scotland, an hourly storage flux correction term is calculated using the single-level method and is found to modify the hourly measured flux by 11%, on average (Nemitz et al., 2002). In Basel, Switzerland, the storage flux is calculated from a vertical profile system measuring $\Delta c_\rho$ at ten different heights in an individual street canyon. These measurements found storage to be particularly relevant during the morning when the onset of thermal mixing vented $CO_2$ from within the canyon and modifies the measured flux by −23% (Feigenwinter et al., 2012). In Baltimore, USA (Crawford et al., 2011), and Beijing, China (Liu et al., 2012), the storage term is acknowledged but assumed to be negligible based on frequent overnight urban instability and a primary focus on monthly and annual exchange totals. Several other studies report buildup of $CO_2$ concentrations on diurnal cycles or recognize potential for measurement uncertainty due to storage, but do not explicitly attempt a storage correction (Grimmond et al., 2002; Coutts et al., 2007; Velasco et al., 2005; Helfter et al., 2011; Pawlak et al., 2011). In a review of urban $CO_2$ flux literature in 2010, there is no mention of storage in guidelines given for processing urban EC flux data (Velasco and Roth, 2010).

Despite the theoretical challenges in calculating $F_S$ from concentration measurements, an examination of a practical, working approximation is needed for urban areas nonetheless. Given the potential for extreme micro-scale horizontal spatial heterogeneity in terms of $CO_2$ concentrations, use of a tower-based vertical profile system is likely impractical for most urban measurement locations because of source area differences between sensors and resulting scale conflict when integrating profile measurements vertically. A solution that is technically easier to implement and avoids this scale conflict is use of concentration changes from a single $CO_2$ concentration sensor located above the roughness sublayer, at the same height as (and usually available from) the EC system. The underlying assumption with this method is that of vertically consistent changes in $CO_2$ concentration from the measurement height down to the surface. This assumption is potentially valid during neutral and unstable conditions when canopy-layer and above-canopy conditions are well-coupled (also when $F_S$ is likely negligible), but could lead to an underestimation of $F_S$ (and net emissions) if the concentration change below measurement height is greater than at measurement height, and an overestimation if there is greater buildup above-canopy relative to the canopy.