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Variability of CO_2 concentrations and fluxes in and above an urban street canyon

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HIGHLIGHTS

- CO_2 fluxes and concentrations were measured at an urban street canyon over one year.
- Fluxes at the top of the canyon show a distinct qualitative correlation with traffic density.
- Fluxes above also strongly depend on traffic but only for eastern wind directions.
- Wind may act as a lid on top of the canyon and reduce turbulent vertical exchange.
- In-canyon vortex has corkscrew like lateral motion and strong influence on CO_2 distribution.

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ABSTRACT

The variability of CO_2 concentrations and fluxes in dense urban environments is high due to the inherent heterogeneity of these complex areas and their spatio-temporally variable anthropogenic sources. With a focus on micro- to local-scale CO_2-exchange processes, measurements were conducted in a street canyon in the city of Basel, Switzerland in 2010. CO_2 fluxes were sampled at the top of the canyon (19 m) and at 39 m while vertical CO_2 concentration profiles were measured in the center and at a wall of the canyon. CO_2 concentration distributions in the street canyon and exchange processes with the layers above show, apart from expected general diurnal patterns due mixing layer heights, a strong dependence on wind direction relative to the canyon. As a consequence of the resulting corkscrew-like canyon vortex, accumulation of CO_2 inside the canyon is modulated with distinct distribution patterns. The evaluation of diurnal traffic data provides good explanations for the vertical and horizontal differences in CO_2-distribution inside the canyon. Diurnal flux characteristics at the top of the canyon can almost solely be explained with traffic density expressed by the strong linear dependence. Even the diurnal course of the flux at 39 m shows a remarkable relationship to traffic density for east wind conditions while, for west wind situations, a change toward source areas with lower emissions leads to a reduced flux.

1. Introduction

Dense population, a high amount of traffic and a small fraction of green areas are the main factors that lead to higher emissions of CO_2 in cities when compared to rural areas. Measuring and quantifying these emissions reliably is difficult because the urban surface is often very heterogeneous and the spatial and temporal distribution of sources is highly variable. Hence, the contribution of cities to the global carbon cycle is a crucial, yet not adequately investigated phenomenon. Quantification attempts, e.g. in modeling studies, are often based on estimations of fossil fuel consumption averaged over long time periods and large areas, even on a city scale (Grimmond et al., 2002), and sometimes adapted to smaller scales using different patterns of urban development as proxy data (Parshall et al., 2010).

It is only recently that investigations in the area of urban metabolism approaches started to become more spatially detailed and more integrated in terms of which processes and factors are included. Christen et al. (2011) for example found a good agreement between measured and holistically modeled carbon fluxes that supported the idea of deriving carbon budgets from bottom-up modeling of emission processes. The question remains as to how well this works for different urban structures, e.g. dense city centers or other more diversified areas.

In this paper we present results from a measurement study on micro- to local-scale CO_2 transport processes in and above a street canyon at a central and diverse urban site. It was not possible to compare our results to modeled carbon fluxes but instead the

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research tries to provide insights into the linking of flux tower data to processes associated with the underlying urban structure.

One year of data is presented and analyzed to understand what factors are eminent for local atmospheric transport processes of CO_2 and the resulting spatial and temporal patterns of the fluxes and concentrations close to the urban surface. The effect of the urban structure i.e. the street canyon on micro-scale in-canyon wind patterns is illustrated. At two different heights the dependence of CO_2 fluxes on wind patterns and traffic, which is the major source of CO_2 in the canyon, is analyzed.

1.1. CO_2 concentrations

Dense urban areas are characterized by a high amount of impervious surfaces and sparse vegetation. Urban boundary layer (UBL) CO_2 concentrations over such areas show generally similar behaviors as over other surface types, e.g. forests. Characteristics are the relative independence of local sources, especially during daytime, and a large diurnal amplitude with an early morning maximum and a midday/afternoon minimum. This diurnal pattern is mainly thought to be a direct effect of UBL height coupled with a dilution of CO_2 during its growth and an accumulation during its decrease in the evening and throughout the night (Vogt et al., 2006). Despite some slight deviations in the size of the amplitude, this characteristic is independent of the height of the measurement inside the roughness sublayer (RSL). Nevertheless, the horizontal concentration distribution close to the ground may show a greater dependence on the spatial source and sink distribution as well as on their strengths. From transect measurements Henninger (2008) statistically derives that on a city scale the differences in near surface ($z = 1.5$ m) CO_2 concentration depend 71% on local traffic density and urban canopy layer (UCL) stability. Similarly, photosynthesis can be expected to have only a very local effect on the diurnal course of CO_2 concentrations in dense urban areas. According to Strong et al. (2011) it becomes relevant during summer mornings within shallow mixing heights.

Several studies (e.g. Helfter et al., 2011; Reid and Steyn, 1997; Strong et al., 2011; Vogt et al., 2006) postulate that entrainment of tropospheric air as well as large-scale horizontal advection of air masses, both with low CO_2 concentrations, must take place during the day. Otherwise, the afternoon drop of CO_2 levels close to background concentration could not be explained as there is normally a high input through emissions at that time of the day. In contrast, nocturnal courses, often under relatively stable atmospheric conditions, are explainable with local source characteristics (Vogt et al., 2006). Strong et al. (2011) provide evidence for these postulations with model results where, on average, advection was the most important CO_2 reduction process at Salt Lake Valley, USA, except for hours with a strong UBL growth where there was stronger fresh air entrainment from above.

1.2. CO_2 fluxes

Cities are generally a net source of CO_2. Reported average F_C from direct measurement studies in urban or suburban areas range from 0.92 (Ramamurthy and Pardyjak, 2011) to 26.0 μmol m^{-2} s^{-1}(Nemitz et al., 2002). While these two studies – as well as many others – only cover a part of the year, long-term studies confirm the range (0.95 (Crawford et al., 2011) to 25.58 μmol m^{-2} s^{-1} (Helfter et al., 2011)). Traffic and domestic heating (or cooling) are the main emitters in urban or suburban surroundings while human and vegetation/soil respiration play a minor part. Daytime vegetation uptake has a limiting effect on fluxes (Coutts et al., 2007; Kordowski and Kuttler, 2010) but it usually can not compensate anthropogenic sources. The vegetation fraction (λ_v) of a study area can be taken as a rough indicator for the influence of plant uptake, even if the effective uptake rate depends on other factors like e.g. plant species or local climate conditions. Measurements over suburban neighborhoods with a high λ_v (e.g. Crawford et al., 2011; Ramamurthy and Pardyjak, 2011) often report – not surprisingly – greater influences than such over more sealed urban surfaces (e.g. Grimmond et al., 2004; Matese et al., 2009). Nevertheless, establishing a dependency between reported λ_v and F_C is not as straightforward as many other factors like the amount and spatial distribution of traffic, the measurement period or the types of the combusted fuels for domestic heating influence F_C.

Thus, contrary to CO_2 concentrations, comparing the diurnal courses of vertical CO_2 fluxes (F_C) between cities reveals patterns that are very different from each other. There is a clear correlation to source dynamics, a fact that can, for example, be seen if fluxes are compared with estimated emissions. A major road's street canyon, like the one investigated in this study, is therefore an ideal experimental site as the dominant source inside the canyon – considering human and plant respiration as negligible in this case – is the directly underlying traffic.

A well established way to assess vertical CO_2 fluxes to and from the atmosphere is the eddy-covariance (EC) technique. It has proven to deliver reliable results over various, relatively homogeneous surfaces, e.g. in the FLUXNET community (Baldocchi, 2008). Its use at urban sites has only recently been intensified with several papers that were published primarily during the last decade. Nevertheless, long-term studies and comparisons between parallel measurements in the same city are still rare.

Major uncertainties with EC measurements in the urban inertial sublayer (ISL) arise through the aforementioned problems of the highly diversified surface structure and non-uniform sources. Thus, proper placement of the sensors in relation to dominant CO_2 sources such as major roads is an important task. Christen et al. (2011) found that due to the location of their tower close to an intersection, the fraction from transportation in the total CO_2 signal measured increased from 47% for the entire homogeneous study area to 70% at that specific location. This is a remarkable increase and it indicates how challenging it is to properly relate source areas to measured fluxes (see e.g. Bergeron and Strachan, 2011; Järvi et al., 2012; Kordowski and Kuttler, 2010).

EC measurements inside the urban RSL are affected by the 3D nature of the flow resulting from the high spatial variability of local roughness elements (Feigenwinter et al., 2012) and fluxes are height dependent inside the RSL (Rotach, 2001). Vertical turbulent transport can be calculated for a point in space but the flux can not be directly attributed to a source area like when EC measurements are done in the ISL, i.e. we do not know a priori what the flux represents. Despite these limitations, we placed an EC system on top of the street canyon in order to capture the influence of the traffic on CO_2 fluxes.

1.3. Street canyon effects

The closer to the ground that measurements are taken, the better they may be verified and related to single local sources but the more they are affected by the surface and its heterogeneities. Which processes influence the vertical transport of CO_2 from source level to measurement level is an important question in urban surroundings. A major focus of this study thus lies on the relationship between traffic as a primary source of CO_2, micro-scale distribution patterns in a street canyon and local-scale (following the definition of scales according to Oke (1987)) flux characteristics in a dense urban environment.

Flow patterns and concentration dispersion in and around urban street canyons can be studied using different means. Besides field experiments on wind, turbulence or concentrations (e.g. DePaul and Sheih, 1985; Rotach, 1995), modeling and wind tunnel studies are