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Path-integrated measurements of carbon dioxide in the urban canopy layer

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ABSTRACT

Continuous CO_2 concentration measurements have been recorded within the city center of Essen, Germany, using a path-integrated measuring system above a typical urban area over the course of nine months (February–October 2010). Mean monthly urban CO_2 concentrations were 396 and 446 ppm in summer and winter, respectively, which were 8.5 % in average higher than at a nearby suburban measuring site. Urban-suburban differences mainly occur due to increased CO_2 emissions from traffic and industry within the urban area, as well as domestic heating in winter.

Among the analyzed meteorological variables, low wind velocities increased CO_2 concentrations as well as high atmospheric stability within the urban boundary layer, respectively. The influence of wind direction reflects the heterogeneous distribution of local CO_2 sources at the recording sites, particularly industrial point sources. Other point sources in the vicinity of the urban site strongly influence the additional point measurements but show no significant effect on the measured CO_2 concentrations by the path-integrated measuring system. Within an eight-day case study, a significant positive correlation between CO_2 concentration and traffic count ($R = 0.26$; $p < 0.05$) was found on weekdays using partial correlation analysis after excluding the influence of meteorological variables. This correlation diminishes when combined with the meteorological components, and mixing layer height shows the strongest negative correlation with measured urban CO_2 ($R = -0.59$). The path-integrated system provides CO_2 concentrations on a greater temporal and spatial scale than common point measurements, which can be influenced by strong adjacent local CO_2 sources.

1. Introduction

The increase in the atmospheric concentration of carbon dioxide (CO_2) is generally accepted as the main contributor to the anthropogenic greenhouse effect (Solomon et al., 2007). Thus, better knowledge of the temporal and spatial behavior of this greenhouse gas is still required. Seasonal and diurnal dependencies of the CO_2 concentration are well known from long-term measurements of pristine air in rural areas around the world (e.g., Keeling et al., 1976; Artuso et al., 2009), which mainly follow the annual and diurnal cycle of photosynthetic activity of vegetation as a function of latitude (e.g., Greco and Baldocchi, 1996; Yuan et al., 2009; Haszpra and Barcza, 2010). However, given that urban areas represent large anthropogenic net CO_2 sources (Velasco and Roth, 2010), these patterns are distorted by local emitters of anthropogenic CO_2 and are mainly devoid of CO_2 sinks. Measuring urban atmospheric CO_2 concentrations with the aim of determining these influences is challenging, and one must consider the topographic and orographic heterogeneity with a spatially irregular distribution of CO_2 sources and sinks. Furthermore, the three-dimensional structure of the city itself, city-specific meteorological phenomena such as the urban heat island (UHI), UHI circulation (Lai and Cheng, 2009) and geographically specific conditions (Grimmond et al., 2004) need to be considered.

A large number of studies for cities in various geographic areas have proven that urban agglomerations are effective CO_2 sources on an annual scale (e.g., Moriwaki and Kanda, 2004; Coutts et al., 2007; Vesala et al., 2008; Pawlak et al., 2011; Crawford et al., 2011). Large urban parks are able to act as CO_2 sinks, at least in the summer, but can generally only attenuate the strength of the urban CO_2 source, as Kordowski and Kuttler (2010) showed in a case study for a 0.7 km^2 urban park in Essen, Germany. Ptak (2009) and others have demonstrated the effects of meteorology and topography on urban CO_2 concentrations, such as cool air drainage bringing fresh air from the urban environment into cities. As a result of these components, a considerably heterogeneous spatiotemporal distribution of CO_2 develops within a city.

Different approaches have been established to determine urban CO_2 concentrations, most of which are common-point or mobile-route measurements. The former are able to record the CO_2

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concentration with a high temporal resolution but have a narrower spatial coverage. A network of such stations distributed over different land-use types within a city is able to offset the missing spatial information of a single site only to a limited extent, and the method is cost- and labor-intensive. Additionally, choosing measuring sites representing specific areas within urban agglomerations is ambitious (Grimmond et al., 2002; Christen and Vogt, 2004). On the other hand, mobile-route measurements provide a high spatial resolution by covering different land-use types (Kuttler and Wacker, 2001; Henninger and Kuttler, 2007), but they mostly miss the temporal variations of the CO_2 concentration.

A path-integrated measuring system (e.g. a tunable diode laser TDL) combines all of the advantages and compensates for the drawbacks of the aforementioned common methods, as it combines a high spatial resolution with a high temporal resolution. In the Central European city of Essen, North-Rhine Westphalia, mobile CO_2 measurements (Henninger, 2008) and CO_2 flux measurements (Kordowski and Kuttler, 2010) have already been made; hence, we focus on the continuous long-term measurement of CO_2 concentration within the urban boundary layer using a monostatic path-integrated system. For comparison, classical point measurements have been made at the same locations in a densely populated urban area and at an additional suburban terrain outside the city center for the time period of February–October 2010.

2. Materials and methods

2.1. Study area

Measurements were carried out in Essen in western Germany, which has approximately 578000 residents in an area of 210 km^2 (City of Essen, 2010). The city is located in the center of the Ruhr area, with a total of 5.2 million people (RVR, 2010). In addition to several densely populated areas spread over the whole municipal area of Essen, industrial and commercial zones (Fig. 1) together with several main roads with high traffic densities characterize the study area. Two sites with different characteristics have been established with the objective of comparing the central business district of Essen to a nearby suburban environment.

Around the urban site, land cover consists of 95% impervious surfaces and 5% green areas, most of which are small urban parks or lawns. The area is mainly commercial and residential with little industry. CO_2 emissions emitted from this area are estimated to be at 34 900 t CO_2 y^{-1} (LANUV NRW, 2011). There are two industrial point sources in the vicinity of the urban measuring site: one is a district heating plant that works on demand only during the cold season and the second is a chemical plant (Fig. 2 left; Table 1). Several main roads with high traffic densities (Fig. 2 left), domestic heating during the cold season, and human respiration provide additional CO_2 emissions (Table 1).

Land cover at the suburban site is characterized by 12% impervious areas, mostly single-story residential buildings situated in the northeastern and eastern sector, and 88% green areas consisting mostly of agricultural areas and forests (Fig. 2 right; Table 1). Here, total anthropogenic CO_2 emissions are estimated to be less than 3000 t CO_2 y^{-1} (LANUV NRW, 2011).

2.2. Instrumentation

2.2.1. Path-integrated measuring system (TDL)

The path-integrated measuring system (Table 2) allows the capture of the mean CO_2 concentration of an open measuring path up to 1000 m in length. A tunable diode laser (TDL) housed within the analyzing unit emits a near-infrared beam

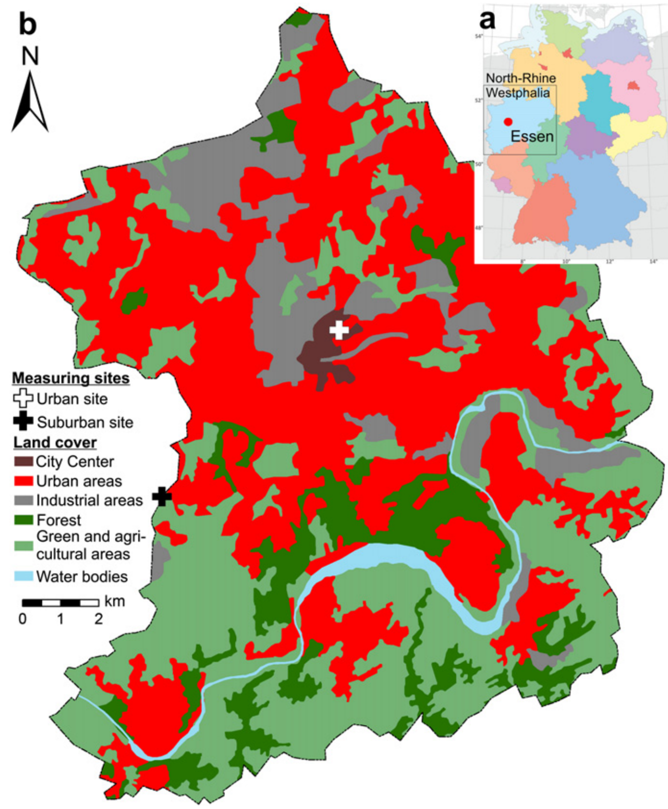

Fig. 1. a) General map of Germany (Bundesamt für Kartographie und Geodäsie, 2011, modified) and the Federal state of North-Rhine Westphalia (black frame) with the city of Essen (red dot). b) Land-cover characteristics in the municipal area of Essen, Germany (based on CORINE data set for 2006, modified) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

($\lambda = 1581$ nm; wave number 6325.1 cm^{-1}), utilizing the absorption properties of the CO_2 molecule at this wavelength. This beam is led to the emitting and receiving unit by optical fiber, where it is emitted onto the open-path and aimed on a retro-reflector. From there it is returned to the receiving unit, converted to an electrical signal by an optical detection plate and subsequently sent to the analyzer by coax. Here, the intensity of the received signal is compared to the emitted signal and to a reference cell containing a CO_2 reference of 385 ppm. This enables the calculation of the mean CO_2 concentration along the given measuring path.

The emitting and receiving unit was installed at the south-eastern edge of the roof of an university building at 34 m above ground level (agl) (Point 1, Fig. 2 left and Fig. 3) and the retro-reflector was installed on the city hall roof at a distance of 352 m and at the same height (Point 2, Fig. 2 left and Fig. 3), resulting in an effective path length of 704 m. It runs roughly north-south above an area that is representative of the city center of Essen, according to land-cover characteristics and amount of traffic. CO_2 concentrations are measured at a rate of 1 Hz and are automatically averaged every 15 s. Due to the open-path method, data availability is influenced by meteorological conditions (i.e., heavy rain, snowfall and dust) that can lead to system failures by suspending the beam. This leads to a higher proportion of missing data (20.6% for the entire dataset) in comparison to the common point measurements (6.5–7.5%, Table 2). After checking and comparing the available data to the urban point measurements, no influence of these data gaps could be identified. Therefore in further analysis, comparison