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Carbon dioxide fluxes in the city centre of Arnhem, A middle-sized Dutch city

Eva Kleingeld[a,b], Bert van Hove[a,c,*], Jan Elbers[b], Cor Jacobs[b]

[a] Wageningen University and Research, Water Systems and Global Change group, The Netherlands
[b] Wageningen Environmental Research (Alterra), The Netherlands
[c] Wageningen University and Research, Meteorology and Air Quality Group, The Netherlands

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ABSTRACT

This paper reports on the temporal variability of carbon dioxide fluxes in the city centre of Arnhem, a middle-sized Dutch city. The fluxes were continuously measured during four years (2012–2016) using the eddy-covariance method. Additionally, continuous meteorological measurements were carried out. We also analysed data from 30-minute traffic counts performed during those years. Results indicate that the city centre of Arnhem is a strong emission source of CO_2 compared to many other cities. The measured annual CO_2 flux equals about 8.0 kg C m^{-2} yr^{-1}. Heterogeneity within the footprint of the EC tower appeared to have no or only a small influence on the estimated annual and seasonal carbon fluxes. Sector analysis shows that CO_2 fluxes are consistently higher in sectors with the highest built-up surface fraction. However, no statistically significant relationship could be determined. Traffic and space-heating related burning of natural gas are the main emission sources. Weekly and diurnal variations in CO_2 flux are clearly correlated with traffic intensity, whereas seasonal variation can largely be explained by space heating demand. Partitioning of the total flux into a heating-related and traffic-related flux revealed that space heating accounts for up to 60% to the total flux during winter. Traffic intensity remains more or less constant throughout the year. In summer, when space heating is absent, CO_2 emission is almost entirely related to traffic intensity. However, our estimations suggest that human respiration could have a non-negligible share in this. The contribution of the small fraction of urban green in the city centre is probably minimal. The annual emissions for the city centre estimated from our EC measurements are 20–25% lower than those reported for the whole city by the official emission inventory. Climate projections for the Netherlands suggest that in 2050 Heating Degree Days would be reduced by 27% resulting into a 32% reduction of the heating-related emission flux, without a change in fossil fuel use.

1. Introduction

Half of the world's population lives in cities, a share that is likely to reach 70% in 2050 (United Nations, 2014). Cities, towns and settlements cover only a tiny fraction (< 1%) of the world's surface (Schneider et al., 2010). Nevertheless, taking into account direct and indirect emissions, urban areas account for 67–76% of global energy use and for 67–76% of global energy-related CO_2 emissions. Taking into account direct emissions only, the urban share of emissions is 44% (IPCC, 2014). The main sources of CO_2 in urban areas are traffic, space heating, industrial processes and respiration. Urban respiration is partly from anthropogenic sources such as waste

* Corresponding author at: Wageningen University and Research, Water Systems and Global Change Group, The Netherlands.
E-mail address: bert.vanhove@wur.nl (B. van Hove).

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decomposition and human respiration and partly from respiration by soils and vegetation. Sinks of CO_2 in urban areas are photosynthesis by vegetation like lawns and trees and carbon sequestration by soils (Christen et al., 2011; Crawford and Christen, 2015; Ward et al., 2015; Bellucco et al., 2017). Net annual average urban CO_2 fluxes vary between 13.2 kg C m^{-2} yr^{-1} and 0.3 kg C m^{-2} yr^{-1}, depending on the characteristics of the urban area in question (Lietzke et al., 2015).

Because urban areas are strong sources of CO_2 emissions, they play a key role in climate change mitigation policies. In order to develop efficient mitigation strategies, reliable estimates of CO_2 emissions from a city are required, as well as insight into the sources and sinks of CO_2. Urban CO_2 emissions and their reductions are often based on emission inventories, which contain a large degree of uncertainty at urban scales (Christen, 2014). The estimation of urban CO_2 emissions at fine spatial scales with remote sensing is a promising new development (Velazco et al., 2011; Schwandner et al., 2017). However, the temporal and spatial resolution of remote sensing is generally still insufficient for a fair comparison with bottom up techniques. Therefore, in order to validate the results of emission inventories and in order to test the remote sensing products, in situ measurements of urban CO_2 fluxes are needed (Christen, 2014).

The only technique that offers long-term, continuous, local scale measurements of CO_2 fluxes in urban areas is eddy-covariance (EC) (Järvi et al., 2012; Kotthaus and Grimmond, 2012; Liu et al., 2012, 2014; Christen, 2014; Weissert et al., 2014). With careful planning, EC measurements can be conducted in urban areas, even though the method was originally developed for flat, horizontally homogeneous surfaces (Foken et al., 2012a; Feigenwinter et al., 2012). EC measurements of urban CO_2 fluxes allow estimates of CO_2 emissions from a city. By relating CO_2 fluxes to land use CO_2 emission sources can in principle be located and their strength estimated. Usually the location of major emission sources is well known. Nevertheless, smaller sources within the urban canopy may be unaccounted for which hampers quantification with traditional approaches. The EC approach has the advantage of measuring CO_2 emitted by small and large, known and unknown sources. Hence, fluxes measured on urban flux towers can be used to validate and improve fine-scale emission models. These data can form the basis for developing mitigation strategies at the neighbourhood scale (Kellett et al., 2013).

In general, relatively few EC multiyear measurement results of CO_2 fluxes of cities have been reported. Here, we present the first Dutch multiyear EC study of urban CO_2 fluxes. This paper discusses the results of over four years of CO_2 flux observations as well as simultaneous measurements of other meteorological variables, made in the city of Arnhem, the Netherlands. The objective of this study is to assess the temporal variations (diurnal, weekly, and seasonal) in CO_2 fluxes, to relate these fluxes to urban land use, traffic intensity and space heating related combustion and finally to compare them with the urban emission inventory used in reports of Dutch GHG emissions. Research questions are: How large is the emission of the city of Arnhem as compared to the emissions of other cities? What is the contribution of each source to the CO_2 emission flux? What would be the influence of climate change? To what extent do the measured emission fluxes agree with official emission inventories (e.g. www.klimaatmonitor.databank.nl) (accessed 25-10-2017)?

2. Material and methods

2.1. Site description

Arnhem is a city with approximately 150.000 inhabitants (CBS Statline, 2016), located in the eastern part of the Netherlands. The municipality of Arnhem covers an area of 102 km^2, of which approximately 5 km^2 (4.9%) is covered by parks, 36 km^2 (35.3%) by forest and green open areas, 16 km^2 (15.7%) agricultural area, 27 km^2 (26.5%) built area and 6 km^2 (5.9%) roads and railways (Gemeente Arnhem, 2016). A large branch of the river Rhine crosses the city to the southwest. Arnhem has a maritime climate. Measurements at the weather station Deelen (WMO code 06275; 52.05 °N, 5.87 °E) about 8 km north of the city centre show an average annual temperature (1981–2010) of 9.8 °C and a mean annual precipitation of 861 mm (Jacobs et al., 2015).

The EC station is located on top of an 18 m high apartment complex close to the city centre (N 51.9848°, E 5.9183°), see Fig. 1. Measurements are performed at 23 m above ground level. A first order analysis of the footprint following the method of Schuepp et al. (1990) shows that the area within a radius of 1 km around the EC station usually contributes > 80% to the measured flux. Approximately 35% of this circular footprint is covered with buildings, 49% is covered by sealed surface and 12% is vegetation, of which 9% is grass and 3% forest. The average building height in the footprint is 11 m and all tall buildings (> 40 m) are located 800 m or more from the EC station (Jacobs et al., 2015). The building on which the measurements are performed is relatively high. We estimate that net measurement height is about 2.1 times the height of the roughness layer (Jacobs et al., 2015). The displacement height and aerodynamic roughness length were calculated using the method of Carraça and Collier (2013) and are 6.5 m and 1.4 m, respectively. According to the land use classification proposed by Stewart and Oke (2012) most of the footprint area corresponds to Local Climate Zone 2 (Compact Midrise). Just outside the 1 km footprint area, a large park is located northwest of the tower and the River Rhine flows through Arnhem south of it.

The effect of land use on the CO_2 fluxes was assessed by means of a sector analysis. The circular footprint was split up into six 60° sectors (see Fig. 1), starting at 0° (i.e. North). Surface cover fractions were determined with ArcGIS 10.3 (ESRI, 2011) using the topographical map 'TOP10 2013' (Netherlands' Cadastre, 2014). The composition of the surface cover derived in this way is shown in Fig. 2.

2.2. Instrumentation and data processing

CO_2 fluxes were measured using an LI-7500 gas analyser (LI-COR Biosciences, Lincoln, USA) and an R3-50 sonic anemometer (Gill, Lymington, UK). Air temperature was measured using a shielded sensor (107, Campbell Scientific, USA) at 1.5 m and 5 m above