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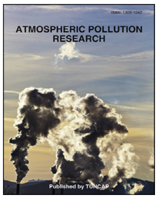

Original article

Spatial variation of near-surface CO_2 concentration during spring in Shanghai

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ABSTRACT

Urban area plays an important role in global carbon cycle, yet few efforts have been made to investigate CO_2 concentration and its spatial heterogeneity in cities. Using Shanghai, the commercial and financial center of mainland China, as a case study, this paper explored the spatial pattern and determinants of near-surface urban CO_2 concentration during spring. A total number of 173 sample points were collected covering the whole urban area, to examine the atmospheric CO_2 concentration across various land use types (transportation, commercial, agricultural, recreational, institutional, residential and industrial land use) and urbanization gradients (heavy, moderately heavy, medium, moderately low, and low urbanization). CO_2 concentrations were measured at a height of 2 m above the ground during 9:00–11:00 am in April and May 2014. The results indicated that CO_2 concentration for the region was 409.4 ± 20.8 parts per million (ppm), showing significant spatial heterogeneity. The daytime ambient CO_2 concentration varied across land use types ($p < 0.05$), with the highest and lowest value appeared in transportation area (420.5 ± 33.3 ppm) and agricultural land (398.9 ± 16.2 ppm). Across the urban gradients of Shanghai, a significant decrease of CO_2 concentration was observed as the distance from urban core increased. With the influence of both high residential density and activities in production, the highest CO_2 concentration occurred in moderate urbanization area (423.9 ± 29.3 ppm), rather than the high urbanization area (417.2 ± 17.5 ppm). Further analysis indicated that the percent of impervious surface cover (ISA) was an important indicator to describe near surface CO_2 concentration with a positive correlation, and the percent of vegetation coverage (Veg) had lower explanatory power with a negative correlation. When buffer distance of spatial scale was 2000 m, atmospheric CO_2 concentration showed the highest correlation with impervious surface and vegetation coverage.

1. Introduction

Carbon dioxide, CO_2, is considered as the most important greenhouse gas in the atmosphere (Keeling et al., 1995; Hofmann et al., 2009; IPCC, 2013). Precise monitoring of atmospheric CO_2 concentration has been systematically conducted for decades at many ground-based sites and networks all over the world (Keeling and Whorf, 2005; Zhang et al., 2007; Sasakawa et al., 2013). These observations reveal the diurnal and seasonal patterns as well as increasing rate of atmospheric CO_2 concentration in undisturbed air with minimal influences of human activity and natural vegetation (Keeling and Whorf, 2005; Zhang et al., 2008). However, atmospheric CO_2 concentration in the surface layer varies significantly over different land uses (Idso et al., 1998, 2001; George et al., 2007; Zhang et al., 2008; Jacobson, 2010). It is highly required to understand the spatial variability of CO_2 in relation to land use in the forecast of future CO_2 levels and its greenhouse effect (Wu et al., 2012).

Urban areas are main contributors to the CO_2 rise in the atmosphere (Le Quéré et al., 2009; Nordbo et al., 2012). Although urban areas currently comprise ~2% of global land area, they release more than 70% of the total CO_2 emissions of anthropogenic origin (i.e., fossil fuel combustion in transportation, industry, and housing) (Churkina, 2008; Rosenzweig et al., 2010). However, much

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attention relating to atmospheric CO_2 focused on areas dominated by biogenic fluxes and homogenous land use patterns such as forest, grassland and cropland (Baldocchi, 2008). Researches in urban areas comprised of heterogeneous land cover and complicated carbon source/sinks have only become developing widely during the past years (Grimmond et al., 2002; Velasco and Roth, 2010; Grimmond and Christen, 2012).

Recent studies carried out in urban areas have focused on the direct measurements of CO_2 concentrations, and fluxes based on eddy covariance (EC) technique over urban sites (Idso et al., 1998; Grimmond et al., 2002; Nordbo et al., 2012). The exchange of CO_2 between the atmosphere and the underlying surface over an urban area is mostly governed by anthropogenic emissions originated from road traffic (Gratani and Varone, 2005; Coutts et al., 2007; Christen et al., 2011), local heating (Soegaard and Moller-Jensen, 2003; Bergeron and Strachan, 2011), as well as biogenic and meteorological conditions, such as photosynthesis, vegetation respiration (Nordbo et al., 2012), wind speed (Day et al., 2002), temperature (Ziska et al., 2004; George et al., 2007) and atmospheric stability (Contini et al., 2012). Apart from direct measurements, several studies report on CO_2 emissions by consumption of fossil fuels or sequestration by biomass from nations or individual urban areas based on consumption statistics (Pataki et al., 2006; Sahay and Ghosh, 2013; Su et al., 2014).

In the past two decades, measurements of atmospheric CO_2 have mainly focused on cities in developed countries (Idso et al., 1998, 2001; George et al., 2007; Henninger and Kuttler, 2007; Henninger, 2008; Buns and Kuttler, 2012; Granieri et al., 2013), with the exception of Delhi and Beijing (Sahay and Ghosh, 2013; Song et al., 2013). However, most studies of atmospheric CO_2 concentration in urban areas are mainly based on the continuous observations in common-points (George et al., 2007; Sahay and Ghosh, 2013) or mobile-route measurements (Idso et al., 1998, 2002; Buns and Kuttler, 2012). These observations are able to record the CO_2 concentration with a high temporal resolution but normally have a small spatial coverage. Although general conclusions have been drawn regarding their significances such as CO_2 levels reach a peak in areas with the most intense human activity, and are higher in the morning than in the afternoon (Idso et al., 1998; George et al., 2007), few of the approaches taken in these studies are capable of quantifying urban CO_2 concentration level on the urban scale (Kort et al., 2012).

As one of the largest megacities in China, Shanghai has undergone rapid urbanization as characterized by an accelerating growth in energy consumption during the past two decades (Li et al., 2013). However, its carbon budget has been mainly estimated from inventories in the past, and so far the efforts made to monitor ambient CO_2 concentration and their spatial variations have been very limited. In this context, we aimed to characterize the spatial patterns and the determinants of near-surface urban CO_2 concentration in Shanghai. To achieve this goal, observations were conducted across urbanization gradient to investigate the spatial heterogeneity of atmospheric ambient CO_2 concentration of the whole city. The relationship between CO_2 concentration and underlying surface (i.e., land use types and landscape structure) was also examined.

2. Data and methods

2.1. Study area

Shanghai (30°40′–31°53′N, 120°51′–122°12′E) is located in the alluvial plain of Yangtze River Delta in East China (Fig. 1), spreading over an area of 6340.5 km^2 including 17 county-level divisions: 16 districts and one county. It has a longitudinal extent of 120 km and a latitudinal extent of 100 km. The land area is flat, with an average elevation of 4 m. Shanghai has a humid subtropical climate and four distinct seasons, with a mean annual temperature of 17.7 °C and a mean annual precipitation of 1222.2 mm in the past ten years (2003–2012, data from Shanghai Meteorological Bureau). As the commercial and financial center of mainland China, Shanghai has experienced rapid and massive urbanization: the total Gross Domestic Product (GDP) in Shanghai was CNY 2.16 trillion (US$ 352.36 billion) in 2012, accounting for 4.5% of the national GDP. The city's population has increased from 11.04 million at the beginning of the Reform and Opening-Up era in 1978, to 23.80 million in 2012, with the cultivated area decreasing from 3601 km^2 to 1990 km^2 during the same period. The energy consumption has grown annually by 12.3% during the period of 1985–2012 (Shanghai Municipal Statistics Bureau, 2013).

2.2. CO_2 concentration measurements

2.2.1. Sampling sites

A total number of 173 sample points were collected covering the whole urban area of Shanghai, to examine the atmospheric CO_2 concentration across various land use types (transportation, commercial, agricultural, recreational, institutional, residential and industrial land use) and urbanization gradients (heavy, moderately heavy, medium, moderately low, and low urbanization) (Fig. 1 and Table 1). The transportation land use (TrLU) were paved roads and mostly were 4-lane double-way roads with several exceptions in less developed area. The commercial land use (CoLU) included office buildings, shopping malls and multi-purpose commercial squares, which were usually multi-story building with a height more than 30 m. The agricultural land use (AgLU) were farmlands, which grow vegetables or grains. The recreational land use (RecLU) selected in this study were the parks scattering in city. The institutional land use (InsLU) involved universities, colleges and research institutions. The residential land use (ResLU) were the communities with at least 30 blocks within which resided more than 1000 dwellers with architectural type ranged widely from low-rise to high-rise buildings. The industrial land use (IndLU) included chemical plants, raw material processing plants and equipment manufacturing factories with an area more than 10 000 m^2. In our study, the land use classifications were conducted based on remote sensing images acquired from Google Earth in 2014. Based on the officially issued document "The overall urban planning of Shanghai (Year 1999–2020)", the urbanization level was determined according to the distance from main ring roads (showed in Fig. 1). Shanghai was classified into five types, namely heavy urbanization (H_urban, within Inner-Ring Rd), moderately heavy urbanization (MH_urban, outside Inner-Ring Rd and within Mid-Ring Rd), medium urbanization (M_urban, outside Mid-Ring Rd and within Outer-Ring Rd), moderately low urbanization (ML_urban, outside Out-Ring Rd and within Suburb-Ring Rd) and low urbanization (L_urban, outside Suburb-Ring Rd).

As the spatial heterogeneity in highly urbanized regions was significantly higher than that in lower urbanized regions, multi-density stratified sampling methodology was used to determine the locations of sampling points in our study. Specifically, the whole territory of Shanghai was first partitioned into 5 km × 5 km grids with ArcGIS 10.0. The density of sampling points in urban areas was four times of the density in suburban areas. In high urbanized area (H_urban, MH_urban and M_urban), the proportion of point density assigned for three urban levels was 3:2:1. In less urbanized area (ML_urban and L_urban), the proportion was 2:1. The spatial distribution of all sampling points was shown in Fig. 1.

2.2.2. Gas sampling strategy

The sampling of near-surface atmospheric CO_2 was conducted during April to May 2014. Temperature inversion and