Spatial variation of near-surface CO₂ 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 CO₂ 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 CO₂ concentration during spring. A total number of 173 sample points were collected covering the whole urban area, to examine the atmospheric CO₂ 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). CO₂ 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 CO₂ concentration for the region was 409.4 ± 20.8 parts per million (ppm), showing significant spatial heterogeneity. The daytime ambient CO₂ 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 CO₂ concentration was observed as the distance from urban core increased. With the influence of both high residential density and activities in production, the highest CO₂ 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 CO₂ 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 2 000 m, atmospheric CO₂ concentration showed the highest correlation with impervious surface and vegetation coverage.

Keywords: CO₂ concentration, Urbanization, Shanghai, Land use

1. Introduction

Carbon dioxide, CO₂, 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 CO₂ 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 CO₂ concentration in undisturbed air with minimal influences of human activity and natural vegetation (Keeling and Whorf, 2005; Zhang et al., 2008). However, atmospheric CO₂ concentration in the surface layer varies significantly over different land uses (Idso et al., 1998; Idso et al., 2001; George et al., 2007; Zhang et al., 2008; Jacobson, 2010). It is highly required to understand the spatial variability of CO₂ in relation to land use in the forecast of future CO₂ levels and its greenhouse effect (Wu et al., 2012).

Urban areas are main contributors to the CO₂ 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 CO₂ emissions of anthropogenic origin (i.e., fossil fuel combustion in transportation, industry, and housing) (Churkina, 2008; Rosenzweig et al., 2010). However, much attention relating to atmospheric CO₂ 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

1 complicated carbon source/sinks have only become developing widely during the past
2 years (Grimmond et al., 2002; Velasco et al., 2010; Grimmond and Christen, 2012).
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5 Recent studies carried out in urban areas have focused on the direct
6 measurements of CO₂ concentrations, and fluxes based on eddy covariance (EC)
7 technique over urban sites (Idso et al., 1998; Grimmond et al., 2002; Nordbo et al.,
8 2012). The exchange of CO₂ between the atmosphere and the underlying surface over
9 an urban area is mostly governed by anthropogenic emissions originated from road
10 traffic(Gratani et al., 2005; Coutts et al., 2007; Christen et al., 2011), local
11 heating(Soegaard and Moller-Jensen, 2003; Bergeron and Strachan, 2011), as well as
12 biogenic and meteorological conditions, such as photosynthesis, vegetation
13 respiration(Nordbo et al., 2012), wind speed(Day et al., 2002), temperature(Ziska et
14 al., 2004; George et al., 2007) and atmospheric stability(Contini et al., 2012). Apart
15 from direct measurements, several studies report on CO₂ emissions by consumption of
16 fossil fuels or sequestration by biomass from nations or individual urban areas based
17 on consumption statistics (Pataki et al., 2006; Sahay and Ghosh, 2013; Su et al.,
18 2014).
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45 In the past two decades, measurements of atmospheric CO₂ have mainly focused
46 on cities in developed countries (Idso et al., 1998; Idso et al., 2001; George et al.,
47 2007; Henninger and Kuttler, 2007; Henninger, 2008; Buns and Kuttler, 2012;
48 Granieri et al., 2013), with the exception of Delhi and Beijing(Sahay and Ghosh, 2013;
49 Song et al., 2013). However, most studies of atmospheric CO₂ concentration in urban
50 areas are mainly based on the continuous observations in common-points (George et
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al., 2007; Sahay and Ghosh, 2013) or mobile-route measurements (Idso et al., 1998; Idso et al., 2002; Buns and Kuttler, 2012). These observations are able to record the CO₂ concentration with a high temporal resolution but normally have a small spatial coverage. Although general conclusions have been drawn regarding their significances such as CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentration in Shanghai. To achieve this goal, observations were conducted across urbanization gradient to investigate the spatial heterogeneity of atmospheric ambient CO₂ concentration of the whole city. The relationship between CO₂ 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 (Figure 1), spreading over an area of 6 340.5 km² 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 1 222.2 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 3 601 km² to 1 990 km² during the same period. The energy consumption has grown annually by 12.3% during the period of 1985-2012(Shanghai Municipal Statistics Bureau, 2013).

Figure 1. Locations of study area and sampling sites for CO₂ concentration.

2.2 CO₂ concentration measurements

Sampling sites. A total number of 173 sample points were collected covering the whole urban area of Shanghai, to examine the atmospheric CO₂ 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).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 1 000 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 m². 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 Figure 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).

Table 1. Distribution of sampling points with respect to land use type and urbanization level.

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 $5\text{ km} \times 5\text{ km}$ 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 Figure 1.

Gas sampling strategy. The sampling of near-surface atmospheric CO_2 was conducted during April to May 2014. Temperature inversion and atmospheric stability have a great impact on the concentration of greenhouse gases, especially in urban environment (Aikawa et al., 2006). Intensity of temperature inversion was moderate in spring ($0.93\text{ }^\circ\text{C}$ per 100 m on 08:00 local standard time) and gradually disappeared after 9:00 (Yang et al., 2006). On the other hand, according to the real-time traffic condition in Shanghai, the morning rush hour started from 7:00 to 9:00. The sampling time during 9:00-11:00 am may be less influenced by automobile exhausts. Therefore, we conduct our in-situ measurements in the morning of weekdays (9:00-11:00 am) on sunny days with clear skies and calm winds, i.e., April 15, April 18, April 23-24, April 28-30, and May 4, 2014, to ensure a better air circulation coupled with relative low traffic volume. The detailed meteorological conditions during the sampling days, including air temperature, wind speed and wind direction, from 11 Meteorological

Stations provided by Shanghai Metrological Bureau, was illustrated in Table 2. As it was very difficult to take samples at all 173 sampling points at once, we performed sampling at 20-24 sampling sites per day. In addition, to minimize the disruptions from local interference, each sampling were conducted at open areas with the sampling site located at least 8-10 m from tall buildings or trees, and no obvious emission sources were recorded throughout the whole sampling process excepted for specific land use types, i.e., transportation land use (TrLU) and industrial land use (IndLU).

Table 2. Metrological conditions during sampling period

We measured all of our sampling points at the height of 2 m above the ground. All air samples were collected through pre-vacuumed sample bags by using syringe equipped with three-way valve. During each sampling visit, triplicate air samples were collected. CO₂ concentration in the gas samples were analyzed by a 7890A gas chromatograph (Agilent Technologies Co. Ltd., USA), equipped with a flame ionization detector (FID). The system was single-point calibrated with 353.7 ppm CO₂ standards after measuring every six consecutive samples. System precision was less than 1% relative standard deviation at approximately ambient concentrations

2.3 Measurements of urban landscape structure

In this study, vegetation-Impervious Surface-Soil (V-I-S) model proposed by Ridd (1995) was utilized to describe the landscape structure around each sampling points. The V-I-S model considered the land cover types of urban environment with

high heterogeneity as a linear combination of three basic biophysical components, namely vegetation, impervious surface area and bare soil. Due to the low proportion of bare soil in Shanghai, our research focused on vegetation, impervious surface and water. As high-quality images was missing during our sampling date, two cloud-free Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) images acquired on 29th August 2013 was utilized. Decision Tree Classification (DTC) was used to divide the complex urban landscape into vegetation (Veg), impervious surface (ISA), water (Wat) and other (Oth) (Hansen et al., 1996; Chan et al., 2001). We used Normalized Difference Vegetation Index (NDVI, Eq.1), Modified Normalized Difference Water Index (MNDWI, Eq.2) (Xu, 2006) and Normalized Difference Impervious Surface Index (NDISI, Eq.3) (Xu, 2010) to detect the urban complex landscape into vegetation, impervious surface, water and other type.

$$NDVI = \frac{NIR - red}{NIR + red} \quad (1)$$

$$MNDWI = \frac{Green - MIR}{Green + MIR} \quad (2)$$

$$NDISI = \frac{TIR - (MNDWI + NIR + MIR) / 3}{TIR + (MNDWI + NIR + MIR) / 3} \quad (3)$$

Where *NIR*, *red*, *green*, *MIR* and *TIR* are the reflectance values in the near-infrared, red, green, mid-infrared and thermal bands, respectively.

The detail procedure for DTC used in our study was illustrated in Figure 2. To evaluate the classification accuracy in this study, we randomly selected 100 samples across Shanghai, and compared the landscape type with that obtained from Google Earth images (Spatial resolution: 4m; Date: 15th April 2014, close to the sampling

time). The results showed that the overall classification accuracy was 81%, which had met the requirements of classification accuracy.

Figure 2. The procedure for the extraction of biophysical components of landscape structure including Vegetation (Veg), impervious surface (ISA) and Water (Wat) with decision tree classification.

In order to further explore the relationship between biophysical structure in the close vicinity of each sampling point and spatial pattern of near-surface CO₂ concentrations, we built up buffers for each sampling site with the distances from 250 m to 3 000 m(with 250 m as interval). The Pearson correlation coefficient (R) between CO₂ concentration and biophysical components (i.e., ISA, Veg, Wat and Oth) for different buffer distances were also calculated.

3. Results and discussion

3.1 Spatial variation of CO₂ concentration in Shanghai

CO₂ concentration showed significant spatial heterogeneity in Shanghai (Figure 3), with an average of 409.4 ± 20.8 ppm. The daytime (9:00-11:00 am) ambient CO₂ concentration varied from 374.4 to 542.3 ppm. The frequency distribution of observed CO₂ concentration was heavily right-skewed (Figure 3), with over 80% of the measurement values falling within the range between 385.0 to 425.0 ppm. The highest CO₂ concentration of 542.3 ppm in this study was observed in Pudong International Airport located in eastern Shanghai near the seashore, which was likely to be caused by vehicle fuel combustion and could contribute significantly to the urban CO₂ dome.

On the other hand, the lowest value of 374.4 ppm was observed at the sampling point near Chenhai road located in Chongming Island. This low value might be explained by the significant buffering effect of local dense vegetation in alleviating the elevation of CO₂ concentration. Both sides of Chenhai road (10 m in width) were surrounded by *Metasequoia glyptostroboides*, a deciduous coniferous forest, which were planted as internal green belts around 15-30 years ago. These mature trees could be act as a strong sink to atmospheric CO₂ concentrations.

Figure 3. Spatial distribution of CO₂ concentration in Shanghai obtained from 173 sampling points. The histogram in the upper left corner shows the frequency distribution of the observed CO₂ concentration values.

The significant spatial heterogeneity of atmospheric CO₂ indicated the presence of an “urban CO₂ dome” in Shanghai, which was also observed in Phoenix (Idso et al., 1998; Idso et al., 2002) and Delhi (Sahay and Ghosh, 2013). CO₂ concentration was >410 ppm in some districts of Shanghai, such as Pudong, Baoshan and main urban zone, whereas CO₂ concentration over Minhang, Jinshan, Qingpu districts was 412.5, 402.6, and 400.3 ppm, respectively. The maximum CO₂ concentration observed over main urban zone was associated with high-intensity human activities, such as high traffic volume in urban core. The high value in Baoshan district were related to its industrial activity, especially the steel production. Chongming, a county of Shanghai and less affected by the large carbon emission from urbanized area, showed the lowest value of 394.2 ppm. The low CO₂ concentration in Chongming Island reflected the important buffering function of natural vegetation ecosystems in

mitigating increasing atmospheric CO₂ mostly contributed by anthropogenic activities.

It was worth noting that the anthropogenic emissions are largely concentrated in urban areas(Kort et al., 2012), with megacities in particular are large anthropogenic emitters, especially in China's economically developed region-Shanghai(Fang et al., 2014). We compared our averaged CO₂ concentration across Shanghai (409.4 ± 20.8 ppm) to the only regional stations of WMO/GAW of Lin'an(LAN) located in Yangtze River Delta economic zone which is about 150 km from Shanghai. Results showed the CO₂ concentration was also higher than that observed in LAN from the 10 m intake in 2011(404.2 ppm)(Fang et al., 2014). This difference was attributed to the carbon emissions from fossil fuel combustion and land use change in urban area (Le Quéré et al., 2009), which also implied that Shanghai behaved as a carbon source in East China.

CO₂ is a well-mixed gas in the atmosphere. Its spatial and temporal variations reflected a combination of anthropogenic emissions, exchange with the biosphere, atmospheric transport, and boundary layer dynamics (Briber et al., 2013). The selection of monitoring sites has significant impact on the observation results. The inconsistent observation conditions (e.g., monitoring height and sampling time) made it very difficult to conduct comparisons among different cities. On the whole, the observed average CO₂ concentration in Shanghai was partly related to the observing period in this study and the geographical location. According to the seasonal variation of CO₂ concentration from existing studies, the sampling period in this study, i.e.,

1 April and May, was usually accompanied with higher air temperature, resulting the
2 lower CO₂ emissions from fossil fuel combustion for heating (Song et al., 2013). On
3 the other hand, Shanghai is located in the northern subtropical region with fair amount
4 of active vegetation in the early spring, which could play an important role in
5 offsetting the local carbon emissions. Furthermore, the high vegetation coverage of
6 38.2% can also partly explain the relatively low CO₂ value in Shanghai (Shanghai
7 Municipal Statistics Bureau, 2013), while cities are estimated as carbon-neutral when
8 the natural fraction is about 80% (Nordbo et al., 2012). In addition, the meteorological
9 condition in Shanghai, a coastal city, was benefit to air convection, which can dilute
10 the atmosphere CO₂ concentration.
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27 **3.2 Variability of CO₂ concentration across land use types and urbanization** 28 **gradients** 29 30 31

32 Atmospheric CO₂ concentration was significantly different among seven land use
33 types (Figure 4a). With the influence of anthropogenic carbon emissions, the
34 transportation land use type had the highest concentration during the study period,
35 which was 420.5 ± 20.9 ppm, and the agricultural land use type has the lowest value
36 of 398.9 ± 13.4 ppm. The commercial land use type has the intermediate value of all
37 seven land use types, which was 410.4 ± 15.4 ppm. It was worth noting that there was
38 a large dispersion of CO₂ concentration over transportation area. This might be
39 attributed to the big different traffic volume of 28 transportation sample points. High
40 concentrations over industrial area were related to point-source pollution (e.g., steel
41 and chemistry industry). Different from other cities around the world, there were
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many people living in the apartments of residential area in Shanghai. The high population density and subsequent household energy consumption lead to the high CO₂ concentration. It was observed that CO₂ concentration over institutional and recreation area were relatively low (InsLU: 404.2± 8.3 ppm; RecLU: 400.2± 10.2 ppm).

Figure 4. Box chart of CO₂ concentration in different land use types (a) and urbanization level (b) during the sampling period. The rectangle represents the median, the upper and lower boxes represent the 75th and 25th percentiles and the upper whiskers represent the 95th and 5th percentiles. The red circles represent the mean value.

Increasing land use change from rural agricultural areas to dense populated urban areas will have significant impact on carbon emissions and cycling (Imhoff et al., 2004; George et al., 2007). A linear function was used to characterize the relationship between CO₂ concentration and distance from the urban core (DUC). Across Shanghai, CO₂ concentration decreases significantly as DUC increases (Figure 5). The correlation was given by:

$$Y_{CO_2} = -0.424X_{DUC} + 420.34, R = 0.33, p < 0.01 \quad (1)$$

This result was consistent with findings in existing studies that atmospheric CO₂ concentrations are closely related to population and associated high traffic volume in city centers (Idso et al., 1998; Idso et al., 2002; George et al., 2007). In addition, CO₂ concentrations also vary significantly for different urban development intensities. The relation between CO₂ concentration and urbanization level took a form of parabola

(Figure 4b), with the highest and lowest CO₂ concentration appeared in medium (423.9 ± 29.3 ppm) and low (401.6 ± 23.5 ppm) urbanized areas, respectively. With the influence of high-density population and productive activities, the highest CO₂ concentration occurred in moderate urbanization area, rather than the high urbanization area (417.2 ± 17.5 ppm). The highest variance of CO₂ concentration appeared in M_urban, which was partly due to the wide range of land uses occurred within a median urbanization areas.

Figure 5. Atmospheric CO₂ concentration across Shanghai as a function of distance to urban core.

To further identify the effects of LUT and UL on CO₂ concentration, a two-way analysis of variance (ANOVA) was performed using the method proposed by (Yu and Harris, 2009). The results were summarized in Table 3, from which the importance order of each influencing factor could be gained. Overall, LUT and UL both have significant influence on the variability of CO₂ concentration ($p < 0.01$). Compared with the influence of LUT, UL was confirmed to be the main factor. The weights of the two influencing factors, i.e., LUT and UL, were 43.4% and 56.6%, respectively. This result stressed the importance of understanding the spatial heterogeneity of atmospheric CO₂ concentration to avoid the introduction of artificial variability that hampers comparative analysis.

Table 3. Results of the ANOVA test on CO₂ concentration. The numbers with brackets were obtained with interaction ANOVA.

3.3 The relationship between CO₂ concentration and landscape structure

Within a certain spatial scale of different buffer distances (i.e., 250m-3 000m, with 250m as interval), the near surface CO₂ concentration was significantly correlated with the ISA and Veg ($p<0.01$) (Figure 6a). The result indicated that ISA was an important indicator to describe near surface CO₂ concentration with a positive correlation ($R = 0.38 \sim 0.51$), and Veg had lower explanatory power with a negative correlation ($R = -0.38 \sim -0.50$). When buffer distance of spatial scale was 2 000 m, atmospheric CO₂ concentration showed the highest correlation with impervious surface and vegetation coverage, with correlation coefficients were 0.51 and -0.50 for ISA and Veg, respectively.

Figure 6. The relationship between CO₂ concentration and landscape structure(i.e., ISA and Veg).The Pearson correlation coefficient (R) between CO₂ concentration and ISA, Veg with buffer distances from 250 m to 3 000 m was illustrated in the left panel(a). The linear relationships between CO₂ concentration and ISA (b) and Veg (c) with 2 000 m buffer distance were shown in the right panel.

We provided the biophysical components (i.e., ISA, Veg, Wat and Oth) for sampling points with respect to land use type when buffer distance was 2 000 m (Table 4). A linear regression model was developed in the present study to simulate the relationship between CO₂ concentration and ISA or Veg with buffer distance of 2 000m (Figure 6b-c). As depicted from Figure 6 b-c, based on regression equation it was concluded that CO₂ concentration increased up to 3.44 ppm, while ISA increased by every 10% and decreased to 3.18 ppm as Veg increased by every 10%. The

conclusion was similar to the results acquired from a meta-analysis based on all available 14 annual CO₂ budget studies and a extraction of 56 individual cities corroborates their inventory-based estimates(Nordbo et al., 2012), which points out that the fraction of natural area was the strongest predictor of urban CO₂ budgets. Cities were considered as carbon source once urban fraction was over 20% (urban fraction = 1 – natural fraction). In addition, with a handful of ISA (31.4%) and abundant vegetation (67.4%), it was not enough to offset local emissions by anthropogenic activity in the Cub Hill suburb of Baltimore, MD (Crawford et al., 2011). The CO₂ flux in a low-storied residential area(May 2010 – April 2011) in Tokyo, Japan (Moriwaki and Kanda, 2004) was six times the downward CO₂ flux at a typical temperate deciduous forest, which could also verify the important influence of ISA on CO₂ concentration to a certain extent. Therefore, we could reduce CO₂ concentration to a certain extent through decreasing ISA and increasing Veg at the same time.

It was noting that R value for CO₂ concentration and landscape structure based on V-I-S model was not very high. This was partly related to the limited information provided by V-I-S model. V-I-S model could provide the landscape configuration near the monitoring site but it does not provide information on closeness and height of the nearby built structure. The determinants for spatial variation of near-surface CO₂ concentration still need further study with more information related to urban landscape structure, especially the urban three-dimensional information.

<p>Table 4. Biophysical components (i.e., ISA, Veg, Wat and Oth) for sampling points</p>

with respect to land use type when buffer distance was 2 000 m.

4. Conclusions

Understanding the atmospheric concentration of carbon dioxide (CO₂) and its spatial heterogeneity in urban area is important for forecasting future CO₂ levels and its greenhouse effect. Using Shanghai, as a case study, this paper investigated the spatial pattern of atmospheric CO₂ concentration and its relationship with underlying surface, including land cover and landscape structure across urbanization gradients. CO₂ concentration showed a significant spatial heterogeneity and it was significantly higher in inner city than that in the suburban area, indicating a typical urban CO₂ dome in Shanghai. Overall, the higher urbanization level lead to the higher CO₂ concentration. When buffer distance of spatial scale was 2 000 m, atmospheric CO₂ concentration showed the best correlation with impervious surface and vegetation coverage. The investigations of this study provided new insights to capture the spatial pattern of CO₂ concentration efficiently, its variation across gradients of urbanization and the effects of landscape structure on the CO₂ concentration.

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Figure captions

Figure 1. Locations of study area and sampling sites for CO₂ concentration.

Figure 2. The procedure for the extraction of biophysical components of landscape structure including Vegetation (Veg), impervious surface (ISA) and Water (Wat) with decision tree classification.

Figure 3. Spatial distribution of CO₂ concentration in Shanghai obtained from 173 sampling points. The histogram in the upper left corner shows the frequency distribution of the observed CO₂ concentration values.

Figure 4. Box chart of CO₂ concentration in different land use types (a) and urbanization level (b) during the study period. The rectangle represents the median, the upper and lower boxes represent the 75th and 25th percentiles and the upper whiskers represent the 95th and 5th percentiles. The red circles represent the mean value of CO₂ concentration.

Figure 5. Atmospheric CO₂ concentration across Shanghai as a function of distance to urban core.

Figure 6. The relationship between CO₂ concentration and landscape structure(i.e., ISA and Veg).The Pearson correlation coefficient (R) between CO₂ concentration and ISA, Veg with buffer distances from 250 m to 3 000 m was illustrated in the left panel(a). The linear relationships between CO₂ concentration and ISA (b) and Veg (c) with 2 000 m buffer distance were shown in the right panel.

Figures

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Tables

Table 1. Distribution of sampling points with respect to land use type and urbanization level.

Number of sampling sites	TrLU	CoLU	AgLU	RecLU	InsLU	ResLU	IndLU	Total
H_urban	2	7	/	2	2	4	/	17
MH_urban	3	6	/	2	4	4	2	21
M_urban	3	3	/	3	2	6	3	20
ML_urban	8	9	11	6	4	13	6	57
L_urban	12	8	17	7	3	5	6	58
Total	28	33	28	20	15	32	17	173

Table 2. Metrological conditions during sampling period.

Date	Time of the day	Temperature (°C)	Wind speed (m·s ⁻¹)	Wind direction
April 15 th	9:00-10:00	16.2	3.7	S-SE
	10:00-11:00	17.5	4.1	S-SSE
April 18 th	9:00-10:00	15.8	3.1	N-NE
	10:00-11:00	15.3	3.4	N-NE
April 23 rd	9:00-10:00	18.5	1.8	SSE
	10:00-11:00	19.9	2.9	SE
April 24 th	9:00-10:00	19.1	3.2	S-SSE
	10:00-11:00	20.1	3.5	S-ESE
April 28 th	9:00-10:00	17.3	2.8	NW
	10:00-11:00	17.4	3.4	NW
April 29 th	9:00-10:00	19.0	3.1	WNW
	10:00-11:00	20.4	3.0	WNW
April 30 th	9:00-10:00	20.9	2.0	SSE
	10:00-11:00	22.6	2.1	ESE
May 4 th	9:00-10:00	17.3	3.1	NE
	10:00-11:00	18.2	3.2	NE

Table 3. Results of the ANOVA test on CO₂ concentration. The numbers with brackets were obtained with interaction ANOVA.

Source	Sum of square	Degree of freedom	Mean of square	F	Prob>F
LUT	8 757.3(5 975.7)	6(4)	1 459.5(1 494.0)	4.13(4.17)	0.0007(0.0032)
UL	7 617.2(1 002.5)	4(1)	1 904.3(1 002.6)	5.39(2.8)	0.0004(0.0966)
LUT*UL	(6 352.7)	(20)	(317.63)	(0.89)	(0.6043)
Error	57 229.7(50 877)	162(142)	(358.29)		
Total	74 899.2	172			

Table 4. Biophysical components (i.e., ISA, Veg, Wat and Oth) for sampling points with respect to land use type when buffer distance was 2 000m.

	ISA(%)	Veg(%)	Wat(%)	Oth(%)
TrLU	56.0	33.4	5.9	4.7
CoLU	68.3	20.3	8.5	2.9
AgLU	33.5	59.3	4.1	3.1
RecLU	50.2	38.3	8.2	3.3
InsLU	65.2	27.0	4.7	3.2
ResLU	69.5	21.8	4.9	3.8
IndLU	62.8	25.7	5.9	5.5

Photograph of the Corresponding Author