Temporal and spatial patterns of carbon dioxide mixing ratios in a subtropical urban environment during spring

Lena F. Weissert[1], Jennifer A. Salmond[1], André Friedel[2], Marissa LaFave[3] and Luitgard Schwendenmann[1]

[1]The University of Auckland, School of Environment, Private Bag 92019, Auckland 1142, New Zealand
[2]University of Applied Sciences Bingen, Berlinstrasse 109, 55411 Bingen am Rhein, Germany
[3]Boston University, School of Earth & Environment, Boston, MA 02215, United States

Correspondence: L.F. Weissert, The University of Auckland, School of Environment, Private Bag 92019, Auckland 1142, New Zealand, email: lwei999@aucklanduni.ac.nz

Short running title: Urban carbon dioxide variability

Abstract

The aim of this study was to quantify the temporal and spatial variability of urban CO_2 mixing ratios in the low- to medium-density subtropical city of Auckland, New Zealand. The relations between CO_2 mixing ratios and urban land use are examined using a combination of fixed and mobile measurements. Spring CO_2 mixing ratios were measured in the morning, afternoon and at night along a transect route covering common urban land uses. Fixed measurements were made at a central urban location, a residential and a rural location. While results from the fixed measurements show increased mixing ratios in the central urban location during daytime, the results from the mobile measurements have shown that CO_2 mixing ratios were strongly dependent on the temporal variability of local CO_2 emissions and uptake associated with different urban land use. Thus, the CO_2 dome reported in previous studies was not observed in this setting. Traffic was likely the dominant influence on morning CO_2 mixing ratios along the mobile measurement route, with highest values observed in industrial areas. Afternoon CO_2 mixing ratios showed a slight decrease with distance from the Central Business District (CBD). During the night, CO_2 mixing ratios were influenced by biogenic CO_2 emissions, particularly when wind speed was low, reaching a maximum in the rural area. Overall, this study shows that a few mobile measurements are sufficient to reveal pronounced spatial patterns of urban CO_2 mixing ratios, which cannot be detected by one or two fixed measurement stations.

Keywords

Urban atmospheric CO_2; fixed and mobile measurements; urban land use types; urban vegetation; CO_2 dome; near-surface CO_2

1. Introduction

Given the significant ecological, social and economic implications of increased mixing ratios of atmospheric carbon dioxide (CO_2), there is a growing interest in quantifying the mean temporal and spatial patterns in the variability of atmospheric CO_2 mixing ratios in different environments. While historically, the majority of CO_2 related research has focused on the contribution of land use changes and energy production on atmospheric CO_2 mixing ratios at regional scales, there has been an increasing shift towards identifying the variability at intra-urban scales (Grimmond et al., 2002; Pataki et al., 2006; Velasco and Roth, 2010). Although urban areas only cover about 2% of the land surface, they are thought to account for more than one third of the directly emitted anthropogenic greenhouse gas emissions (Satterthwaite, 2008). However, to date, measurements of CO_2 mixing ratios in urban areas have often been limited to a small number of predominantly short term case studies, which consider one or two fixed measurement points in a city (e.g. Basel, Switzerland (Vogt et al., 2006); Melbourne, Australia (Coutts et al., 2007); Montreal, Canada (Bergeron and Strachan, 2011); Baltimore, US (Crawford et al., 2011); Chicago, US (Moore and Jacobson, 2015)), representative at a local scale (10^2 – 10^4 m). Some studies used aircraft-based measurements of atmospheric CO_2 mixing ratios and atmospheric transport models to provide top-down estimates of CO_2 emissions at the urban scale (10^4 – 10^5m) (e.g. Indianapolis, US (Mays et al., 2009); Sacramento, US (Turnbull et al., 2011); Paris, France (Bréon et al., 2015)). These studies have shown significantly higher CO_2 mixing ratios in large cities compared to the rural background (Idso et al., 1998; Idso et al., 2001; Idso et al., 2002; Nasrallah et al., 2003; Soegaard and Moller-Jensen 2003; Gratani and Varone, 2005; Font et al., 2013). This phenomenon is referred to as CO_2 dome, and in its conceptual form, is considered similar in shape and dimension to the urban heat island. The dome describes the assumption that CO_2 mixing ratios are higher in urban centres compared to the lesser-developed and rural surroundings, mostly due to local anthropogenic CO_2 emissions (Idso et al., 1998; Balling et al., 2001; Idso et al., 2001; Briber et al., 2013).

In many urban areas traffic emissions are the dominant control on the temporal and spatial variability of anthropogenic CO_2 emissions (Idso et al., 2001; Grimmond et al., 2002; Grimmond et al., 2004; George et al., 2007; Guerney et al., 2009). Mean CO_2 mixing ratios are seen to peak around 08:00 in the morning, when a combination of high traffic emissions and shallow boundary layer depths enhance near surface CO_2 mixing ratios (Coutts et al., 2007; Velasco et al., 2009; Dahlkoetter et al., 2010; Ward et al., 2015). In contrast, CO_2 mixing ratios were shown to be at a minimum during the midday / early afternoon periods, coinciding with peak CO_2 uptake by vegetation (due to photosynthetic processes) and deeper mixing layers (Reid and Steyn, 1997; Nasrallah et al., 2003; Coutts et al., 2007). Some (e.g. Crawford et al., 2011; Ward et al., 2015), but not all studies (e.g. Velasco et al., 2009) report an increase in CO_2 mixing ratios in the late evening, often in the winter months, which has been attributed to increased emissions from domestic heating rather than traffic emissions from the evening rush hour (Crawford et al., 2011; Ward et al., 2015).

Although vegetation has the potential to play a significant role in modifying the diurnal and seasonal trends in CO_2 mixing ratios at local scales within urban areas, opinions about the impact of urban vegetation on CO_2 mixing ratios at urban to regional scales differ amongst authors (Coutts et al., 2007;

Bergeron and Strachan, 2011; Pataki et al., 2011; Peters and McFadden, 2012; Pincetl et al., 2012). Studies demonstrate that whilst there may be some evidence of increased uptake of CO_2 during the day, especially in the summer, carbon sequestration by urban vegetation is generally not sufficient to compensate for urban CO_2 emissions (Grimmond et al., 2002; Coutts et al., 2007; Crawford et al., 2011). In addition, vegetated areas can contribute to higher CO_2 mixing ratios due to soil and plant respiration, particularly during nighttime (Henninger and Kuttler, 2010).

Given the complexity of sources and sinks of CO_2 in urban areas, it is unlikely that measurements from one or two fixed stations can accurately reflect the intra-urban variability in ambient CO_2 mixing ratios (Henninger and Kuttler, 2010). Thus, although fixed stations can provide important insights into the temporal and spatial variability of CO_2 mixing ratios at a given location (10^2 – 10^4m), mobile measurements are required as an additional tool to monitor urban air quality at a high spatial resolution (Kuhlbusch et al., 2014; Van den Bossche et al., 2015). To date, only few mobile studies investigated the spatial variability of near-surface CO_2 mixing ratios (Phoenix, US (Idso et al., 1998; Idso et al., 2001); Essen, Germany (Henninger and Kuttler, 2007; Henninger and Kuttler, 2010)). Early studies in Phoenix revealed a strong dome shape to ambient CO_2 mixing ratios. More recent work, however, emphasized the correlation between urban land use and the mean CO_2 mixing ratios with results showing strong spatial variability depending on anthropogenic emissions, urban form, meteorological processes and biogenic controls (Henninger and Kuttler, 2010). Generally, however, there is a lack of information about the influence of different urban land uses (e.g. commercial, residential, industrial, urban parkland) on intra-urban CO_2 levels in different cities and from different climatic regions (Henninger, 2011).

Although the importance of combining fixed measurements with mobile studies to determine urban CO_2 was highlighted by Henninger and Kuttler (2010), only one study combined tower based CO_2 mixing ratios with mobile measurements, which indicated large local variability of near-surface CO_2 mixing ratios (Crawford and Christen, 2014). That study was located in a residential neighbourhood in Vancouver, Canada and no studies to date compared fixed CO_2 measurements with mobile CO_2 mixing ratios across different urban land uses.

To address these research gaps we quantified the spatial and temporal variability of CO_2 mixing ratios in austral spring in the subtropical city of Auckland, New Zealand, using a combination of fixed and mobile monitoring techniques. In particular, we examined the shape and form of the CO_2 dome and considered anthropogenic and biogenic controls on CO_2 mixing ratio patterns. We also compared results from the mobile measurements in the surroundings of the fixed stations to the weekday data obtained at the three fixed monitoring stations to assess differences in the local variability of CO_2 sources.

Given the projected rates of rapid urbanization, an improved understanding of the complex controls on the urban carbon cycle may be critical to mitigating future global emissions (Rosenzweig et al., 2010). Further, since increased CO_2 mixing ratios may have a positive influence on plant productivity, and increased urban CO_2 mixing ratios may simulate near-future environmental changes, a better understanding of the intra-urban variability of CO_2 may help us to improve our estimates of the impact of increased CO_2 on non-urban ecosystems

(Idso et al., 1999; Carreiro and Trippler, 2005).

2. Methods

2.1 Study site

Unlike other major cities, Auckland is characterised by a large proportion of low- to medium-density suburban housing and a comparably small Central Business District (CBD) (4km^2, Miskell et al., 2015). The city is also located in a relatively pristine environment, away from downwind sources of anthropogenic pollutants. Further, in the absence of significant industry in the region, the majority of anthropogenic CO_2 in austral spring is generated locally by traffic and domestic heating, rendering this an ideal case study to ascertain the relations between urban land use and CO_2 mixing ratios. Auckland's climate is subtropical and oceanic with mild winters (Mackintosh 2001). The study was undertaken during austral spring (September – November), when temperatures typically range between 12.7°C – 15.7°C and rainfall is 85.8 – 105.1mm (20 year mean) (NIWA 2013). The vegetation cover in Auckland is dominated by evergreen plants, which maintain high photosynthetic rates across all seasons (Weissert et al., under review).

2.2 Fixed monitoring of CO_2 mixing ratios

At three fixed monitoring stations CO_2 mixing ratios were measured continuously from September – November 2014 to compare the collected mobile data with the fixed data. The fixed stations were located at the University of Auckland (CBD) (height: 12m), Botany Downs (residential) (height: 10m) and Ardmore (rural) (height: 3m) (Fig. 1). CO_2 mixing ratios at the CBD and rural site were measured at 10min intervals using a CO_2 gas analyser (WMA-4, PP systems International Inc., Amesbury, MA, US). At the residential site, CO_2 mixing ratios were recorded at approximately 1.2s intervals using a Picarro carbon isotope analyser (G2131-i, Picarro Inc., Santa Clara, CA, US).

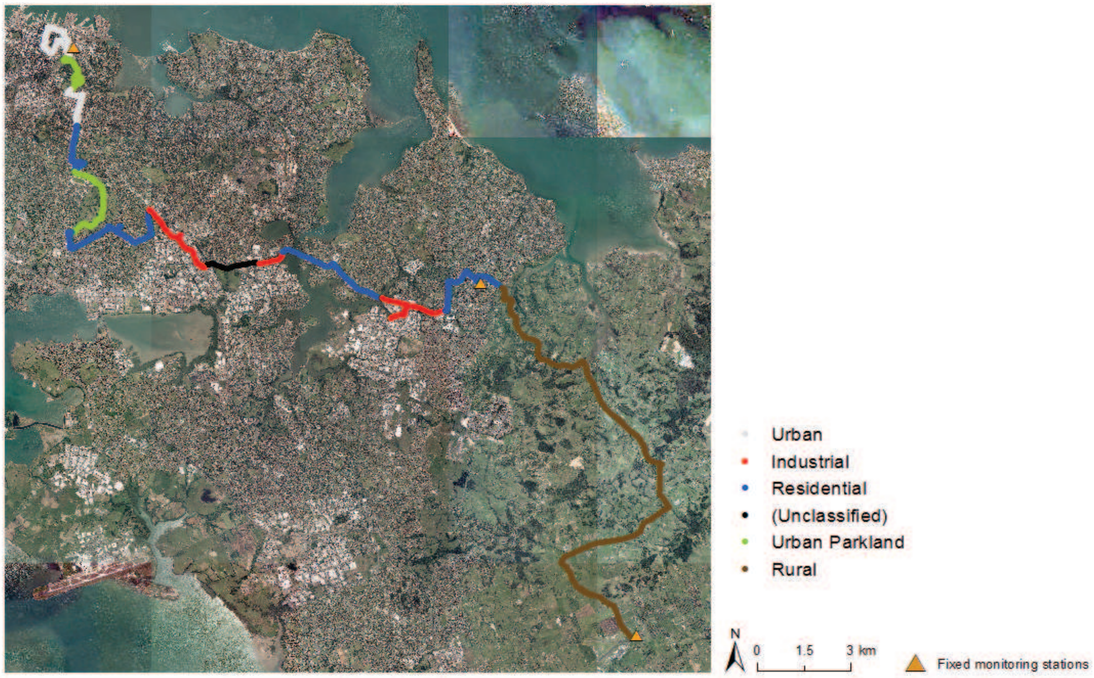

Figure 1.a) Transect route.

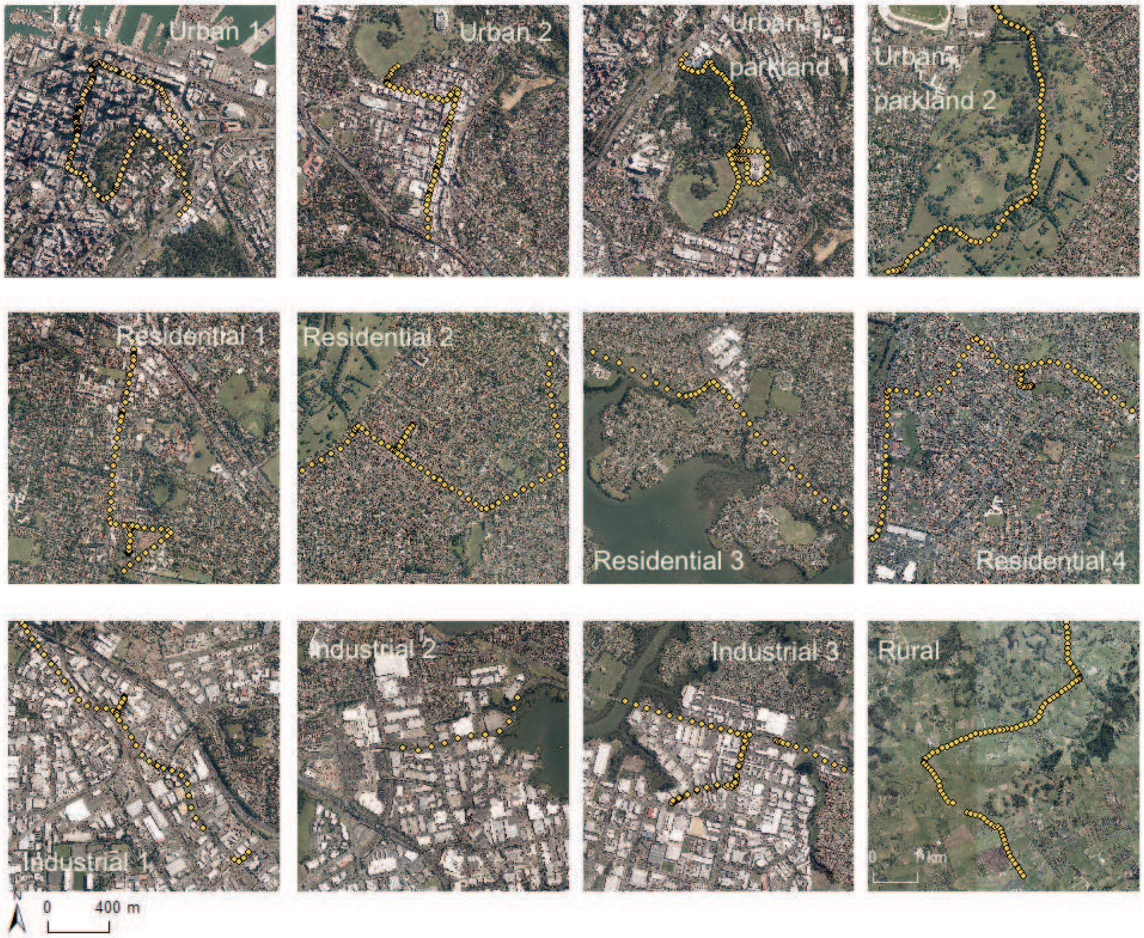

Figure1.b) 12 land use sections used for the statistical analysis (LINZ - Land Information New Zealand, 2013).

The WMA-4 gas analysers were calibrated before and after the study using two standard gases (standard 1, CO_2 = 392.82ppm, standard 2: CO_2 = 450.50ppm). The WMA-4 CO_2 gas analysers have an 'auto-zero' technology, which ensures long-term stability and accuracy (better than 1% of the span concentration (max. 450ppm) over the calibrated range). The Picarro carbon isotope analyser was calibrated using the same two standard gases. While it is generally recommended to calibrate the Picarro isotope analyser at least every 10h (Vogel et al., 2013), this was not possible for our setup. The weekly CO_2 drift was on average 1ppm. A comparison of the CO_2 analysers and the carbon isotope analyser was run from January 21 – January 22, 2015. The readings agreed well with an $R^2 >$ 0.9 and were comparable within 1 – 2ppm.

In addition, we measured wind speed and direction using a sonic anemometer (Windmaster, Gill Instruments Limited, Hampshire, UK) at Botany Downs. No wind data was collected at Ardmore and at the University of Auckland. Thus, wind speed and direction for Ardmore and Botany Downs is based on measurements taken at an air quality station 10km NW from Ardmore (Wiri) and 2km south of the University of Auckland (Khyber pass), respectively (Auckland Council, air quality monitoring programme, unpublished data). Wind directions were predominantly from the west at the CBD and the rural station, while south-westerlies dominated at the residential site (Fig. 2).

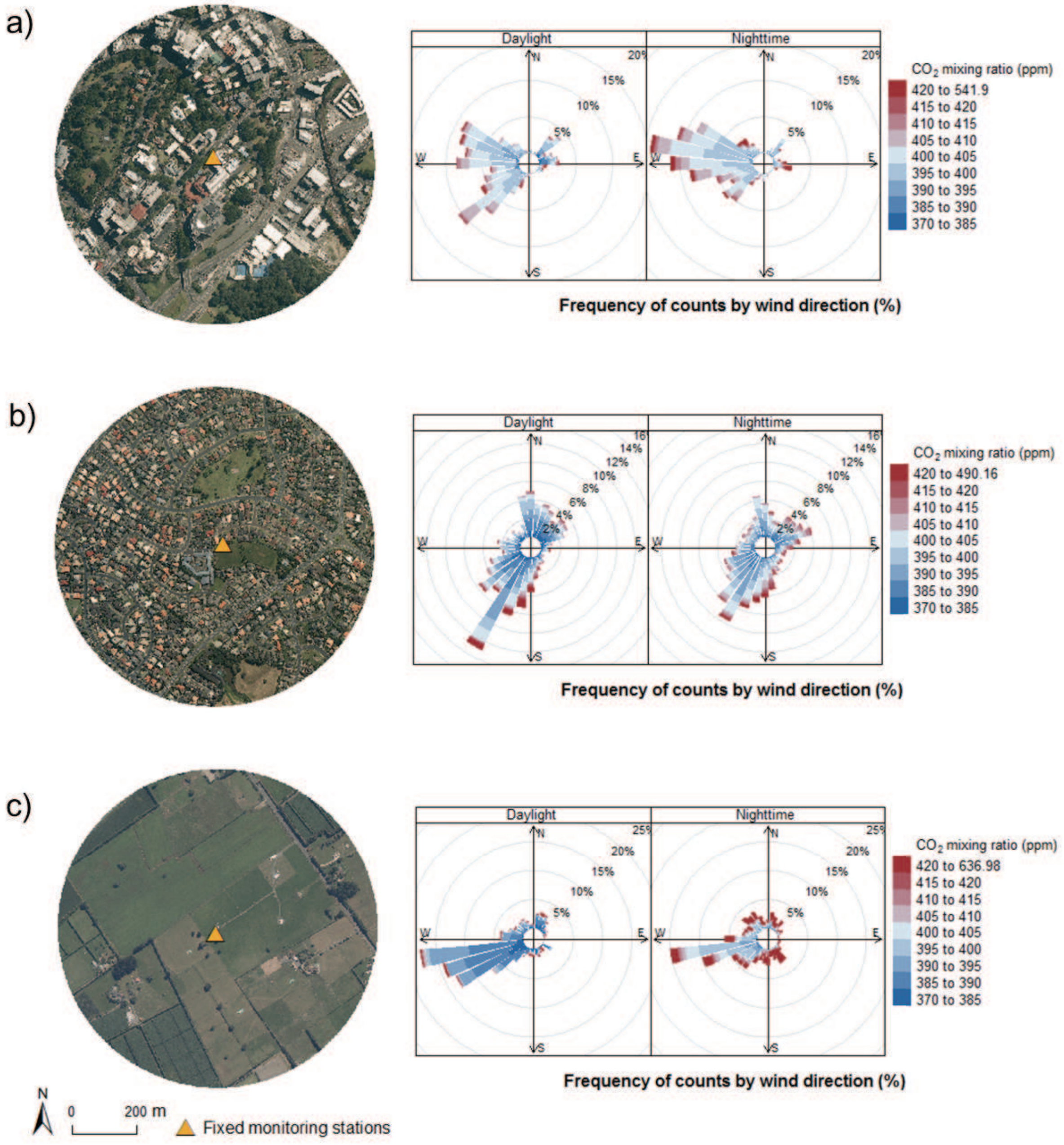

Figure 2. Aerial photos of area surrounding the fixed monitoring stations within a 500m radius of daytime and nighttime CO_2 mixing ratios by wind directions (a) CBD, b) residential area (Botany Downs), c) rural area (Ardmore).

2.3 Mobile monitoring of near-surface CO_2 mixing ratios

Mobile measurements were used to measure near-surface (height: 1.8m) CO_2 mixing ratios. The study was undertaken along a transect route, extending about 50km in a south-easterly direction from Auckland's Central Business District (CBD) through residential neighbourhoods into the Auckland rural area (Fig. 1a/b). The transect route covered five typical land use types in urban areas (urban, industrial, residential, urban parkland and rural). Major highways were avoided to reduce skewed measurements caused by heavy vehicular traffic.

The transect route was driven a total of nine times between September and October 2014. Three measurement campaigns were conducted during the day (11:00 - 15:00 New Zealand Standard Time, NZST), three at night (22:00 - 01:00 NZST) and three in the morning (06:30 - 09:00 NZST). These times were chosen because they reflect times of key differences in CO_2 mixing ratios based on traffic and biogenic respiration patterns (Soegaard and Moller-Jensen, 2003). The measurement campaigns were conducted during similar meteorological conditions (low wind speeds, clear skies) (Henninger and Kuttler, 2010) (Table 1). Temperatures ranged between 13.7°C and 18.9°C during daytime and from 9.6°C to 13.1°C during nighttime measurements and wind was dominated by south-westerlies (Table 1).

Transect Nr.	Time	Temperature (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Wind direction
Transect 1	Afternoon	15.6 (0.7)	64.4 (4.2)	2.5 (0.9)	SW
Transect 2	Afternoon	17.5 (0.7)	58.4 (3.1)	2.3 (0.9)	W
Transect 3	Afternoon	18.9 (1.2)	59.9 (5.8)	1.7 (0.8)	SW
Transect 1	Morning	13.7 (0.8)	71.4 (2.8)	na[1)]	na
Transect 2	Morning	12.3 (0.4)	84.0 (3.8)	na	na
Transect 3	Morning	15.5 (0.5)	76.1 (2.8)	na	na
Transect 1	Night	9.6 (1.7)	89.2 (5.0)	0.3 (0.6)	SE
Transect 2	Night	11.8 (0.4)	87.8 (3.8)	0.9 (0.7)	SW
Transect 3	Night	13.1 (1.7)	90.5 (5.5)	0.5 (0.5)	SW

[1)] na = data not available

Table 1. Mean meteorological parameters measured along the transect during different times of the day. Values in brackets are standard deviations (temperature and relative humidity were measured continuously along the transect, wind speed and wind direction were only measured at the nine stations along the transect route during the afternoon and night transect).

While driving, CO_2 mixing ratios were continuously measured at a 1.6s interval using a WMA-4 CO_2 analyser (WMA-4, PP Systems Inc., Amesbury, MA, US) and recorded on a laptop (Dell Latitude E6440). Outside air was drawn into the analyser through a flexible polyethylene tube that exited the rear passenger window and that was fixed onto the roof of the vehicle at a height of 1.8m above the ground. An i-Button sensor (Maxime Integrated, San Jose, CA, US), mounted in a radiation shield on the roof of the vehicle, and a global positioning system (GPS) device were also used during each transect campaign to measure humidity and temperature (4s interval) continuously and to record geographical location data (1s interval). Measurements were taken from the left-hand side of the vehicle to minimize the effect of exhaust from passing vehicles on the measurements. To further ensure the accuracy of the measurements, the vehicle was kept at a distance of at least two meters from other vehicles (Henninger and Kuttler, 2010). Any unpredicted detours, long stops or excessive exposure to exhausts were noted and removed from the data.

In addition to the mobile measurements, we measured wind speed and wind direction at nine locations along the transect route using a Kestrel weather sensor (Kestrel 4000, Kestrel-Meters.com, Birmingham, US). Due to the need to keep the duration of the transect the same between sampling periods and the increased traffic density during the morning rush hour, we did not stop during the morning transects.

2.4 Data analysis

Outputs from fixed monitoring stations were averaged at 10min intervals. Due to the larger temporal variability of the mobile measurements, the mobile data was averaged at 5s intervals for the data analysis. To minimize the impact of sporadic exhaust plumes the mean and standard deviation was calculated separately for each land use and values exceeding the mean plus three standard deviations were removed (Brantley et al., 2014).

Land use	Distance to the CBD	Number of lanes	Traffic density (vehicles day^{-1})	Vegetation cover (%)	Travel speed (m s^{-1})	Spikes removed (%)
Urban 1	1	2	7,338	23	22	5.5
Urban parkland 1	2	2	8,356	63	19	2.3
Urban 2	3	4	14,433	12	24	0.9
Residential 1	5	4	11,578	21	32	2.0
Urban parkland 2	8	2	na	82	25	1.1
Residential 2	10	2	798	51	31	0.6
Industrial 1	10	4	10,237	23	35	1.3
Residential 3	11	4	10,847	43	49	5.8
Industrial 2	11	6	55,566	36	47	4.4
Industrial 3	12	6	10,847	20	35	1.7
Residential 4	12	2	3,001	45	32	1.2
Rural	22	2	2,576	90	54	1.1

Table 2. Distance to the CBD, dominating number of lanes, mean weekday daily traffic density (Auckland Transport 2015), vegetation cover within 200m of the road, mean travel speed and the percentage of spikes that were removed at the 12 sections along the transect route.

Calculating spikes separately for each land use was used to account for differences in the CO_2 mixing ratio due to the variability of CO_2 sources and sinks at different land uses. Between 0.63% (residential 2) and 5.75% (residential 3) of data was removed following the spike removal procedure

(Table 2). Spikes were more common in areas with high traffic (ρ = 0.71, p = 0.015). Further, we removed periods where the vehicle speed was below 5km h^{-1} (Crawford and Christen 2014). Spikes from the fixed monitoring stations were determined visually to remove physically implausible CO_2 mixing ratios due to instrument malfunction and maintenance. In addition, we used summary statistics that are less affected by outliers (median, IQR). Given the uncertainties and difficulties in determining the background trend in CO_2 and temperature, the CO_2 data and temperature data was not detrended.

For the statistical analysis, the transect route was divided into 12 sections representing the five dominant land uses. The sections include urban (urban 1 and urban 2), industrial (industrial 1, industrial 2, industrial 3), residential (residential 1, residential 2, residential 3, residential 4), urban parkland (urban parkland 1, urban parkland 2) and rural (Fig. 1b, Table 2). For each of the 12 land use sections (Fig. 1b) we estimated the vegetation cover within a 200m distance of the road based on a multispectral image classification using ArcGIS (v.10.2.2). This distance was chosen based on the typical measurement height:fetch ratio of 1:100 expected in urban areas (Oke, 2006). In addition, we compared CO_2 mixing ratios along the transect route with traffic count data (daily weekday averaged) provided by Auckland transport (Auckland Transport, 2015). If traffic data was not available for a road section we chose traffic density monitored at a close-by, representative road.

Spearman rank (ρ) correlation tests were undertaken to examine the relationship between CO_2 mixing ratios along the transect route and vegetation cover, travel speed, distance to the CBD and wind characteristics. A Kruskal-Wallis test and a post hoc test after Nemenyi was undertaken to assess differences between land uses (urban, industrial, residential, urban parkland and rural) and time (morning, afternoon, nighttime).

We also compared mobile measurements with fixed measurements. For the mobile data we used 10min averaged CO_2 mixing ratios measured in the transect section representative of urban 1 (n = 26), residential 4 (n = 18) and rural (n = 31) (Fig. 1b). For the fixed stations we used 10min averaged data matching the time periods from the mobile measurements (CBD: n = 17, residential: n = 14, rural: n = 31). A Mann Whitney Wilcoxon test (U) was used to test for significant differences between the mobile and fixed measurements. All results are reported in local standard time (NZST, including daylight saving) on a 24-hour period.

3. Results and Discussion

3.1 Temporal variability of CO_2 mixing ratios at the three fixed monitoring stations

Diurnal CO_2 mixing ratios were analysed separately for weekend and weekdays (Fig. 3). On weekdays, CO_2 mixing ratios in the CBD and in the residential area followed a similar diurnal cycle reaching a maximum in the morning (08:00) and a minimum in the afternoon (15:00). This pattern has also been observed in other cities (e.g. Rome, Italy (Gratani and Varone, 2005); Basel, Switzerland (Vogt et al., 2006); Melbourne, Australia (Coutts et al., 2007); Portland, US (Rice and Bostrom, 2011); Boston, US (Briber et al., 2013)) and reflects the diurnal variability of CO_2 sources and sinks and boundary layer depth. Although our results are limited to spring, measurements elsewhere have shown similar diurnal patterns. However, seasonal differences in the magnitude of maximum and minimum diurnal CO_2 mixing ratios were observed in Rome, Italy (Gratani and Varone, 2005), Valladolid, Spain

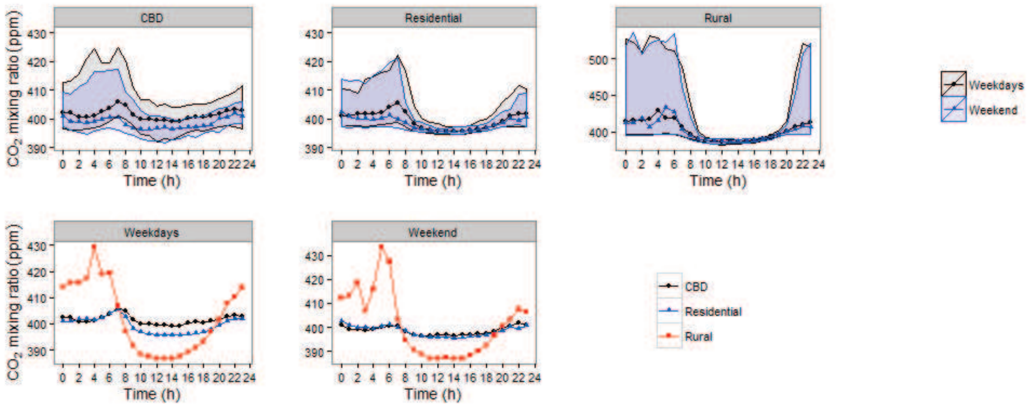

Figure 3. Median weekday and weekend diurnal CO_2 mixing ratios measured at the three fixed monitoring stations (CBD; residential (Botany Downs); rural (Ardmore)). The shaded area represents the interquartile range. Due to the large interquartile range at the rural site a different scale was used for the rural site. For better comparison the median weekday and weekend diurnal cycle of all three sites is plotted in a figure in the bottom panel.

(Angeles Garcia et al., 2012) or Boston, US (Briber et al., 2013). Values during winter were generally higher as a result of heating-related emissions, increased vehicular traffic and reduced photosynthetic CO_2 uptake (Gratani and Varone, 2005; Angeles Garcia et al., 2012; Briber et al., 2013). A shallower boundary layer during winter may have also contributed to higher CO_2 mixing ratios, however, this was not mentioned in these studies. Thus, the diurnal pattern we observed during spring in Auckland may change with season, however, due to the large proportion of evergreen vegetation resulting in CO_2 uptake across all seasons (Weissert et al., under review), we expect differences to be smaller compared to values obtained in cities in the northern hemisphere with a colder climate and mostly deciduous trees.

The diurnal pattern at the rural site differed from the CBD and residential area (Fig. 3). CO_2 mixing ratios peaked at night with values exceeding 440ppm between 01:00 and 07:00. A maximum was reached at 05:00. In the afternoon, rural CO_2 mixing ratios were below CO_2 mixing ratios recorded at the residential site and the CBD and the minimum was reached earlier at 13:00, likely due to stronger photosynthetic CO_2 uptake. A notable feature of the diurnal cycle in the rural area is the large variability at nighttime (Fig. 3). Nighttime CO_2 mixing ratios in the rural area were negatively correlated to air temperature and wind speed ($\rho = -0.31$, $p < 0.001$ and $\rho = -0.53$, $p < 0.001$, respectively). Low wind velocities and temperatures can increase atmospheric stability at night, limiting the horizontal and vertical dispersion of CO_2 (Büns and Kuttler, 2012). This effect is clearly evident when comparing rural nighttime CO_2 mixing ratios between calm and windy nights (mean wind speed: 1.9m s^{-1} and 5m s^{-1}, respectively) (Fig. 4). In fact, it shows that the rural diurnal cycle is comparable to the residential and urban cycle during windy conditions, when CO_2 from biogenic respiration is well dispersed. The weekend diurnal cycle followed a similar pattern as the

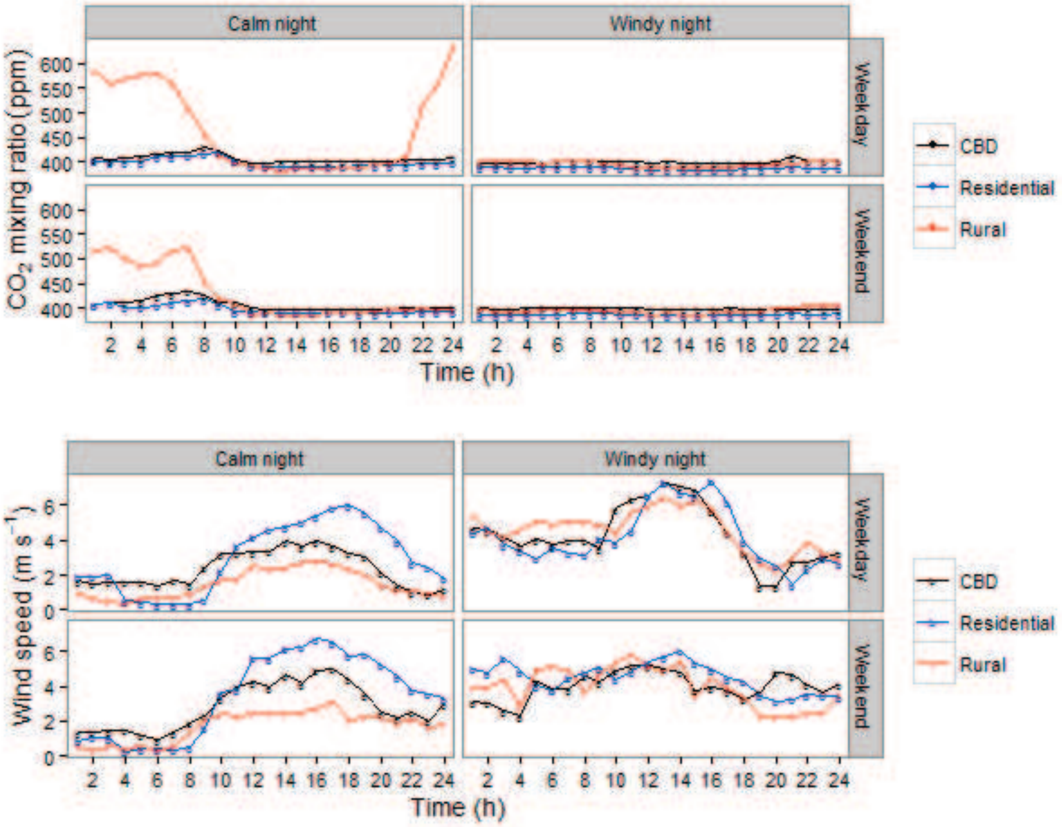

Figure 4. Comparison between the diurnal pattern of CO_2 mixing ratios measured during calm and windy nighttime conditions at the three fixed monitoring stations.

weekday cycle, peaking in the morning and reaching a minimum in the afternoon (Fig. 3). However, the magnitude of the peak and the minimum was considerably lower in the CBD during weekends compared to weekdays (Fig. 3). Apart from the morning peak, which was higher during weekdays, the residential CO_2 mixing ratio showed little weekend-weekday difference. In the rural area, the weekday diurnal cycle is comparable to the weekend diurnal cycle (Fig. 3). The larger magnitude of the weekend reduction in the CBD compared to the residential and rural area, is likely due to higher weekday traffic density in the urban area (Coutts et al., 2007; Bergeron and Strachan, 2011; Crawford et al., 2011; Ward et al., 2015). While vehicle related CO_2 emissions are a relevant source of CO_2 at all times in the urban area, they are likely limited to the morning rush hour at the residential site (Fig. 3). A similar trend was reported by Idso et al., (2001), who observed large weekday-weekend differences in the urban area, but no weekday-weekend differences in the residential and rural areas.

Daily averaged CO_2 mixing ratios measured in the CBD were above values observed in the residential and rural site, which would suggest the presence of a CO_2 dome. However, differences were small (2ppm and 3ppm, respectively) (Fig. 3) and at nighttime, CO_2 mixing ratios reached a maximum in the rural area (434ppm), with similar means observed in the residential area (403ppm) and the CBD (405ppm). During the measurement period, the prevailing winds at the monitoring station located in the CBD resulted in the advection of air from a park and a major two-lane road throughout most of the experiment. Similarly, CO_2 mixing ratios at the residential site were influenced by a major two-lane road, which may explain the small difference from the CBD during daytime. The rural site was downwind from pasture and a local airfield (Fig. 2).

Differences between the daily averaged CO_2 mixing ratios in the CBD, residential and rural CO_2 mixing ratios (2ppm and 3ppm, respectively) were within the same range (5ppm) measured in Portland, OR, US (Rice and Bostrom, 2011), but below observations from Baltimore, US (50ppm) (George et al., 2007) or Phoenix, US (100 - 200ppm) (Idso et al., 2002). Differences in traffic density and vegetation cover explain some of these sometimes large inter-urban differences. Unlike some other cities, Auckland's traffic is not linearly decreasing with distance to the CBD (Table 2). Local topography and associated wind patterns also play an important role in CO_2 mixing ratios observed in urban areas (Wang and Ostoja-Starzewski, 2004; Rice and Bostrom, 2011). Auckland is strongly influenced by coastal wind patterns and daytime conditions are rarely calm, so the opportunities for the local build-up of CO_2 are limited. In contrast, the strong CO_2 dome in Phoenix, US, for example, is partly due to the mountains surrounding the city, which favour the development of katabatic winds and inversions (Wang and Ostoja-Starzewski, 2004).

The diurnal weekday amplitude in Auckland's CBD (7ppm) and the residential area (10ppm) measured by the fixed monitoring stations are below observations from Portland, US (23 – 32ppm) (Rice and Bostrom, 2011) or Basel, Switzerland (61ppm) (Vogt et al., 2006), but compare to findings from Melbourne, Australia during summer (approx. 10ppm) (Coutts et al., 2007). Differences in the diurnal amplitude between cities can be attributed to local variability of CO_2 emissions (traffic, domestic heating), the strength of photosynthetic CO_2 uptake by vegetation and local meteorology (Briber et al., 2013).

Overall, the results from the fixed measurements do not provide any evidence of a strong CO_2 dome as observed in other cities, where CO_2 mixing ratios were shown to be highest in the urban centre at all times (Idso et al., 1998; Idso et al., 2001; Idso et al., 2002; Soegaard and Moller-Jensen, 2003; Gratani and Varone, 2005; Pataki et al., 2007).

3.2 Mobile measurements

CO_2 mixing ratios measured along the transect varied significantly between measurement times ($\chi 2(2) = 3449.70$, $p < 0.001$), reflecting the strong diurnal cycles observed at the fixed monitoring sites. Across all locations, the median CO_2 mixing ratios were highest at night (424ppm, IQR: 45), followed by the morning (423ppm, IQR: 36) and afternoon (396ppm, IQR: 15) (Fig. 5). We also found significant differences in the CO_2 mixing ratio among land uses ($\chi^2(4) = 522.26$, $p < 0.001$). CO_2 mixing ratios at night reached a maximum in the rural area with significantly ($p < 0.01$) higher CO_2 mixing ratios than urban and industrial areas (Fig. 5). Biogenic respiration and low wind speed (Table 1, section 3.1) likely explain the high nighttime CO_2 mixing ratios in the rural area (Henninger and Kuttler, 2010). During the morning, CO_2 mixing ratios were significantly ($p < 0.01$) higher in the industrial area compared to other land uses (Fig. 5). The industrial road section has six lanes and traffic density is high (Table 2). A comparison of CO_2 mixing ratios measured across land uses revealed significantly ($p < 0.05$) higher CO_2 mixing ratios in the urban and industrial area in the afternoon, with highest values observed in the CBD (urban 1) (Fig. 5). Higher CO_2 mixing ratios in the CBD were likely due to a combination of low travel speed (Table 2), resulting in longer time spent in

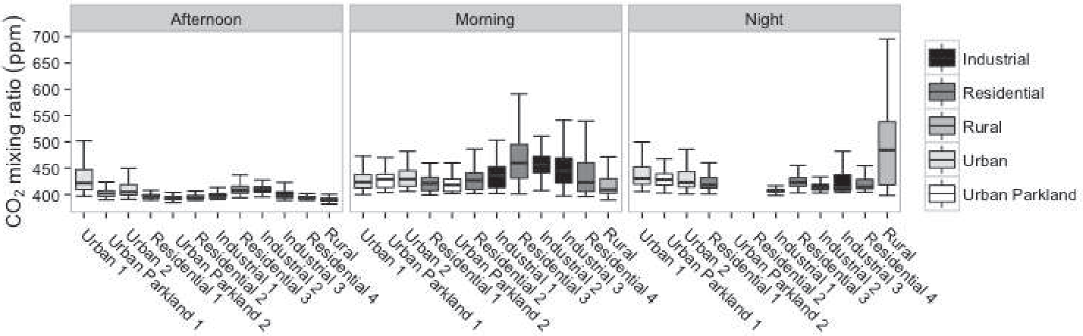

*Figure 5. CO_2 mixing ratio measured during different times and runs at different land uses along the transect (the upper and lower hinges represent the 25th and 75th percentiles, the upper and lower whisker extend 1.5*inter-quartile range from the hinge). Due to the nighttime closure of Urban Parkland 2 the transect route slightly differed at night and no results are available for urban Parkland 2 and Residential 2.*

queuing traffic and reduced turbulence from passing vehicles, less vegetation and the presence of tall buildings along the road, which limit vertical mixing of CO_2 emissions (Gratani and Varone, 2005; Salmond et al., 2010; Lietzke and Vogt, 2013).

No significant correlations were found between CO_2 mixing ratios and vegetation cover, travel speed or distance to the CBD (Fig. 6). However, there was a tendency for highly vegetated areas to have increased CO_2 mixing ratios at nighttime ($\rho = 0.42$, $p > 0.05$) and lower CO_2 mixing ratios during the afternoon ($\rho = -0.53$, $p > 0.05$), as a result of biogenic CO_2 emissions and uptake, respectively. Distance to the CBD had no influence during the morning or at nighttime, but a slight decrease in CO_2 mixing ratios with distance from the CBD was observed during the afternoon ($\rho = -0.49$, $p > 0.05$).

These results agree with observations from the fixed measurements, providing no evidence of a strong CO_2 dome. In Auckland, land use does not change linearly with distance to CBD, as it is the case for Phoenix, US, where a strong CO_2 dome was observed (Idso et al., 2002; Wentz et al., 2002). Thus, CO_2 mixing ratios in Auckland are dependent on land use and the diurnal variability of control factors (i.e. traffic and biogenic emissions and uptake). A strong correlation between near-surface CO_2 mixing ratios and land use was also reported by Henninger and Kuttler (2010) conducting mobile measurements in Essen, Germany.

These results show that a few mobile measurements undertaken across different land uses and times allow assessing the spatial and temporal variability of near-surface CO_2 mixing ratios and factors that drive variability. In particular, they provide detailed information about the spatial variability of CO_2 mixing ratios, which cannot be detected by one or two fixed measurement stations. Nevertheless, mobile measurements have some limitations that need to be acknowledged. Mobile measurements are sensitive to local CO_2 sources and are therefore limited by the high spatial and temporal variability of local CO_2 emissions (mainly traffic). To minimise uncertainty and increase representativeness, a larger set of transect runs, in particular during different seasons, would be required (Henninger and Kuttler, 2010; Van den Bossche et al., 2015). Also, since we chose calm and clear days for our mobile measurements it would be interesting to conduct mobile measurements during windy weather situations for comparison (Henninger and Kuttler, 2010). In addition, the background variability of temperature and CO_2

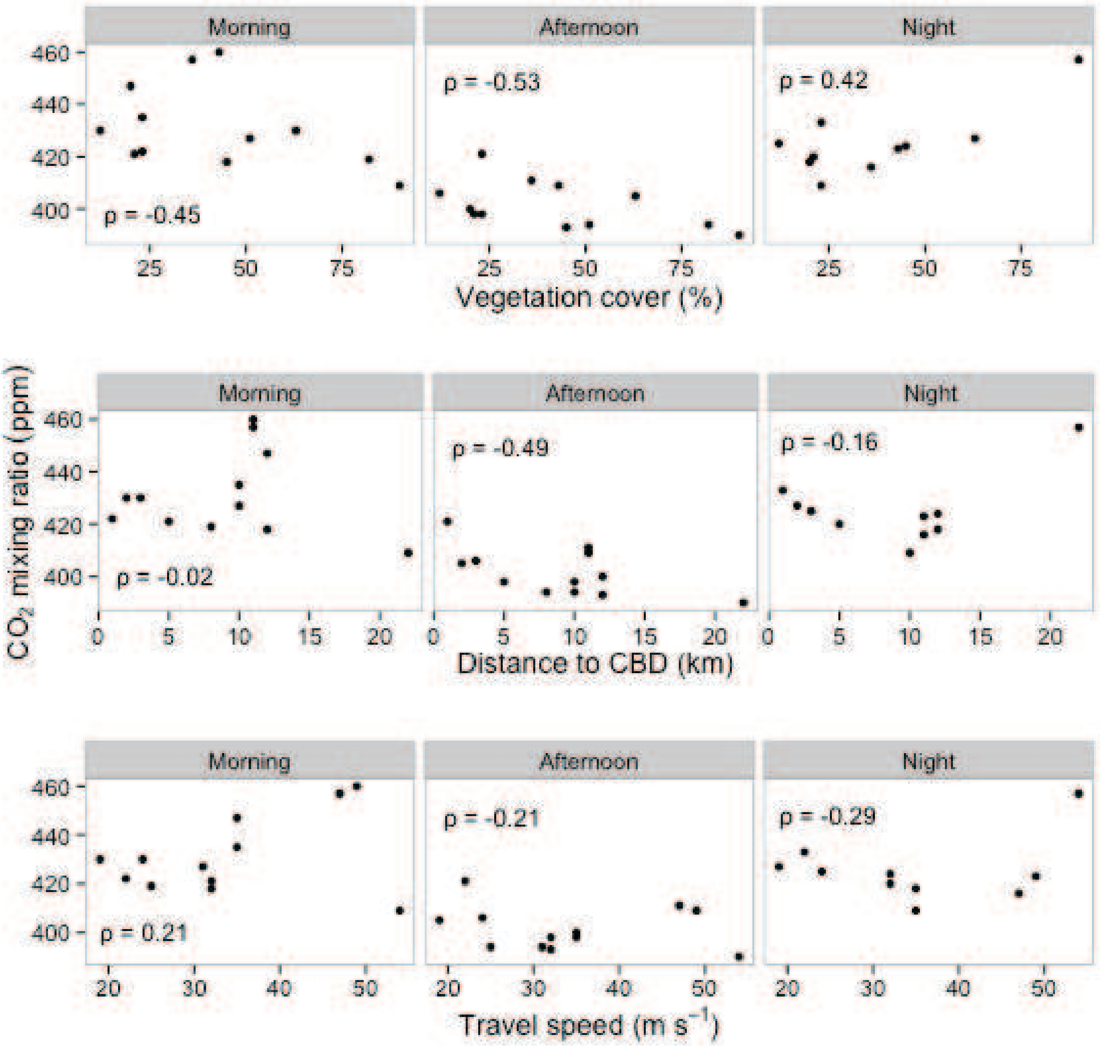

Figure 6. Correlations between CO_2 mixing ratios and vegetation cover, distance to the CBD and travel speed (ρ is the spearman's rank correlation coefficient, no correlations were significant, p > 0.05).

mixing ratios was not accounted for. However, we chose periods when background CO_2 changed little to minimise a bias introduced by changing background CO_2.

3.3 Comparison between mobile and fixed CO_2 measurements

The mobile and fixed measurements both demonstrated significant spatial differences in CO_2 mixing ratios between the three sites. However, median near-surface CO_2 mixing ratios from mobile measurements were higher than the CO_2 mixing ratios measured at the fixed stations, by 5% in the CBD (U = 28, n = 43, $p < 0.001$) and by 2% in the residential area ($p > 0.05$) (Fig. 7). Mobile and fixed measurements yielded the same results in the rural area. Differences in the location and height of the mobile and fixed measurements likely explain these variations. While fixed CO_2 measurements were taken approx. 1.5 – 3 times above the urban canopy layer (= thickness of the average height of the main roughness elements (Oke, 2006)) and provide a blended average of local urban CO_2 emissions and uptake, mobile near-surface CO_2 mixing ratios are closer to the CO_2 sources (mainly traffic), which explains the higher values (Crawford and Christen, 2014; Van den Bossche et al., 2015). This is particularly evident in the CBD (urban 1), where near-surface CO_2

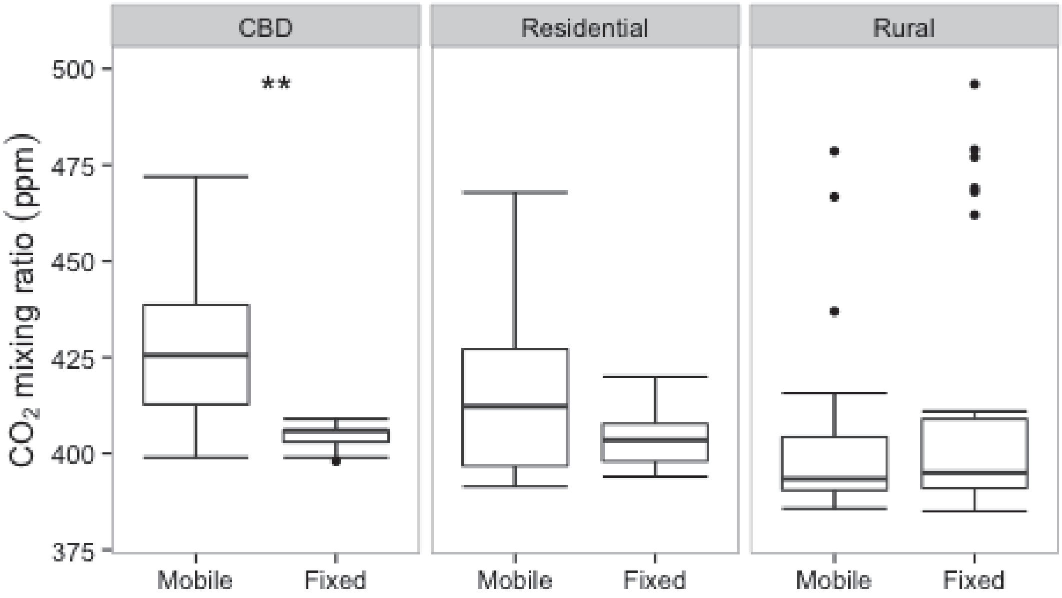

*Figure 7. Comparison between mobile measurements in the surroundings of the fixed monitoring stations (urban 1, residential 4, rural) and the data obtained at the three fixed monitoring sites (CBD, residential, rural) (the upper and lower hinges represent the 25th and 75th percentiles, the upper and lower whisker extend 1.5*inter-quartile range from the hinge, dots correspond to outliers, ** ($p < 0.01$) indicate a significant difference between the mobile and the fixed measurements).*

mixing ratios are influenced by low travel speed and tall buildings, which limit vertical and horizontal mixing of CO_2 emissions and therefore result in occasionally high CO_2 mixing ratios. The height difference between the mobile and fixed measurements was highest in the CBD and decreased towards the rural area, which may partly explain the larger gap observed in the CBD.

4. Conclusion

A comparison between the fixed stations located in the CBD, a residential and a rural area showed the typical pattern observed in other cities with highest daytime CO_2 mixing ratios in the CBD, which is often interpreted as an urban CO_2 dome. However, nighttime measurements and our results from the mobile measurements along a transect route have shown that spatial variability of CO_2 mixing ratios was strongly dependent on land use, meteorological conditions and time of the day. Thus, we cannot simply call it an urban CO_2 dome and measurements from one to two fixed stations in an urban area could be misleading.

As urban areas and CO_2 emissions continue to grow, it is important to improve urban CO_2 monitoring networks combining fixed with mobile measurements. Although, a limited number of mobile measurements may not be representative for a whole urban area, they provide an insight into the influence of vegetation and the spatio-temporal variability of local CO_2 sources and sinks. Such information could help develop low carbon action plans by identifying areas for green infrastructure aiming to mitigate urban CO_2 emissions. Further, due to the high nighttime CO_2 mixing ratios observed in highly vegetated areas, it is important to assess the contribution of biogenic as well as anthropogenic CO_2 sources.

References

Angeles Garcia, M., Luisa Sanchez, M. and Perez, I. A. 2012. Differences between carbon dioxide levels over suburban and rural sites in Northern Spain. *Environmental Science and Pollution Research*, **19**, 432-439. doi:10.1007/s11356-011-0575-4.

Auckland Transport 2015. *Traffic count data from 2008 - February 2015*. Retrieved 20 November 2015, from https://at.govt.nz/about-us/reports-publications/traffic-counts/.

Balling, R. C., Cerveny, R. S. and Idso, C. D. 2001. Does the urban CO_2 dome of Phoenix, Arizona contribute to its heat island? *Geophysical Research Letters*, **28**, 4599-4601. doi: 10.1029/2000gl012632.

Bergeron, O. and Strachan, I. B. 2011. CO_2 sources and sinks in urban and suburban areas of a northern mid-latitude city. *Atmospheric Environment*, **45**, 1564-1573. doi: 10.1016/j.atmosenv.2010.12.043.

Brantley, H. L., Hagler, G. S. W., Kimbrough, E. S., Williams, R. W., Mukerjee, S., & Neas, L. M. 2014. Mobile air monitoring data-processing strategies and effects on spatial air pollution trends. *Atmospheric Measurement Techniques*, **7**, 2169-2183. doi:10.5194/amt-7-2169-2014.

Bréon, F. M., Broquet, G., Puygrenier, V., Chevallier, F., Xueref-Remy, I., Ramonet, M., . . . Ciais, P. 2015. An attempt at estimating Paris area CO_2 emissions from atmospheric concentration measurements. *Atmospheric Chemistry and Physics*, **15**, 1707-1724. doi:10.5194/acp-15-1707-2015.

Briber, B., Hutyra, L., Dunn, A., Raciti, S. and Munger, J. 2013. Variations in Atmospheric CO_2 Mixing Ratios across a Boston, MA Urban to Rural Gradient. *Land*, **2**, 304-327. doi: 10.3390/land2030304.

Büns, C. and Kuttler, W. 2012. Path-integrated measurements of carbon dioxide in the urban canopy layer. *Atmospheric Environment*, **46**, 237-247. doi:10.1016/j.atmosenv.2011.09.077.

Carreiro, M. M., & Tripler, C. E. 2005. Forest remnants along urban-rural gradients: examining their potential for global change research. *Ecosystems*, **8**, 568-582. doi:10.1007/s10021-003-0172-6.

Coutts, A. M., Beringer, J. and Tapper, N. J. 2007. Characteristics influencing the variability of urban CO_2 fluxes in Melbourne, Australia. *Atmospheric Environment*, **41**, 51-62. doi: 10.1016/j.atmosenv.2006.08.030.

Crawford, B., Grimmond, C. S. B. and Christen, A. 2011. Five years of carbon dioxide fluxes measurements in a highly vegetated suburban area. *Atmospheric Environment*, **45**, 896-905. doi: 10.1016/j.atmosenv.2010.11.017.

Crawford, B. and Christen, A. 2014. Spatial variability of carbon dioxide in the urban canopy layer and implications for flux measurements. *Atmospheric Environment*, **98**, 308-322. doi: 10.1016/j.atmosenv.2014.08.052.

Dahlkoetter, F., Griessbaum, F., Schmidt, A. and Klemm, O. 2010. Direct measurement of CO_2 and particle emissions from an urban area. *Meteorologische Zeitschrift*, **19**, 565-575. doi: 10.1127/0941-2948/2010/0492.

Font, A., Grimmond, C. S., Morgui, J.-A., Kotthaus, S., Priestman, M. and Barratt, B. 2013. Cross-validation of inferred daytime airborne CO_2 urban-regional scale surface fluxes with eddy-covariance observations and emissions inventories in Greater London.

Atmospheric Chemistry and Physics, **13**, 13465 - 13493. doi:10.5194/acpd-13-13465-2013.

George, K., Ziska, L. H., Bunce, J. A. and Quebedeaux, B. 2007. Elevated atmospheric CO_2 concentration and temperature across an urban-rural transect. *Atmospheric Environment*, **41**, 7654-7665. doi:10.1016/j.atmosenv.2007.08.018.

Gratani, L. and Varone, L. 2005. Daily and seasonal variation of CO_2 in the city of Rome in relationship with the traffic volume. *Atmospheric Environment*, **39**, 2619-2624. doi: 10.1016/j.atmosenv.2005.01.013.

Grimmond, C. S. B., King, T. S., Cropley, F. D., Nowak, D. J. and Souch, C. 2002. Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago. *Environmental Pollution*, **116**, S243-S254. doi: 10.1016/s0269-7491(01)00256-1.

Grimmond, C. S. B., Salmond, J. A., Oke, T. R., Offerle, B. and Lemonsu, A. 2004. Flux and turbulence measurements at a densely built-up site in Marseille: Heat, mass (water and carbon dioxide), and momentum. *Journal of Geophysical Research-Atmospheres*, **109**, Issue D24. doi: D2410110.1029/2004jd004936.

Guerney, K. R., Mendoza, D., Zhou, Y., Fischer, M. L., Miller, C. C., Geethakumar, S. and De la Rue du Can, S. 2009. High Resolution Fossil Fuel Combustion CO_2 emission fluxes for the United States. *Environmentmal Science and Technology*, **43**, 5535 - 5541. doi: doi:10.1021/es900806c.

Henninger, S. and Kuttler, W. 2007. Methodology for mobile measurements of carbon dioxide within the urban canopy layer. *Climate Research*, **34**, 161-167. doi:10.3354/cr034161.

Henninger, S. and Kuttler, W. 2010. Near surface carbon dioxide within the urban area of Essen, Germany. *Physics and Chemistry of the Earth*, **35**, 76-84. doi:10.1016/j.pce.2010.03.006.

Henninger, S. 2011. 'A mobile measuring methodology to determine near surface carbon dioxide within urban areas'. In: *Air quality-models and applications* (ed. Popovic, D.). InTech, 173 - 194.

Idso, C. D., Idso, S. B. and Balling, R. C. 1998. The urban CO_2 dome of Phoenix, Arizona. *Physical Geography*, **19**, 95-108. doi:10.1080/02723646.1998.10642642.

Idso, C. D., Idso, S. B., & Balling, R. C. 1999. The relationship between near-surface air temperature over land and the annual amplitude of the atmosphere's seasonal CO_2 cycle. *Environmental and Experimental Botany*, **41**, 31 - 37. doi:10.1016/S0098-8472(98)00047-1.

Idso, C. D., Idso, S. B. and Balling, R. C. 2001. An intensive two-week study of an urban CO_2 dome in Phoenix, Arizona, USA. *Atmospheric Environment*, **35**, 995-1000. doi: 10.1016/s1352-2310(00)00412-x.

Idso, S. B., Idso, C. D. and Balling, R. C. 2002. Seasonal and diurnal variations of near-surface atmospheric CO_2 concentration within a residential sector of the urban CO_2 dome of Phoenix, AZ, USA. *Atmospheric Environment*, **36**, 1655-1660. doi:Pii s1352-2310(02)00159-010.1016/s1352-2310(02)00159-0.

Kuhlbusch, T. A. J., Quincey, P., Fuller, G. W., Kelly, F., Mudway, I., M. Viana, X. Querol, A. Alastuey, K. Katsouyanni, E. Weijers, A. Borowiak, R. Gehrig, C. Hueglin, P. Bruckmann, O. Favez, J. Sciare, B. Hoffmann, K. EspenYttri, K. Torseth, U. Sager, C. Asbach, U. Quass. 2014. New Directions: The future of European urban air quality monitoring. *Atmospheric Environment*, **87**, 258-260. doi: 10.1016/j.atmosenv.2014.01.012.

Lietzke, B. and Vogt, R. 2013. Variability of CO_2 concentrations and fluxes in and above an urban street canyon. *Atmospheric Environment*, **74**, 60-72. doi:10.1016/j.atmosenv.2013.03.030.

LINZ - Land Information New Zealand 2013. *Auckland 0.5 m Rural Aerial Photos (2010 - 2012).* LINZ / National Imagery.

Mackintosh, L. 2001. *Overview of New Zealand Climate*. NIWA, Education and training. Retrieved 18 July, 2013, from http://www.niwa.co.nz/education-and-training/schools/resources/climate/overview.

Mays, K. L., Shepson, P. B., Stirm, B. H., Karion, A., Sweeney, C., & Gurney, K. R. 2009. Aircraft-Based Measurements of the Carbon Footprint of Indianapolis. *Environmental Science & Technology*, **43**, 7816 - 7823. doi:10.1021/es901326b.

Miskell, G., Salmond, J., Longley, I., & Dirks, K. N. 2015. A Novel Approach in Quantifying the Effect of Urban Design Features on Local-Scale Air Pollution in Central Urban Areas. *Environmentmal Science and Technology*, **49**, 9004-9011. doi:10.1021/acs.est.5b00476.

Moore, J. and Jacobson, A. D. 2015. Seasonally varying contributions to urban CO_2 in the Chicago, Illinois, USA region: Insights from a high-resolution CO_2 concentration and $\delta^{13}C$ record. *Elementa: Science of the Anthropocene*, **3**, 000052. doi: 10.12952/journal.elementa.000052.

Nasrallah, H. A., Balling, R. C., Madi, S. M. and Al-Ansari, L. 2003. Temporal variations in atmospheric CO_2 concentrations in Kuwait City, Kuwait with comparisons to Phoenix, Arizona, USA. *Environmental Pollution,* **121**, 301-305. doi: Pii s0269-7491(02)00221-x10.1016/s0269-7491(02)00221-x.

NIWA 2013. *Climate data and activities*. Retrieved 28 November, 2015, from https://http://www.niwa.co.nz/education-and-training/schools/resources/climate.

Oke, T. R. 2006. *Initial guidance to obtain representative meteorological observations at urban sites.* Instruments and Observing Methods (IOM), World Meteorological Organization (WMO) / TD. No. 1250; IOM 81. 51pp, Geneva, Switzerland.

Pataki, D. E., Alig, R. J., Fung, A. S., Golubiewski, N. E., Kennedy, C. A., McPherson, E. G., Nowak, D. J., Pouyat, R. V. and Romero Lankao, P. 2006. Urban ecosystems and the North American carbon cycle. Global Change Biology, 12, 2092-2102. doi: 10.1111/j.1365-2486.2006.01242.x.

Pataki, D. E., Xu, T., Luo, Y. Q. and Ehleringer, J. R. 2007. Inferring biogenic and anthropogenic carbon dioxide sources across an urban to rural gradient. *Oecologia*, **152**, 307-322. doi: 10.1007/s00442-006-0656-0.

Pataki, D. E., Carreiro, M. M., Cherrier, J., Grulke, N. E., Jennings, V., Pincetl, S., Pouyat, R. V., Whitlow, T. H. and Zipperer, W. C. 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, **9**, 27-36. doi: 10.1890/090220.

Peters, E. B. and McFadden, J. P. 2012. Continuous measurements of net CO_2 exchange by vegetation and soils in a suburban landscape. *Journal of Geophysical Research-Biogeosciences*, **117**, 1-16. doi: 10.1029/2011jg001933.

Pincetl, S., Gillespie, T., Pataki, D. E., Saatchi, S. and Saphores, J.-D. 2012. Urban tree planting programs, function or fashion? Los Angeles and urban tree planting campaigns. *GeoJournal*, **78**, 475-493. doi: 10.1007/s10708-012-9446-x.

Reid, K. H. and Steyn, D. G. 1997. Diurnal variations of boundary-layer carbon dioxide in a coastal city - Observations and comparison with model results. *Atmospheric Environment*, **31**, 3101-3114. doi: 10.1016/s1352-2310(97)00050-2.

Rice, A. and Bostrom, G. 2011. Measurements of carbon dioxide in an Oregon metropolitan region. *Atmospheric Environment*, **45**, 1138-1144. doi:10.1016/j.atmosenv.2010.11.026.

Rosenzweig, C., Solecki, W., Hammer, S. A., & Mehrotra, S. 2010. Cities lead the way in climate-change action. *Nature*, **467**, 909 - 911.

Salmond, J. A., Pauscher, L., Pigeon, G., Masson, V. and Legain, D. 2010. Vertical transport of accumulation mode particles between two street canyons and the urban boundary layer. *Atmospheric Environment*, **44**, 5139-5147. doi:10.1016/j.atmosenv.2010.09.002.

Satterthwaite, D. 2008. Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environment and Urbanization*, **20**, 539-549. doi:10.1177/0956247808096127.

Soegaard, H. and Moller-Jensen, L. 2003. Towards a spatial CO_2 budget of a metropolitan region based on textural image classification and flux measurements. *Remote Sensing of Environment*, **87**, 283-294. doi:10.1016/s0034-4257(03)00185-8.

Turnbull, J. C., Karion, A., Fischer, M. L., Faloona, I., Guilderson, T., Lehman, S. J., Tans, P. P. 2011. Assessment of fossil fuel carbon dioxide and other anthropogenic trace gas emissions from airborne measurements over Sacramento, California in spring 2009. *Atmospheric Chemistry and Physics*, **11**, 705-721. doi:10.5194/acp-11-705-2011.

Van den Bossche, J., Peters, J., Verwaeren, J., Botteldooren, D., Theunis, J. and De Baets, B. 2015. Mobile monitoring for mapping spatial variation in urban air quality: Development and validation of a methodology based on an extensive dataset. *Atmospheric Environment*, **105**, 148-161. doi:10.1016/j.atmosenv.2015.01.017.

Velasco, E., Pressley, S., Grivicke, R., Allwine, E., Coons, T. et al. 2009. Eddy covariance flux measurements of pollutant gases in urban Mexico City. Atmospheric *Chemistry and Physics*, **9**, 7325-7342. doi: 10.5194/acp-9-7325-2009.

Velasco, E. and Roth, M. 2010. Cities as Net Sources of CO_2: Review of Atmospheric CO_2 Exchange in Urban Environments Measured by Eddy Covariance Technique. *Geography Compass*, **4**, 1238 - 1259. doi:10.1111/j.1749-8198.2010.00384.x.

Vogel, F. R., Huang, L., Ernst, D., Giroux, L., Racki, S., & Worthy, D. E. J. 2013. Evaluation of a cavity ring-down spectrometer for in situ observations of $^{13}CO_2$. *Atmospheric Measurement Techniques*, **6**, 301-308. doi:10.5194/amt-6-301-2013

Vogt, R., Christen, A., Rotach, M. W., Roth, M. and Satyanarayana, A. N. V. 2006. Temporal dynamics of CO_2 fluxes and profiles over a central European city. *Theoretical and Applied Climatology*, **84**, 117-126. doi: 10.1007/s00704-005-0149-9.

Wang, G. and Ostoja-Starzewski, M. 2004. Influence of topography on the Phoenix CO_2 dome: a computational study. *Atmospheric Science Letters*, **5**, 103-107. doi:10.1002/asl.67.

Ward, H. C., Kotthaus, S., Grimmond, C. S., Bjorkegren, A., Wilkinson, M. and co-authors 2015. Effects of urban density on carbon dioxide exchanges: Observations of dense urban, suburban and woodland areas of southern England. *Environmental Pollution*, **198**, 186-200. doi: 10.1016/j.envpol.2014.12.031.

Weissert, L. F., Salmond, J. and Schwendenmann, L. under review. Photosynthetic CO_2 uptake and carbon sequestration of deciduous and evergreen tree species grown in an urban environment. Urban Forestry & Urban Greening.

Wentz, E. A., Gober, P., Balling, R. C. and Day, T. A. 2002. Spatial patterns and determinants of winter atmospheric carbon dioxide concentrations in an urban environment. *Annals of the Association of American Geographers*, **92**, 15-28. doi: 10.1111/1467-8306.00277.

Submitted to *Weather and Climate Journal* August 2015, revised and accepted December 2015.