TEMPORAL AND SPATIAL PATTERNS OF NEAR-SURFACE CO_2 CONCENTRATIONS IN SINGAPORE

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SUMMARY

Continuous CO_2 concentrations have been monitored at various land-use types by means of (a) fixed stations, (b) short-term spatial sampling, and (c) car traverses using closed-path infrared gas analyzers to characterize and study the temporal and spatial patterns of near-surface CO_2 concentration in Singapore. The methodology is supplemented by intra-urban and -rural sampling which aims to investigate the spatial variability of CO_2 that may arise due to site-specific characteristics (e.g. geometry, vegetation density) within both land-use types. Relationship between CO_2 concentration and traffic, and other meteorological variables (e.g. wind speed and direction, rainfall) is sought and analyzed over diurnal, monthly and seasonal time scales with data presented in the form of 10-minute ensembles.

Analysis of the 8-month ensemble data shows a distinct diurnal pattern of CO_2 concentration at the rural site which exhibits a mean nighttime high (455 ppm) and daytime low (353 ppm) CO_2 concentrations with a mean diurnal amplitude of 103 ppm attributed to the daily photosynthetic-respiration cycle. The pattern is not repeated at the urban site which instead shows smaller mean diurnal amplitude (33 ppm) and two concentration peaks at 1230 hrs (404 ppm) and at 1900 hrs (413 ppm). Monthly variation of CO_2 concentration at both the urban and rural sites shows a downward trend since the start of the observation period. Seasonal analysis of concentration data shows higher values at both sites during the southwest monsoon. Spatial sampling at the various urban land-use types and intra-urban and -rural locations shows a larger variability in mean maximum but lower variability in mean minimum concentrations. Car traverses, which show higher midday CO_2 concentration in the city-centre (mean maximum: 420 ppm) compared to its surroundings, confirm the existence of an urban CO_2 dome in Singapore.

The results observed can be understood in terms of the extent of urbanization and associated anthropogenic activities (largely traffic), the amount of vegetation and the role of meteorological variables in modulating the magnitude of CO_2 concentration observed at the study sites. Results of the present study are consistent with most of the findings observed in mid-latitude cities.

KEYWORD(S):

Tropical city; CO_2 concentration; enhancement; urban climate.

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CHAPTER 1

– INTRODUCTION –

It has been widely recognized that carbon dioxide (CO_2) plays an increasingly important role in global climate change. Emphasis has been placed on CO_2 rather than other greenhouse gases because it forms the single largest contributor (55 %) to the total greenhouse warming potential and because of other factors like its long residence time in the atmosphere, its well-mixed nature and its connectedness to economic growth (Griffin, 2003). In the Intergovernmental Panel on Climate Change (IPCC) climate change experiment using the various Special Report on Emission Scenario schemes (A1B, A1FI, A1T, A2, B1 and B2), both ambient air temperature and CO_2 concentration increase concomitantly as projected by climate models since CO_2 is a primary driver of climate change (IPCC, 2007). The increase in the air temperature occurs because of interferences of CO_2 (and other greenhouse gases) with the transmission, absorption and re-emission of longwave radiation or commonly known as the greenhouse effect (IPCC, 2007). Apart from greenhouse gases, it is important to recognize other variables such as oceans, clouds, aerosols, and land-use change which play the role of feedback mechanisms in the climate system that can either amplify or diminish the effects of a change in climate forcing (National Research Council, 2003; IPCC, 2007).

Cities and their associated activities such as the burning of fossil fuels to run daily needs like traffic and home/office heating show enhanced CO_2 concentration which according to several studies have approximated the levels of CO_2 concentration used in climate change scenarios (e.g. Idso et al., 1998; Nasrallah et al., 2003). Therefore, Oke (1997a) suggested the notion that cities could be use as “natural laboratories for the study of climate change”.

1.1 ANTHROPOGENIC SOURCES OF CO_2 – ROLE OF CITIES

Sources of CO_2 are divided into two categories: natural and anthropogenic. Natural sources, made up of biomass burning (1 %), soil (28 %), vegetation (28 %) and oceans (43 %), contribute 770 Gt of CO_2 annually (Lenz and Cozzarini, 1999). This contrasts with anthropogenic sources which emit 28 Gt of CO_2 per year with contributions from power stations (24 %), residential burning (23 %), industry (19 %), biomass burning (15 %) and various modes of transportation (19 %) (Lenz and Cozzarini, 1999). Although the figures given in Lenz and Cozzarini may be outdated, they contain, to the author's knowledge, the most detailed breakdown of both natural and anthropogenic sources of CO_2, as opposed to recent studies like IPCC (2007) and the U.S. Environment Protection Agency (EPA) (2008) which only focus on anthropogenic CO_2 emissions. The contribution of natural sources to the global yearly CO_2 emissions is large compared to anthropogenic sources but in the last few decades, anthropogenic sources of CO_2 have been introduced into the climate system at a much faster rate than the system can maintain the balance between emissions and absorption.

Cities form the biggest source of anthropogenic CO_2 (Korhonen and Savolainen, 1999; IPCC, 2007). As they grow in size, so do activities which consume fossil fuel, primarily for the production of energy for electricity and heat for homes/offices, for manufacturing activities and for traffic usage (EPA, 2008). In addition, city expansion will result in extensive land-use change practices in order to accommodate the needs of the growing city population (Korhonen and Savolainen, 1999; IPCC, 2007). The development of large cities introduces changes that are unique to the urban environment e.g. introduction of new surface materials, creation of an urban canopy layer and emission and concentration of heat, moisture and pollutants. Goldman (1976) gives four primary examples of how the urban landscape modifies atmospheric variables. First, changes in the reflective-absorptive character of the surface cause a temperature build-up within the urban area due to the absorption of radiation during the day and re-emission at night which is controlled by the material and geometry of the urban structure. Second, the presence of cities changes the distribution of heat sources and sinks. These changes include the contributions from humans, concentration of heating and air conditioning units as well as other heat generation sources. Third, changes in airflow caused by rough ground surfaces and large obstructions are evident. Rough ground surfaces result in more turbulent vertical exchange of mass and energy. Fourth, the various activities that operate within cities create changes in the constituents of air and water. Increased CO_2 concentration and aerosol loading arising from increased activities like traffic, industry and office/home heating and decreased plant coverage within the city are some examples of modifications to the atmospheric constituents. These in turn perturb the pre-urban fluxes of heat, mass and momentum and lead to changes in every climatic element like incoming solar radiation, wind speed and direction, evaporation, etc. These inadvertent climate modifications are thought as microcosms of the changes that human activities may beget at the global scale (Oke, 1997b). Consequently, cities are often citied as harbingers of climate change (Ziska et al., 2003) or as laboratories for the study of climate change (Oke, 1997a).

The effects of urbanization have been examined for a number of atmospheric variables including humidity, temperature and precipitation. However less attention has been paid to the influence of urbanization on the level of atmospheric CO_2 concentration in urban areas which is dependent on anthropogenic, biogenic and meteorological factors. A summary given in Grimmond et al. (2002) based on a number of observations in mid-latitude cities indicated large variability in CO_2 concentration thus reflecting the high diversity of urban areas in terms of anthropogenic and biogenic influences. The extent of urbanization on CO_2 concentration needs to be quantified, not merely by means of fossil fuel consumption estimates but rather by direct measurements (Grimmond et al., 2002). This issue forms the main topic of the present thesis which will be explored with data from the tropical-equatorial city of Singapore.

1.2 ORGANIZATION OF THESIS

The structure of the thesis is as follows: Chapter 2 reviews and summarizes existing literature on CO_2 concentration in cities. It begins first with a section which discusses the factors controlling the strength of atmospheric CO_2 concentration drawing upon examples from various cases studies before turning the attention to the spatial and temporal patterns. Emphasis will be placed on the variation of CO_2 concentration over diurnal and seasonal time scales, and addressing why variation amongst studies exists. A section on methodological challenges and review of experimental techniques used by past studies is also provided. The research objectives of the present thesis are outlined in Chapter 3. Chapter 4 describes the methodology used in this study. This includes a detailed description of fieldwork sites, instrumentation techniques and data analysis procedures. The results will be presented in Chapter 5. Chapter 6 provides a discussion of the results in respect to factors that control the strength of CO_2 concentration and compares the present observation with those from past studies. Chapter 7 concludes the thesis with a summary and outlines directions where future work can be carried out.

CHAPTER 2

– LITERATURE REVIEW –

Observations of CO_2 concentration can be categorized as temporal and spatial studies. Studies in the former category examine the patterns of CO_2 concentration over different time scales, typically diurnal, monthly and seasonal. In the latter category, studies seek to compare the difference in CO_2 concentration across different land-use types. The majority of past studies have been carried out over natural, vegetated surfaces including forests (e.g. Woodwell et al., 1973; Clarke, 1969; Allen Jr., 1971; Culf et al., 1997; Bakwin et al., 1998; Buchmann and Ehleringer, 1998; Williams et al., 2001; Pattey et al., 2002). Many of the rural CO_2 concentration studies also form part of the larger study involving the CO_2 exchange in major vegetation types (e.g. AMERIFLUX, EUROFLUX and ASIAFLUX). The number of studies conducted in cities is small and observations are limited to locations in the mid-latitudes (e.g. Chicago and Phoenix, U.S.A.; Kuwait City, Kuwait; Paris, France; Krakow, Poland; Essen, Germany; Rome, Italy; Kugahara and Nagoya, Japan; Basel, Switzerland). Table 2.1 gives a summary of the past urban CO_2 studies, the range of CO_2 concentrations observed and other important findings. A majority of studies in Table 2.1 have been carried out over a short period of time, usually few days to months (e.g. Ghauri et al., 1994; Derwent et al., 1995; Reid and Steyn, 1997; Idso et al., 2001; Grimmond et al., 2002) but nonetheless are adequate to capture temporal variation (e.g. weekday-weekend, winter-summer) of CO_2 concentration. In contrast, only a few long-term studies spanning years to investigate annual variation are available (e.g. Tanaka et al., 1983; Aikawa et al., 1995; Nasrallah et al., 2003; Kuc et al., 2003).

The main technique used in these studies involved a single station at one location to estimate the level of CO_2 concentration in cities. However, a number of them failed to observe the corresponding reference or background value which is usually taken from a rural location (e.g. Davies and Unam, 1999; Velasco et al., 2005; Coutts et al., 2007). This is necessary since only then can the effect of urbanization on the level of atmospheric CO_2 concentration be quantified. Some studies have attempted overcome this problem by measuring CO_2 concentrations across different land-use types (including rural) by means of mobile sampling (e.g. Berry and Colls, 1990b; Henninger and Kuttler, 2004; Ziska et al., 2004; Gratani and Varone, 2005; Kèlomé et al., 2006). With regards to the type of instruments used, closed-path infra-red CO_2 gas analyzers have been popular (e.g. Reid and Steyn, 1997; Davies and Unam, 1999; Idso et al., 2002; Pataki et al., 2003). However, open-path analyzers primarily employed for CO_2 flux measurements have also been used to derive CO_2 concentration data (e.g. Grimmond et al., 2002; Moriwaki et al., 2006; Vogt et al., 2006; Coutts et al., 2007). No standard height requirement is available for observing near-surface CO_2 concentration but many of the studies observed at a height of 1.5 – 5 m (e.g. Berry and Colls, 1990a; Derwent et al., 1995) although greater heights were also used in some studies (e.g. Tanaka et al., 1983; Aikawa et al., 1995; Nasrallah et al., 2003; Velasco et al., 2005)

Unlike in rural environments, the nature of CO_2 concentration such as its patterns and strength in urban environments are erratic and are dependent on the interplay of various factors in which most of them relate to the characteristics of the urban structure itself. Although studies have attempted to characterize the behavior of CO_2 concentration over time, no unique urban "picture" exists (Vogt et al., 2006). Some of the factors controlling the signature of CO_2 will be explored in more detail in the following section.

Table 2.1: Summary of urban CO_2 concentration studies listed in chronological order.

Study Area &Reference	Technique & sensor used	Study Period	Range of CO_2 concentrations	Comments
Cincinnati, Ohio (USA) Clarke and Faoro* (1966)	Technique: Sampling height at 3.7 – 4.6 m Sensor: Lura-Lift IRGA.	May – Aug 1963	Maximum 411 ppm in early morning (0600 hrs) Minimum 323 ppm afternoon (1300 – 1700 hrs) Urban enhancement at 0300hrs = 67 ppm	
New Orleans, Los Angeles (USA) Clarke and Faoro* (1966)	Method not given	16 Sep – 16 Dec 1963	Maximum 377 ppm (0300 – 0600 hrs) Minimum 320 ppm (1300 – 1600 hrs) Urban enhancement at 0300 hrs = 51 ppm	
St. Louis, Montana (USA) Clarke and Faoro* (1966)	Method not given	Mar – May 1964	Maximum 346 ppm (0700 hrs) Minimum 332 ppm (1200 – 1400 hrs) Urban enhancement at 0300hrs = 10 ppm	
Sendai (Japan) Tanaka et al. (1983)	Technique: 30 m above ground (roof building 20 m) and 0.5 m above an unvegetated field within a suburban location Sensor: Hitachi-Horibia IRGA	Dec 1978 – June 1981	Diurnal variation: up to 24 ppm; greatest in the warm season – maximum June 1979 (354 ppm) Minimum in afternoon; maximum in early morning Winter: 2 week maxima just after sunset and before noon. Mean: 1 – 15 ppm less at 30 m than 5 m	

Nottingham & Sutton Bonington (UK) Berry & Colls (1990a)	Technique: 1.5 m over 20 cm grass (rural site, Sutton Bonington) and 4 m from concrete walkway (urban site, Nottingham). Inlets are at least 40 m away from small sources e.g. traffic and chimney. Sampling interval at 10-minute average Sensor: ADC Type 225	Dec 1984 – Jul 1985.	Summer (June – Jul): Rural maximum: 382 ppm Rural minimum: 331 ppm Urban maximum: 365 ppm Urban minimum: 344 ppm Winter (Dec – Jan): Rural maximum: 362 ppm Rural minimum: 350 ppm Urban maximum: 371 ppm Urban minimum 361 ppm	No significant difference in concentration between 4 m and ground level at the urban site. Seasonal average showed no significant difference in CO_2 concentration in the summer. In winter, mean urban CO_2 concentration is 5 ppm higher than rural mean.
Nottingham & Sutton Bonington (UK) Berry & Colls (1990b)	Technique: Traverse with sequential sampling at 1.5 m at 9 locations across the rural-suburban-inner city transect. 125 completed runs at pre-dawn and late afternoon (1400 – 1600 hrs) Sensor: ADC Type LCA2	Dec 1984 – Jul 1985	Winter (Dec – Mar): Rural maximum: 360 ppm Suburban maximum: 363 ppm Inner city maximum: 373 ppm Summer (Apr – Jul): Rural maximum: 400 ppm Suburban maximum: 390 ppm Inner city maximum: 377 ppm	CO_2 concentrations at pre-dawn runs are higher than afternoon runs at all sites irrespective of season. Diurnal amplitude significantly greater in summer than in winter. Small trends of increasing CO_2 towards the city are observed both at night and during the day during winter months. In summer, the trend is reversed at night due to contribution by diurnal cycle of photosynthesis/respiration cycle.
Karachi (Pakistan) Ghauri et al. (1994)	Technique: Sampling at 13 sites. Height of observation not given Sensor: Not given	15 days in May 1990	Busy urban streets exceeded 370 ppm	
Nagoya (Japan) Aikawa et al. (1995)	Technique: Sampling on top of a 14 m building within a university campus which is 8 km far from the downtown region. Sensor: NDIR IRA-102	Nov 1990 – Dec 1993	1991: 381 ppm 1992: 382 ppm 1993: 377 ppm	Summer lower than winter. Urban lower during the day, higher at night. Rush hour detected morning and afternoon
South Kensingston, London (UK) Derwent et al. (1995)	Technique: Sampling at 5 m above ground and 5 m from road Sensor: Chrompack volatile organic compound (VOC) air analyzer	Jul 1991 – June 1992	Mean quarterly weekday concentrations: 3rd quarter of 1991: 384 ppm 4th quarter of 1991: 427 ppm 1st quarter of 1992: 418 ppm 2nd quarter of 1992: 417 ppm	

Vancouver, British Columbia (Canada) Reid & Steyn (1997)	Technique: Sensors mounted onto a 30 m tower with sampling conducted at two heights at 22.5 m and at 5 m above surrounding terrain over a suburban area Sensor: LI-6262	3 – 24 June 1993	Mean peak-to-peak amplitude: 27 ppm, high at 40 ppm, low at 13 ppm Nocturnal mean: 387 ppm Daytime mean: 361 ppm (range: 355 – 363 ppm) Daily mean: 375 ppm	Summer-time concentration shows a later afternoon minimum and overnight maximum around the upwind background concentration. Late afternoon minimum is due to strength of photosynthetic activity and strong mixing of local anthropogenic sources within a deep mixed layer.
Manchester, New Hampshire (USA) Shorter et al.* (1998)	Technique: Whole city traverse at 3 periods: pre-rush hour, rush hour, and post rush hour Sensor: LI-6262	Nov 1997 and June 1998	November 1997: Build up of CO_2 evident during rush hours. Range: 370 – 510 ppm June 1998: Range: 375 – 725 ppm (19 June) Samples from individual car's exhaust could be identified	
Phoenix, Arizona (USA) Idso et al. (1998)	Technique: Before dawn and mid-afternoon traverses along 4 transects with sequential sampling at 2 m at 1.6 km intervals using medical syringes which draw 10 ml of air at each interval. Sensor: ADC-225-MK3.	7 – 11 Jan	City centre: Maximum at 555 ppm Outskirts (rural): 370 ppm	Pre-dawn values greater than afternoon values due to possibly solar-induced convective mixing and photosynthetic uptake by urban vegetation CO_2 concentration rose to 724 ppm during traffic congestion along the freeway.
Kuching, Sarawak (Malaysia) Davies and Unam (1999)	Technique: Sampling site located in a large clearing beside University campus 30 km from south of Kuching. Height of sensor not given. Sensor: LI-6200	22 – 27 Sep and 8 Oct 1997	Clear day: 330 – 340 ppm Hazy days: Exceeded 390 ppm. Maximum recorded exceeds 450 ppm	Study investigates the effect of the 1997 Indonesian forest fires on atmospheric CO_2 concentration levels in Kuching, Sarawak.
Phoenix, Arizona (USA) Idso et al. (2001)	Technique: Traverse at pre-dawn and in the afternoon along 4 transects for 14 days with sensors located at 2 m above the ground Sensor: LI-800	Jan 2000	Non-urban: Weekday: 378 ppm Weekend: 373 ppm City-centre: Highest weekday peak: 650 ppm Lowest weekday peak: 471 ppm Mean maximum (weekday): 529 ppm Mean maximum (weekend): 510 ppm	Peak concentration at city centre is 75 % greater than surrounding rural area. City peak enhancements vary from 43 % (weekdays) to 38 % (weekends). No weekday-weekend difference in CO_2 concentration in surrounding residential areas.

Phoenix, Arizona (USA) Idso et al. (2002)	Technique: Sampling (1-minute average) at 2 m over a residential location Sensor: LI-800	1 – 21 Dec 2000	Daily min: 390 ppm Daily max: 491 ppm (winter, before midnight) Daily max: 424 ppm (summer, before sunrise) Nocturnal mean: Cold season: 461 ppm Warm season: 410 ppm	Daily minimum CO_2 concentration occurred in the afternoon; invariant over the year. Daily maximum occurred at night and varied seasonally with air temperature.
Phoenix, Arizona (USA) Day et al. (2002)	Technique: Sampling (5-minute average) at 2 m over 2 contrasting vegetation types (desert vs turf) at 2 different locations (near city centre vs metropolitan edge) Sensor: LI-800	15 Mar – 3 Apr 2000	Mean: 396 ppm (centre) vs 377 ppm (edge) Daytime mean: 383 ppm (centre) vs 375 (edge) Nighttime mean: 409 ppm (centre) vs 385 (edge) (“centre” and “edge” refer to measurements near the urban centre and at the edge of the city, respectively)	High concentrations over sites near urban centre than at the city edge at all hours of the day with greatest difference at night
Chicago, Illinois (USA) Grimmond et al. (2002)	Technique: Sampling (15-minute average) mounted on a 27 m tower at suburban site Sensor: LI-6262	14 June – 11 Aug 1995	Mean: 384 ppm Nocturnal average: 405 ppm Nocturnal maximum: 441 ppm Daytime average: 370 ppm Daytime minimum: 338 ppm	Mid-afternoon minimum of CO_2 concentrations attributed to strength of biospheric photosynthesis and strong mixing of local anthropogenic sources. High nighttime values due to lower mixed layer, poor atmospheric mixing, biospheric respiration and continued anthropogenic emissions
Al-Jahra, Kuwait City (Kuwait) Nasrallah et al. (2003)	Technique: Sampling at 3 m tower above a 7 m building over a suburban site Sensor: Monitor Lab 9820	17 June 1996 – present	Hourly mean: 369.19 ppm Hourly maximum: 742 ppm Hourly minimum: 321 ppm Mean weekday: 370 ppm Mean weekend: 369 ppm Lowest mean: 369 ppm (Friday)	Annual cycle with highest concentration values in February and lowest values in September due to growth and decay of vegetation in Northern Hemisphere as well as fluctuations in motor traffic. Weekly cycle with highest values during weekdays. Diurnal cycle with highest values after sunset and lowest values in late afternoon due to variation in atmospheric stability and road traffic
Krakow (Poland) Kuc et al. (2003)	Technique: Sampling over a heavily polluted urban environment. Regional CO_2 reference is used. Sensor: Gas chromatograph (HP Series 5890)	1995 – 2000	Maximum: 490 ppm Minimum: 345 ppm Amplitude: 145 ppm Regional average: 370 ppm (Values are sample data from 4 consecutive sampling days)	Intense surface fluxes of CO_2 associated with anthropogenic activities result in elevated atmospheric CO_2 concentration levels. CO_2 enhancement up to 150 ppm

Salt Lake City, Utah (USA) Pataki et al. (2003)	Technique: Sampling (5-minute average) at 18 m within a university campus (residential neighborhood 300 m radius from sampling site) Sensor: LI-7000	1 Jan – 31 Dec 2002	Summer: 375 – 400 ppm Winter: 390 – 480 ppm (Values are nighttime CO_2 concentrations)	Highest CO_2 concentration in wintertime.
Mexico City (Mexico) Grutte (2003)	Technique: Rooftop sampling within university campus. Height not given. Sensor: FTIR spectrometer	11 – 29 Sep 2001	Mean diurnal maximum: 385 ppm Mean diurnal minimum: 365 ppm Mean: 374 ppm	Low CO_2 concentration during midday (1400 hrs), high during nighttime (2200 hrs). 2 peaks in concentration attributed to morning and evening automotive emissions. Concentration peaks more evident during working days.
Essen, North Rhine-Westphalia (Germany) Henninger & Kuttler (2004)	Technique: Frequent spatial and temporal measurements of CO_2 during winter and summer at different meteorological conditions, seasons, and days at 1.5 m across different land uses. Sensor: Not given	Dec 2002 – Feb 2003 Jun – Aug 2003	Winter (Dec – Feb): Day: 402 ppm Night: 427 ppm Average: 415 ppm Summer (Jun – Aug): Day: 369 ppm Night: 417 ppm Average: 393 ppm	Steadily increasing concentration from rural to urban areas (otherwise known as the urban CO_2 dome) is not generally true for any city due to the dependency of CO_2 concentration on various meteorological factors and city structure
Baltimore (USA) Ziska et al. (2004)	Technique: Sampling done at three sites: rural (organic farm), suburban (city park) and urban (<0.5 km from city centre). Height of sensor not given. Sensor: S151, Quibit Systems	2002	Rural: 385 ppm Suburban: 401 ppm Urban: 466 ppm	
Rome (Italy) Gratani & Varone (2005)	Technique: Measurements at 2 m before dawn and in the late afternoon at different land uses Sensor: EGM-1	1995 1998 2001 Jan – May 2004	City centre: Average peak: 477 ppm Maximum: 505 ppm Highest weekday: 505 ppm Highest weekend: 414 ppm Parks: 491 ppm (average) Outside city: 414 – 368 ppm (average)	Daily trend exhibit a peak in early morning due traffic and stable atmosphere. Weekly patterns show lowest values during weekends when traffic density was deduced by 72 %. Annual tend shows peak in winter (18 % higher than in summer) due to traffic density. Higher CO_2 concentration in urban centre than surrounding areas

Mexico City (Mexico) Velasco et al. (2005)	Technique: Sensors mounted on top of a 25 m tower above a 12 m building in the residential and commercial suburbs of Iztapalapa. Sensor: NOAA IRGA	7 – 29 Apr 2003	Maximum: 398 – 444 ppm (0630 – 0800 hrs) Average Maximum: 421 ppm Minimum: 375 ppm (1000 – 1230 hrs)	Morning peak attributed to anthropogenic emissions, nocturnal respiration and shallow early morning mixed layer. CO_2 concentration drops by 20 ppm due to traffic reduction during the national holiday (Holy Week) and by 6 ppm during school holidays.
Kugahara, Tokyo (Japan) Moriwaki et al. (2006)	Technique: Sensors mounted at the top of a 29 m tower. Vertical profiling at 11 levels (0.7 - 29 m) at suburban residential location. Sensor: LI-7500	Nov – Dec 2004.	Temporal: Average: 406 – 444 ppm Minimum values at 1400 hrs Maximum values at nighttime Amplitude: 38 ppm Vertical profile: Δ CO_2 (29 minus 3 m) almost homogenous during daytime in unstable cases	Location of emission sources in the middle or upper level within the canopy where turbulent intensity is greater results in well-mixed CO_2 concentration and homogeneous vertical profile during unstable conditions.
Sperrstrasse, Basel (Switzerland) Vogt et al. (2006)	Technique: Vertical profiling of CO_2 concentration with sensors mounted on a 30 m tower. Sampling at 10 heights (0.1 - 31 m). Sensor: LI-6262	Dec 2001 – Jul 2002	Minimum: 362 ppm (around 1900 hrs) Maximum: 423 ppm (1700 – 1900 hrs)	Daytime CO_2 concentrations do not correlate to local sources i.e. minimum daytime CO_2 values occurred together with maximum traffic load. No significant difference in CO_2 measured between 1.5 m and 31 m
Cotonou (Benin) Kèlomé et al. (2006)	Technique: Initial sampling at 86 sites in both urban and suburban areas followed by long-term sampling at 10 sites (high and low traffic zones) Sensor: Not given	Sep 2001 2002 – 2004	Mean: 650 ppm Maximum: up to 900 ppm Rural baseline: 380 ppm	Main trade center, industrial zones, harbor area and main crossroads in high traffic zones constitute areas of highest CO_2 concentration ranging from 400 – 900 ppm. Source of CO_2 in these areas come from oil-powered vehicles, local industries and outdoor restaurants which burn wood and charcoal.
Melbourne (Australia) Coutts et al. (2007)	Technique: Sensors located at 40 m from ground at two suburban sites (Preston and Surrey Hills) with differing surface characteristics particularly vegetation cover. Sensor: LI-7500	Feb 2004 – June 2005	Summer: 364 ppm Winter: 370 ppm	Low CO_2 concentration variability at 40 m Effect of wind direction from the north and south brings higher and lower CO_2 concentrations respectively CO_2 concentration at Surrey Hills were almost always lower than at Preston during summer due to variability of emissions (natural and anthropogenic) and the evolution of the atmospheric boundary layer

* Adapted from Grimmond et al. (2002)

2.1 FACTORS CONTROLLING THE STRENGTH OF CO_2 CONCENTRATION

The strength of CO_2 concentration at a particular site and at a given time is dependent on the interplay of biospheric, anthropogenic and meteorological factors. The primary contributor of enhanced CO_2 concentration in cities is largely emissions from vehicular exhausts or point sources (e.g. power stations) (Berry and Colls, 1990a, 1990b; Idso et al., 1998, 2001, 2002; Grutte, 2003; Gratani and Varone, 2005). Values from these sources can reach a level of up to 700 ppm which is equivalent to almost a doubling of CO_2 concentration used in climate change scenarios (Idso et al., 1998, 2001; Nasrallah et al., 2003; Kèlomé et al., 2006; cf. Table 1). The values presented in these studies are extreme values observed only under particular conditions. For example, Idso et al. (1998) observe that CO_2 concentration rose to 724 ppm during traffic congestion along the freeway while Kèlomé et al. (2006) recorded highest CO_2 concentration of up to 900 ppm in the main trade center, industrial zones, harbor area and main crossroads in high traffic zones.

Two main factors which are able to influence concentration can be identified: (1) The presence of an air temperature inversion at night and in the early morning which traps vehicular-generated CO_2 near the ground, and (2) solar-induced convective mixing during the midday which greatly dilutes the air's CO_2 concentration near the ground (Cleugh, 1995; Balling Jr. et al., 2001; Grimmond et al., 2002; Idso et al., 2002; Nasrallah et al., 2003; Gratani and Varone, 2005). Secondary controlling factors include wind speed and direction, or canyon geometry which restricts the upward movement of CO_2 concentration because of tall buildings and congested thoroughfares (Idso et al., 2002; Nasrallah et al., 2003; Gratani and Varone, 2005). Although vegetation has the effect of reducing the magnitude of daytime CO_2 concentration, it may not be enough to counteract the significant anthropogenic sources (Grimmond et al., 2002).

2.1.1 ROLE OF ATMOSPHERIC STABILITY

The dispersion of pollutants and CO_2 is largely controlled by the prevailing stability condition. Atmospheric stability is viewed as the relative tendency for an air parcel to move vertically (Oke, 1987). All components of the surface energy balance - fluxes of sensible heat (Q_H), latent heat (Q_E), sub-surface heat (Q_G), and solar radiation - are crucial in this process. The surface heats up by means of solar heating. In turn, this creates rising masses of warm air called thermals. The thermals increase in size with height until they are restricted in upward movement by mixing with cooler air from above. Several studies have found lower CO_2 concentration during the midday period attributable to this solar-induced convective mixing which dilutes the atmospheric CO_2 concentration near the ground (e.g. Berry and Colls, 1990a, 1990b; Aikawa et al., 1995; Reid and Steyn, 1997; Idso et al., 2002; Nasrallah et al., 2003; Moriwaki et al., 2006; Vogt et al., 2006; Coutts et al., 2007). During unstable atmospheric conditions, the air is well-mixed hence is effective in the process of CO_2 dispersal. At night and in the early morning, the situation is reversed due to air temperature inversion. Temperature inversion refers to the increase in temperature with height, brought about by radiative cooling from the surface or by warming from above. Cooling at the surface restricts the upward movement of air unlike daytime thermals. This hinders the vertical transfer of CO_2. The presence of air temperature inversions at night and in the early morning can potentially trap CO_2 emitted near the ground by traffic and other anthropogenic sources as well as respiratory activities by humans, vegetation and soil micro-organisms, increasing the near-surface concentration. However, stable conditions close to the surface are not usually observed in cities, even at night (e.g. Vogt et al., 2006). This is because nighttime stability is disrupted by the nocturnal warming of the urban surface and increased forced convection due to frictional influence of the city (Oke, 1987). In addition, nighttime stability in the form of ground-level inversion rarely occurs in cities.

Instead, stability is often experienced at higher levels in the city as elevated inversions about 100 – 500 m above the city (Oke, 1987).

2.1.2 ROLE OF WIND SPEED AND WIND DIRECTION

Wind speed and wind direction play an important role in CO_2 transport and diffusion in both urban and rural areas. Observations of wind speed and wind direction in urban locations are more problematic than they are for rural areas. Cities are known to alter both these components. Consequently, observations made close to the buildings do not necessarily reflect the actual behavior of synoptic wind (Oke, 2004).

Generally, the higher the wind speed, the higher the dilution i.e. lower CO_2 concentration per unit volume. Many studies have confirmed this relationship (e.g. Allen Jr., 1971; Day et al., 2002; Moriwaki et al., 2006). Wind speed also governs the intensity of turbulent activity i.e. greater wind speeds mean greater turbulent activity brought about by forced convection due to friction between the air and the surface roughness elements (Oke, 1987). Urban wind speeds are reported to be lower than rural wind speeds (e.g. Lee, 1979; Fortuniak et al., 2006). For example, Lee (1979) observed that mean urban wind speeds in London are 20 – 30 % lower than those outside the city, especially during the day. Similarly, Fortuniak et al. (2006) recorded urban wind speeds which are 34 – 39 % lower than at the rural location. However, measurements from both studies cannot be used as representative of the behavior of wind in cities because the pattern of wind speed below the roof level bears little resemblance to that above the roof level (Lee, 1979; Oke, 1987). In Lee's (1979) study, the height of the anemometer (69.8 m) at the urban site (London Weather Centre) is greater than the average building height (24 – 30 m). Measurements are hence representative of the gross airflow of the over the city. This contrasts with the study by Fortuniak et al. (2006) in which measurements are representative of local conditions (sensors are located at a height of 11 m above the ground where the average building height, z_h, is about 20 m). Measurements are therefore representative of micro-scale conditions. Within the canopy, wind speeds are significantly lower than at the top of the canopy. For example, Vogt et al. (2006) show that there is a large difference in wind speed within (mean: 0.5 m/s) and above (mean: 2 m/s) the canopy layer. However, the CO_2 concentration within the canopy cannot be quantified based on wind speed alone. Other factors like traffic-induced turbulence, atmospheric stability and strength of emissions are also important.

It is also necessary to consider the influence of wind direction because it determines the path followed by the emitted CO_2 (Oke, 1987). For a sensor, this could mean contribution from various sources within its concentration footprint, resulting in enhanced concentration of CO_2 or no enhancement. Clarke (1969) commented that the magnitude of CO_2 concentration in an urban area during nocturnal hours of the growing season as observed in Cincinnati, Ohio (USA) may not necessarily be representative of the magnitude of CO_2 concentration from combustion sources alone but may be influenced by contributions from natural sources which also existed within urban areas (e.g. parks, lawns, human respiration, soil respiration). Additionally, rural emissions of CO_2 may be transported into urban areas by the prevailing wind. The effect of wind direction on CO_2 concentration has also been studied by Day et al. (2002) who conducted near-surface CO_2 concentration measurements over four contrasting sites in the metropolitan area of Phoenix, Arizona (USA). The four sites represented high productivity turf and low productivity desert near the urban centre and at the edge of the metropolitan area. The levels of CO_2 concentration were higher over sites near the urban centre (“In” sites) than at the edge of the metropolitan area (“Out” sites) at all hours of the day with the greatest difference at night (Table 2.2). Wind speed and direction are the main controlling factors identified by the authors in bringing about the diurnal course of CO_2 concentrations at these sites. High CO_2 concentrations are observed when both “In” and “Out” sites are downwind of the urban centre (402 ppm for “In” sites versus 388 ppm for “Out” sites) with respective nighttime values being 16 – 18 ppm higher than daytime values (Table 2.2). The role of wind direction was also illustrated in the study by Coutts et al. (2006) in Melbourne (Australia) in which they observed lower CO_2 concentration at their sampling sites due to the influence of southerly winds which advect “pristine” air from the southern ocean. In Essen (Germany), the higher-than-normal rural CO_2 concentration as observed by Henninger and Kuttler (2004) was due to the influence of urban plume transported by winds from northeast/east direction.

Table 2.2: Average daily, daytime and nighttime CO_2 concentrations (ppm) at sites near the urban center “In” versus the edge of the metropolitan area “Out”, and at turf vs. desert sites, along with the difference in concentration between contrasting sites. Source: Day et al. (2002).

Site	Daily Wind Direction			Daytime Wind Direction			Nighttime Wind Direction		
	All winds	Down	Up	All winds	Down	Up	All winds	Down	Up
In	398	402	396	384	385	383	410	413	409
Out	384	388	377	375	377	375	391	393	385
Difference	14	14	19	9	8	8	19	20	24
Turf	398	401	390	379	381	379	410	412	407
Desert	387	389	384	380	381	379	391	394	388
Difference	9	12	6	-1	0	0	19	19	19

2.1.3 STRENGTH OF EMISSION SOURCES

CO_2 emissions are dependent on the source type, derived from four sources: (1) Mobile i.e. traffic, (2) static local sources e.g. residential heating, (3) semi-static i.e. vegetation and (4) remote sources located outside the city-centre e.g. power plants (Soegaard and Møller-Jensen, 2003). In cities, the strength of CO_2 concentration is dictated by road traffic activity where peaks in near-surface CO_2 concentrations are reported to coincide with the intensity in traffic load corresponding to peak hours (e.g. Takagi et al., 1998; Grutter, 2003; Gratani and Varone, 2005; Velasco et al., 2005; Vogt et al., 2006). Some studies have noted reduced traffic load – hence drop in CO_2 concentration – during weekends or national holidays. In Mexico City (Mexico), Velasco et al. (2005) observed an average CO_2 concentration drop by 20 ppm during the national holiday while during school holidays, the concentration dropped by 6 ppm. In Phoenix, Arizona (USA), Idso et al. (2001) reported higher weekday values in the city-centre but not in other land-use types such as rural.

CO_2 concentration in rural areas, on the other hand, is significantly removed from the influence of road traffic activity. Instead, the temporal patterns of CO_2 concentration in rural areas are largely determined by the cycle of assimilation and respiratory activities of vegetation and soil micro-organisms. Additionally, some studies have also reported the strength of photosynthetic sinks in reducing the intensity of CO_2 concentration in urban areas during daytime (e.g. Day et al., 2002; Grimmond et al., 2002).

It is also important to consider the sitting of sensors which determines the strength of CO_2 emissions detectable (Schmid, 1997). In a study conducted by Day et al. (2002), the influence of traffic on the observed CO_2 concentration was not apparent but was noted elsewhere (e.g. Wentz et al., 2002; Vogt et al., 2006). This was due to sampling sites in Day et al.'s study being 150 – 200 m away from vehicle thoroughfares. In Mexico City, the proximity of Grutte's (2003) sampling site to a dense network of roads resulted in a later and longer morning CO_2 concentration peak than that observed by Velasco et al. (2005) at a different site.

2.2 TEMPORAL VARIATION OF CO_2 CONCENTRATION

Temporal variation of CO_2 concentration has occupied the majority of past studies. The patterns of CO_2 concentration observed over rural areas or over natural, vegetated surfaces are generally well-understood. The main characteristics of the typical diurnal trend of CO_2 concentration can be summarized as follows: (1) High concentration at night with maximum value during pre-dawn hours, (2) sharp decrease in concentration following sunrise, (3) low concentration during daytime with minimum value attained at around noon, (4) gradual increase in concentration following sunset and (5) large diurnal amplitude i.e. the difference between highest and lowest CO_2 concentrations. Table 2.3 provides a summary of CO_2 concentration values observed at rural sites, confirming the general characteristics outlined above. There is considerable variability in nighttime maximum, daytime minimum and consequently the amplitude of CO_2 concentrations. This variability is attributed to factors like site characteristics (e.g. vegetation type, vegetation density) and prevailing meteorological conditions which influences the values of CO_2 concentration. For example, the low diurnal amplitude (31 ppm) observed in Sutton Bonington, Nottingham (UK) (Berry and Colls, 1990a) was due sampling over short grass (< 20 cm) (Table 2.3). This contrasts significantly with the amplitude in other studies (> 100 ppm) which were conducted over or near densely vegetated environments such as agricultural field (Allen Jr., 1971), forest (Woodwell et al., 1973; Culf et al., 1997) and pasture (Clarke, 1969). Variability in CO_2 concentrations as shown in Table 2.3 should also be seen in the context of increasing global background of CO_2 concentration which has increased from approximately 325 ppm in the first study in 1969 to approximately 370 ppm at the end of the millennium.

Table 2.3: Comparison of CO_2 concentration (ppm) values at rural sites

Location, Land-use & Reference	Cincinnati, Ohio (USA)	Ithaca, New York (USA)	Long Island, New York (USA)	Sutton Bonington, Nottingham (UK)	Rondônia, (Brazil)
	Pasture	**Agricultural Field**	**Forest**	**Short Grass**	**Forest**
	Clarke (1969)	**Allen Jr. (1971)**	**Woodwell et al. (1973)**	**Berry and Colls (1990a)**	**Culf et al. (1997)**
Mean Minimum (Daytime)	297	< 300	290 – 300	345	360
Mean Maximum (Nighttime)	422	350 – 500	> 500	376	486
Mean Diurnal	322	325 – 400	395 – 400	360	423
Mean Diurnal Amplitude	125	100 – 200	210 – 200	31	126

Note: Daytime minimum and nighttime maximum CO_2 concentrations in Woodwell et al. (1973) are lowest and highest observed values, respectively.

Due to the lack of vegetation, diurnal patterns of CO_2 concentration in cities are largely dependent on the patterns of road traffic, the main source of CO_2 in urban areas (EPA, 2008). This is evident during the day when patterns of CO_2 concentration are disrupted by a series of time-dependent peaks which are closely related to traffic. Urban areas also exhibit much smaller diurnal amplitude as compared to rural areas. Large diurnal amplitude over rural areas is due to the photosynthetic-respiratory action by natural vegetation and soil micro-organisms. The uptake of CO_2 during photosynthesis reduces the daytime ambient concentration while the release of CO_2 during respiration increases its value at night. This interplay of absorption and emission results in large diurnal amplitude. In urban areas, this interplay is absent. During the day, urban CO_2 concentration rises with traffic load. At night, following the reduction of traffic activities, the concentration of CO_2 is lower than what was during the day. In addition, low urban CO_2 concentration at night is also influenced by the prevailing atmospheric instability which dilutes the concentration. This contrasts with the rural site in which stable atmospheric conditions at night due to ground inversion increases the near-surface CO_2 concentration.

The two characteristics of urban CO_2 concentration patterns mentioned represent an ideal situation in which factors influencing the strength of CO_2 concentration such as local meteorology are not taken into consideration. Studies however have reported large variability in CO_2 concentration patterns and values which explain why a representative urban pattern has yet to be found (Moriwaki et al., 2006). Additionally, most studies are conducted over short periods, usually days and several months. This presents the lack of data for a truly comparative temporal study.

The diurnal course of CO_2 concentration as observed in urban areas can be identified by four stages (Reid and Steyn, 1997): (1) Low concentration in the afternoon, (2) rapidly rising concentration after sunset, (3) pre-dawn maximum and (4) rapid decrease till noon (Figure 2.1). This pattern is caused by the interplay of daily anthropogenic (largely traffic), biospheric (nocturnal respiration) and meteorological (shallowest mixed layer heights at night) activities which influence the strength of CO_2

concentration. Other studies have observed similar diurnal variation (e.g. Berry and Colls, 1990a; Grimmond et al., 2002; Velasco et al., 2005; Moriwaki et al., 2006; Coutts et al., 2006). However, the same pattern could not be found by Aikawa et al. (1995), Idso et al. (2002) and Nasrallah et al. (2003). A comparison of maximum and minimum CO_2 concentration values is given in Table 2.4. The large diurnal variability reflects the diversity of urban areas especially in terms of anthropogenic and biogenic activities (Vogt et al., 2006). While most studies have reported diurnal amplitudes ranging 20 – 60 ppm (Table 2.4), there are cases where the amplitude exceeds 100 ppm. Large amplitude reflects the degree of anthropogenically-induced (largely industrial) atmospheric pollution. In the study by Kuttler (1982) of the Ruhr district in Germany, the level of CO_2 concentration in a polluted atmosphere is 350 – 700 ppm. This contrasts with 310 – 330 ppm range in an unpolluted atmosphere in the same study. In a more recent study, Kuc et al. (2003) reported that the maximum diurnal amplitude derived from the urban monitoring station at Krakow (Poland) is 145 ppm (maximum: 490 ppm versus minimum: 345 ppm). This study illustrates the influence of a heavily polluted urban atmosphere (Krakow) on the CO_2 concentration level. The effect of atmospheric pollution derived from non-industrial sources on the CO_2 concentration has also been investigated. Davies and Unam (1999) reported a 17 – 28 % increase in CO_2 concentration observed in urban Kuching, Sarawak (Malaysia) following the sudden release of CO_2 from deforestation and biomass burning in Indonesia in 1997. In this study, the maximum CO_2 concentration observed during the haze period was 450 ppm which contrasted with the 330 – 340 ppm range observed during clear days.

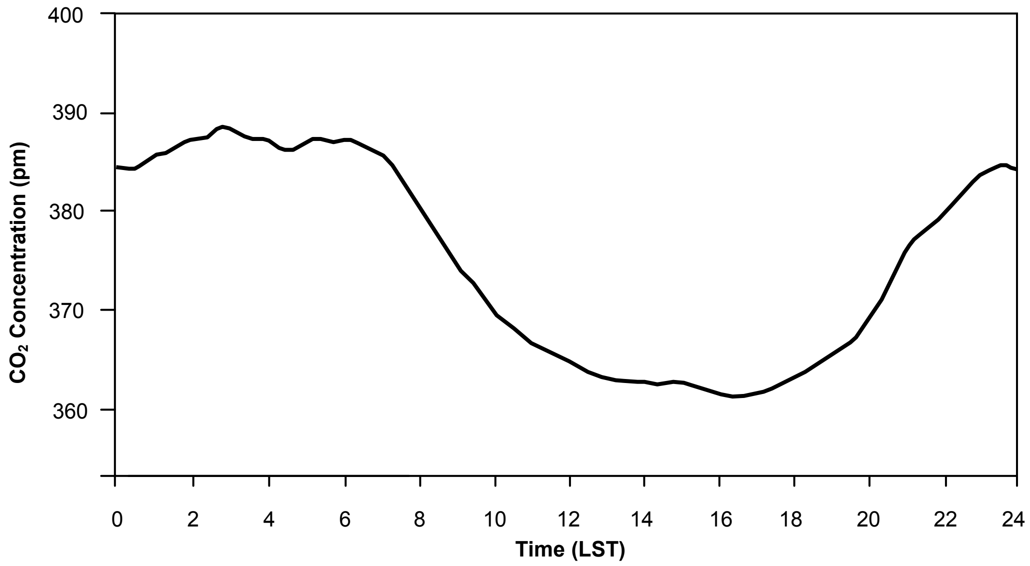

Figure 2.1: Typical diurnal cycle of atmospheric CO_2 concentration at an urban site in Vancouver, British Columbia. Source: Reid and Steyn (1997)

Table 2.4: Comparison of CO_2 concentration (ppm) values at urban sites. Parentheses denote number of sample days.

Location & Reference	Vancouver (Canada)	Chicago (USA)	Mexico City (Mexico)	Kugahara (Japan)	Basel (Switzerland)
	Reid and Steyn (1997)	Grimmond et al. (2002)	Velasco et al. (2005)	Moriwaki et al. (2006)	Vogt et al. (2006)
Mean Maximum (Pre-dawn)	387	405	421	444	423
Mean Minimum (Afternoon)	361	370	375	406	362
Mean Diurnal Amplitude	26 (11)	35 (13)	46 (23)	38 (60)	61 (28)

In the study by Aikawa et al. (1995) in Nagoya (Japan), pre-dawn maximum CO_2 concentration is not observed. The authors report higher nighttime (2400 hrs) and lower daytime (1530 hrs) CO_2 concentrations with values reaching 385 ppm and 366 ppm, respectively. The authors relate the lower daytime concentration to strong solar radiation which enhances atmospheric mixing hence effective dilution of CO_2. After sunset, the formation of the inversion layer results in lesser mixing thus increases the CO_2 concentration level. The diurnal pattern of CO_2 concentration as observed by Nasrallah et al. (2003) in Al-Jahra, Kuwait City (Kuwait) is consistent with the Nagoya study. However, the interesting feature in the Al-Jahra study is the presence of midday and midnight peaks in CO_2 concentrations in which midday peak is lower than that at midnight. The diurnal cycle displays lowest value of 367.9 ppm near sunset followed by rising CO_2 concentration which peaks at 371.2 ppm before midnight. Afterwards, concentration drops to 368.3 ppm at 0600 hrs and continue to rise again to a midday peak of 369.5 ppm. The diurnal amplitude in this study is very small i.e. 3 ppm as opposed to 19 ppm in the Nagoya study. However, it is to note that the small diurnal amplitude is based on mean annual data (1996 – 2001). These values can therefore not be directly compared with the data in Table 2.4 which are usually based on a few days/months only. The authors explain the observed diurnal course by both the daily cycle of meteorological and anthropogenic factors. The decrease in concentration from midnight to pre-dawn hours was due to the mixing of fresh air streaming into the metropolitan area brought about by winds from the west-northwest. The influence of traffic is reflected in the rise in concentration from dawn till midday. At noon, the effects of high wind speed and low traffic load yield decrease in concentration till about sunset. The sharp rise to maximum concentration from sunset till midnight is a consequence of low wind speed, coupled with the influence of high traffic load and the presence of a stable atmosphere that characterize the situation at that time of the day.

Comparing datasets for different seasons, Idso et al. (2002) observed greater diurnal variability in winter months of December/January compared to the summer months of July/August (Fig. 2.2a). The course of the diurnal cycle is similar to the one observed by Nasrallah et al. (2003) but with a diurnal amplitude of about 100 ppm. Several important features that can be identified in Figure 2.2a: (1) Nighttime CO_2 concentration is higher in winter, (2) identical patterns of decreasing concentration in both winter and summer from 1000 – 1300 hrs, (3) higher concentration in summer from 1400 – 1700 hrs, and (4) steep rise in concentration from 1630 hrs in winter.

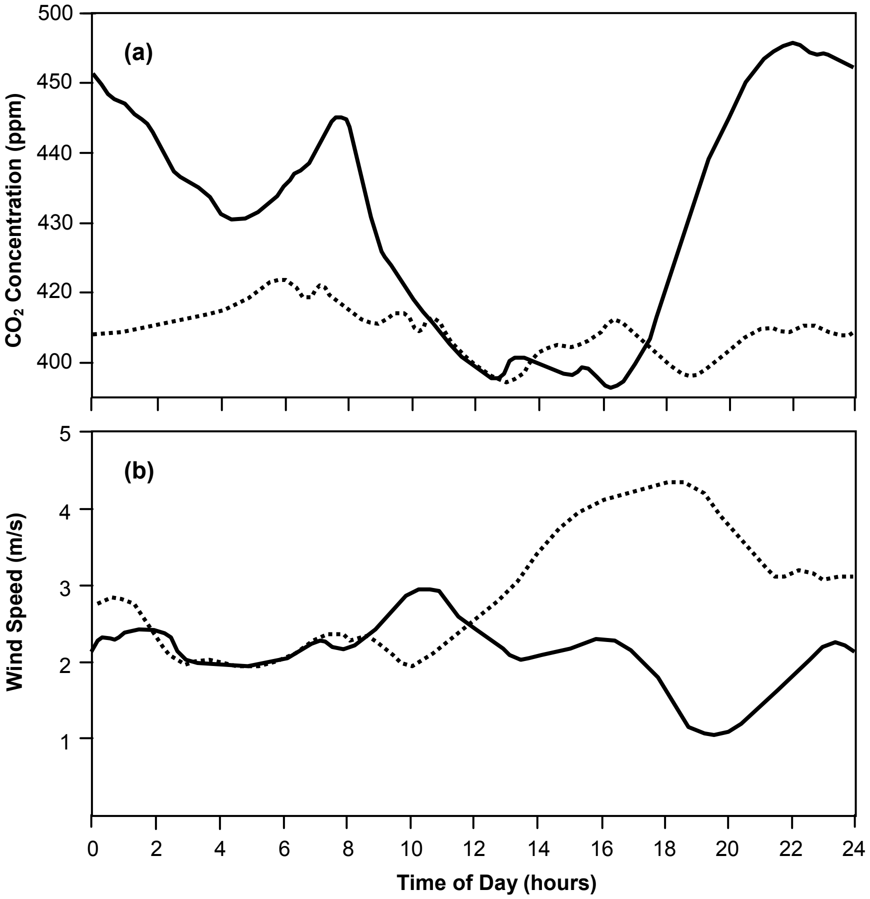

Figure 2.2: Comparison between summer (Jul-Aug) (dotted line) and winter (Dec-Jan) (solid line) variables of: (a) CO_2 concentration and (b) wind speed in Phoenix, Arizona from 1 - 21 December 2000. Source: Idso et al. (2002).

The diurnal course of CO_2 concentration in Phoenix, Arizona (USA) can be explained by the following factors (Idso et al., 2002). First, higher concentration in summer from 1400 - 1700 hrs is due to the difference in wind speed. Figure 2.2b shows the mean diurnal course of wind speed in winter and summer. From the figure, it can be seen that summer wind speed is progressively stronger from 1200 hrs onwards. Higher wind speed imports CO_2-rich air from the highways, giving rise to higher CO_2 concentration in summer from 1400 - 1700 hrs. After 1700 hrs, the air gets mixed with pristine rural air, resulting in decreasing CO_2 concentration from 1700 - 1830 hrs. Second, higher winter (mean: 464 ppm) than summer (mean: 410 ppm) CO_2 concentration observed at night and in the early morning is because the presence of much stronger and more frequent air temperature inversions in the coldest part of the year. Third, steep rise in concentration in winter from 1630 hrs is reflective of the season's shorter day-length, and the earlier development of air temperature inversion which coincides with the afternoon highway traffic peaks. Consequently, CO_2 from traffic is emitted into calm, developing inversion layer contributing to rapidly rising concentration which peaks about midnight rather than at pre-dawn, as would have otherwise be observed elsewhere (e.g. Reid and Steyn, 1997). Fourth, the rapid decrease in winter concentration from midnight to 0400 hrs is due to winds importing rural air (this time from eastern and slightly northern rural areas) in addition to low traffic load. The influence of morning peak traffic on winter CO_2 concentration becomes evident between 0500 – 0800 hrs. Afterwards, solar-induced convective mixing reduces the concentration to an afternoon low.

There is agreement amongst studies in different cities on the mean seasonal (winter versus summer) CO_2 concentration. While there is a difference between the mean summer and winter concentrations, most studies report higher values in winter than summer with large variability in absolute differences (Table 2.5). The large winter-summer difference is attributed to changes in the proportions of fossil fuel combustion (e.g. increased local heating) and biogenic respiration at different times of the year (Aikawa et al., 1995; Pataki et al., 2003; Soegard and Møller-Jensen, 2003; Henninger and Kuttler, 2004). It is also important to consider the role of atmospheric stability in influencing the concentration of atmospheric CO_2 during different seasons (Coutts et al., 2007).

Table 2.5: Mean seasonal variation of CO_2 concentration (ppm) over urban areas. Parenthesis denotes percentage difference.

Location & Reference	**Nottingham (UK)**	**London (UK)**	**Phoenix, Arizona (USA)**	**Kuwait City (Kuwait)**	**Salt Lake City, Utah (USA)**	**Essen (Germany)**	**Rome (Italy)**	**Melbourne (Australia)**
	Berry and Colls (1990a)	**Derwent at al. (1995)**	**Idso et al. (2002)**	**Nasrallah et al. (2003)**	**Pataki et al. (2003)**	**Henninger and Kuttler (2004)**	**Gratani and Varone (2005)**	**Coutts et al. (2007)**
Summer	355	417	410	370	375 – 400	393	388	364
Winter	366	427	464	369	390 – 480	415	463	370
Difference	12 (3 %)	10 (2 %)	54 (12 %)	1 (0.2 %)	15 – 80 (3.8 – 16 %)	22 (5 %)	75 (16 %)	7 (2 %)

Notes: (a) Values in Pataki et al. (2003) are nighttime CO_2 concentrations; (b) Data in Nasrallah et al. (2003) are annual variation.

Seasonal variation of rural CO_2 concentration has not been investigated to a large extent. However, studies such as Clarke (1969) in Cincinnati, Ohio (USA) and Berry and Colls (1990a) in Sutton Bonington, Nottingham (UK) show that similar variability exists in terms of maximum and minimum values. In addition, both studies observed that summer months are associated with larger diurnal amplitude compared to winter months. This is due to the fact that summer months are associated with highest CO_2 release rates by vegetation and lower nocturnal mixing at night (Oke, 1987).

The observed seasonal patterns of CO_2 concentration summarized above are typical of mid-latitude cities which are marked by pronounced seasonal cycle in vegetation growth. Tropical cities on the other hand are characterized by a year-long growing season. This has implications on the respiratory and assimilative activities of tropical vegetation and soil micro-organisms which are dependent on soil moisture and soil temperature. For example, Kumagai et al. (2004) in their study in a Bornean tropical rainforest reported highest transpiration rate during the wet period and lowest during the dry. This may translate into higher and lower nocturnal CO_2 concentrations during the respective periods. Although such trend is typical of rural environments, urban areas may also exhibit similar behavior of CO_2 concentrations due to factors such as higher

Leaf Area Index in urban compared to rural areas and the role of irrigation and garden/park management which may boost the productivity of urban vegetation and hence the level of CO_2 concentrations. There have not been any published studies conducted in tropical cities to give insight on the seasonal trend of CO_2 concentration at either rural or urban areas. It is therefore one of the aims of the present thesis to investigate the seasonal variation of CO_2 concentration using data from Singapore.

2.3 SPATIAL VARIATION OF CO_2 CONCENTRATION

A phenomenon that has been closely associated with cities is the urban heat island (UHI) which by definition refers to the increased nocturnal air temperature observed in an urban environment compared to its rural surroundings (Oke, 1987). In terms of CO_2 concentration, early studies have reported higher CO_2 concentration in the city-centre compared to surrounding areas (e.g. Berry and Colls, 1990b). Recently, Idso et al. (1998) coined the expression "urban CO_2 dome", describing it as the progressive increase in anthropogenic CO_2 concentration towards the city-centre which forms a blanket - or dome - of higher CO_2 concentration over the city-centre. To date, research on CO_2 concentration has focused on urban-rural differences (e.g. Berry and Colls, 1990a, 1990b; Ziska et al., 2004) otherwise known as CO_2 enhancement which is defined as the difference between urban and background (often rural) CO_2 concentrations i.e. $\Delta CO_{2(urban\text{-}rural)}$. The distinction between the urban CO_2 dome and the urban CO_2 enhancement is less defined. Perhaps the main difference lies in the methodology which allows a dome structure to be detected. The urban CO_2 dome can be observed by means of traverses (e.g. Idso et al., 1998, 2001; Henninger and Kuttler, 2004) or by a series of fixed stations across the city covering different land-use types (e.g. Berry and Colls, 1990a).

There have not been many investigations into the urban CO_2 dome, making it difficult to generalize the characteristics of the phenomenon. The work by Idso el al. (1998 and 2001) in Phoenix, Arizona (USA) remains the most comprehensive study so far and the results will be used to form the bulk of this section. While there are studies which attempt to characterize the CO_2 dome using data-sets from a single or limited number of stations, not all of them can be used to confirm or compare the nature of the CO_2 dome as observed elsewhere because of insufficient spatial coverage by fixed stations (e.g. Nasrallah et al., 2003) or because the adopted methodology was not clearly defined (e.g. Gratani and Varone, 2005). Nonetheless, these studies confirm the conclusion that the build-up of CO_2 concentration in city-centre is due to anthropogenic sources, attributable primarily to fossil fuel combustion. The urban CO_2 dome illustrates another example of how urbanization alters the climate, hence providing concrete reasons why there should be emphasis on city-scale investigations in context of global climate change.

2.3.1 CHARACTERISTICS OF THE URBAN CO_2 DOME

The urban CO_2 dome describes the progressive increase in anthropogenic CO_2 concentration towards the city which forms a blanket, or dome, over the city. The dome is formed due to the build-up of CO_2 over urban areas due to localized burning of fossil fuels from sources such as automobile exhaust and aerial effluents of commercial activities (Idso et al., 2001). The CO_2 dome peaks in the city-centre, corresponding to maximum CO_2 concentration and progressively reduces in concentration towards the urban fringes (Fig. 2.3).

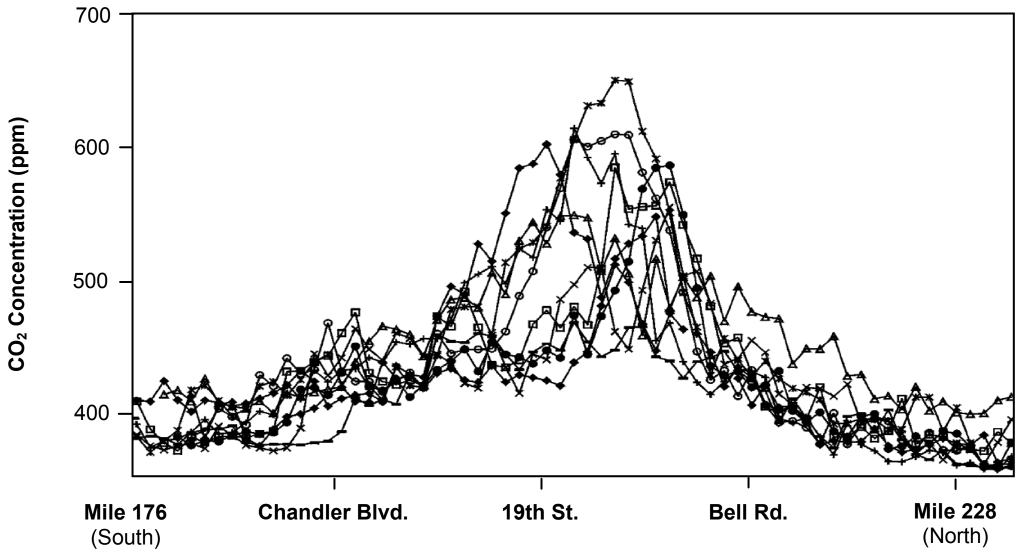

Figure 2.3: The urban CO_2 dome of Phoenix, Arizona as observed in January 2000. Abscissa shows location along the transect. Source: Idso et al. (2001)

Temporal sampling of the CO_2 dome reveals that CO_2 concentration is highest during afternoon (1400 hrs) and pre-dawn (0500 hrs) hours with the latter values being considerably higher than the former (Fig. 2.4). The observation is consistent with findings from an earlier study (Idso et al., 1998). The authors relate the lower midday concentration to enhanced vertical mixing and airflow from the southwest to the northeast (Idso et al., 2001). Comparison of weekday-weekend data reveals higher CO_2 concentration on weekdays (Fig. 2.4). This unquestionably shows the influence of road traffic and commercial activities on weekdays. Weekday-weekend differences were not observed over the surrounding areas (e.g. residential, rural).

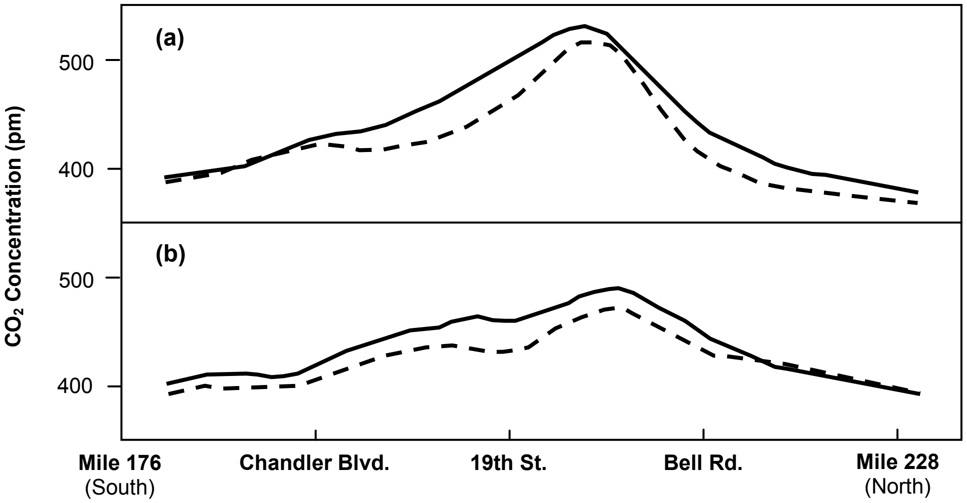

Figure 2.4: Temporal patterns of urban CO_2 concentration dome of Phoenix, Arizona during weekdays (solid line) and weekends (dotted line) at: (a) pre-dawn (0500 hrs) and (b) noon (1400 hrs) in January 2000. Abscissa shows the location along transect. Source: Idso et al. (2001).

2.3.2 VARIATION IN INTENSITY OF THE URBAN CO_2 DOME

The magnitude and extent of the urban CO_2 dome cannot be generalized because of site-specific and time-dependent factors such as pre-urban land-use, regional climate, meteorological controls (e.g. atmospheric stability, solar declination), urban architecture and morphology (e.g. canyon geometry, extent of vegetation cover). It is also important to consider the amount of emission by local sources (e.g. traffic) within the urban area which probably forms the most vital component in influencing the intensity of CO_2 concentration inside the dome (Henninger and Kuttler, 2004). These factors determine the spatial and temporal ability of CO_2 to mix in the atmosphere. Existing CO_2 dome studies have identified a strong but highly variable urban CO_2 dome (Idso et al., 2001) (Table 2.6). Data from Idso et al. (2001) show highest peak in CO_2 concentration and hence largest enhancement. Even the lowest recorded urban CO_2 concentration is 28% greater than the rural baseline value. The mean city-centre peak CO_2 concentration within the dome also shows higher weekday values. These findings are consistent with datasets from Gratani and Varone (2005) (although the methodology is not defined) which noted highest CO_2 concentration of 505 ppm (mean: 477 ppm) in Rome's city-centre. In addition, the study also confirms the difference between weekday and weekend CO_2 concentrations.

Table 2.6: Comparison of CO_2 concentrations (ppm) measured in the city-centre with rural baseline values. Values in parentheses are CO_2 enhancement, $\Delta CO_{2[uban\text{-}rural]}$, expressed as percentages.

Location & Reference	**Phoenix, Arizona (USA)**	**Rome (Italy)**	**Paris (France)**	**Cotonou (Benin)**
	Idso et al. (2001)	**Gratani and Varone (2005)**	**Widory and Javoy (2005)**	**Kèlomé et al. (2006)**
Maximum	650 (76 %)	505 (25 %)	542 (30 %)	650 (71 %)
Minimum	471 (28 %)	389 (-4 %)	413 (-1 %)	-
Mean Maximum	529 (43 %) (Weekday)	477 (18 %)	-	-
Mean Minimum	510 (38 %) (Weekend)	-	-	-
Mean Rural Baseline	369	405	418	380

Spatial variation in the CO_2 dome appears to be strongly related to the level of urbanization (Wentz et al., 2002). For example, the level of CO_2 concentration in an urban site in Baltimore (USA) as observed by Ziska et al. (2004) was 466 ppm. This contrasts with values at the rural (385 ppm) and suburban (401 ppm) sites. Gratani and Varone (2005) noted that CO_2 concentration ranges from 405 ppm for zones outside the city with the lowest traffic levels to 453 ppm for zones outside the historical centre with high traffic volume. They also reported intra-urban variability in CO_2 concentration with higher CO_2 concentration observed in an urban park (461 ppm) than at residential zones inside the city with low traffic levels (421 ppm). Such intra-urban variability is also present in a study conducted by Widory and Javoy (2003) in Paris (France). CO_2 concentrations were measured at various locations including within streets, over gardens, in suburbs and in the surrounding open countryside. Apart from the intra-urban variability in which the CO_2 concentration ranges from 413 – 542 ppm, there is also significant spatial variability in other land-uses. In the suburbs, the CO_2 concentration ranges from 393 – 415 ppm while at the open countryside, it ranges from 387 – 461 ppm. In Cotonou (Benin), Kèlomé et al. (2006) observed that CO_2 concentration can reach as high as 900 ppm in locations such as the main trade centre, industrial zone, harbour area and at main crossroads in high traffic zones.

Henninger and Kuttler (2004) argue that the urban CO_2 dome is not generally observed in every city. This is because many factors, such as meteorological conditions, influence the CO_2 concentration. These factors are in turn influenced by the heterogeneous structure of the urban centre which consequently may give rise to lower CO_2 concentration. The urban CO_2 dome of Phoenix, Arizona is possibly an extreme and exceptional case because the presence of topography (valley location) and local meteorology favors the development of such an intense CO_2 dome (Idso et al., 1999; 2001; Balling Jr. et al., 2001; Wentz et al., 2001; Nasrallah et al., 2003). Apart from the Cotonou study, no such pronounced dome has been found elsewhere (e.g. Henninger and Kuttler, 2004).

2.4 VERTICAL VARIATION OF CO_2 CONCENTRATION WITHIN THE URBAN CANOPY

CO_2 concentration within the urban canopy does not show much variability with height (Moriwaki et al., 2006; Vogt et al., 2006). In the case of Basel (Switzerland), Vogt et al. found that although the CO_2 observations at 1.5 m is related to the intermittent traffic load, there is no significant difference (< 10 ppm) between the concentrations measured at that level and at 31 m, where z_h = 14.6 m. They also observed that CO_2 concentration always decreases with height. Strongest gradient was measured at the street level (z/z_h = 0.2, where z refers to height of measurement). From the street level to the top of the canyon (z/z_h = 1), the vertical profile of CO_2 concentration does not vary much. Similarly, low gradient was observed above the canyon level to the top of the tower (z/z_h = 2.1). Vogt et al. relate this low variability, especially during the second half of the night, to the well-mixed nature of CO_2 concentration between the surface and at the top of the tower during unstable atmospheric conditions and when the traffic load is low. For example, biggest concentration gradient at the street layer (368 – 376 ppm) was observed between 1600 - 2000 hrs during highest traffic and good mixing. In contrast, smallest concentration gradient at the street layer (421 - 425 ppm) was observed during conditions of low traffic and low mixing between 0300 – 0700 hrs. Moriwaki et al. also observe very low vertical variability within an urban canyon (z_h = 7.3 m) in Kugahara, Tokyo (Japan). The authors observed that CO_2 concentrations are almost 0 ppm from the surface level (z/z_h = 0.1) to the top of the measurement tower (29 m, z/z_h = 3.9) during unstable conditions. During stable conditions, the CO_2 concentration below the rooftop level (z/z_h = 1) shows low variability (37 – 42 ppm) but above that level, the concentration decreases with height from about 35 ppm (z/z_h = 1.2) to 0 ppm (z/z_h = 3.9).

Different explanations are used to explain the low CO_2 concentration variability observed at different heights within the urban canyon. In Basel, the source of CO_2 concentration is from traffic which is located near the street level where turbulent intensity is small. The well-mixed nature of the urban canyon during unstable conditions facilitates the vertical transfer of CO_2, resulting in almost a homogeneous vertical profile. In contrast, the source of CO_2 in the case of Kugahara is from ventilating fans used for home heating located at the middle and upper levels of the canopy where the turbulent intensity is larger. The resulting profile is homogeneous. The dispersion of CO_2 is sensitive to canopy geometry where a low H/W ratio (where H and W refer to height of building and width of street canyon, respectively) increases the dispersive potential of CO_2. In Basel, the H/W ratio is 1 while in Kugahara, it is 0.65. The ratios seem high, indicating a low dispersive potential of CO_2.

2.5 METHODOLOGICAL CHALLENGES

The different nature – be it temporal or spatial – of CO_2 concentration studies necessitates different methodologies in order to meet the scope and aims of respective studies. This means that the technique required to investigate the urban CO_2 enhancement which is temporal in nature would be different from that used to study the urban CO_2 dome, which is a spatial phenomenon. There are two common sets of techniques: (1) Point measurements using multiple sensors mounted at fixed stations (e.g. Grimmond et al., 2002; Nasrallah et al., 2003) and (2) car traverses documenting spatial patterns across different land-uses (e.g. Idso et al., 1998, 2001; Henninger and Kuttler, 2004). Each method has advantages and disadvantages and may consequently account for differing estimates of CO_2 concentration. The advantage of car traverses is that one is able to more fully characterize conditions along different land-uses, including detecting inhomogeneous fields of emission that are characteristic of urban landscapes (Henninger and Kuttler, 2004). However, it is difficult to obtain a large sample with frequent repetition hence limiting the temporal resolution of the observations. Observations at fixed sites allow a high temporal resolution but only for a spatially-limited field of emission (Soegaard and Møller-Jenssen, 2003).

Considering the methodological challenges, many of the fundamental issues associated with meteorological observations within the urban surface layer revolve around the sitting and exposure of sensors (Grimmond et al., 2002; Oke, 2004; Grimmond, 2006). The choice of location for instrument sitting poses a problem for urban environments more than it does for rural locations. The standard practice is to locate sensors in such a manner that they monitor conditions that are representative of the environment that they are intended to measure. Guidelines for the sitting of CO_2 sensors are not available. There is no significant difference in CO_2 concentration measured at the standard 2 m height and at higher levels. This was illustrated in the study by Berry and

Colls (1990a) who noted no marked difference in CO_2 concentration measured at 4 m and near the ground level. At higher levels within the canopy layer ($z/z_h \leq 1$), no significant difference was observed (Moriwaki et al., 2006; Vogt et al., 2006). At levels higher than the canopy layer ($z/z_h > 1$), there is low vertical variability in CO_2 concentrations but only for unstable cases (Moriwaki et al., 2006; Vogt et al., 2006). Moriwaki et al. (2006) has shown that for stable cases, concentrations above the canopy layer are decreasing with height. Coutts et al. (2007) commented that at higher levels, the variability of CO_2 concentration would be lower than that observed near the ground level. Urban CO_2 concentration studies nonetheless tend to incorporate the 2 m height in their methodology (e.g. Idso et al., 2001; Day et al., 2002; Gratani and Varone, 2005). The reason might be due to convenience of comparing different variables at the same height (e.g. comparing temperature and CO_2 concentration at 2 m) rather than at different heights.

Another issue that has to be considered is the identification of appropriate measurement sites within the urban area. In the case of CO_2 concentration, traverses could be used as preliminary investigation of spatial patterns of CO_2 concentration within the urban area. Needless to say, traverses are time and labor intensive and may be too ambitious to undertake especially when the size of the urban area is very big and when the scope of the traverse is to merely obtain preliminary findings. In addition, one disadvantage of traverse is that meaningful spatial comparison is difficult to assess since climate variables are constantly changing with time. This may throw some doubt on the representativeness of the findings particularly when identifying sites with the highest or lowest CO_2 levels for instrument sitting. On the other hand, traverse presents a viable approach to studying the urban CO_2 dome property. It is also possible to use the Urban Climate Zone (UCZ) model introduced by Oke (2004) which incorporates the Urban Terrain Zone classification developed earlier by Ellefsen (1990/91). The importance of the UCZ is not its absolute accuracy to describe the site but its ability to classify areas of a settlement into districts that are similar in their capacity to modify the local climate. One shortcoming of this approach is that its classification has been developed for basic climate variables like wind speed and temperature. CO_2 concentration is not necessarily higher in areas with highest building density since CO_2 concentration depends on the emission sources and the meteorological characteristics of the planetary boundary layer.

Considering the identification of a suitable rural site for climate observations, there seem to be no consensus on what constitutes “rural”. This creates problems especially in studies which require a rural reference for the computation of, for example, the UHI intensity or the degree of CO_2 enhancement which consequently leads to different estimates of the phenomena. Lowry (1977) provides a framework for the consideration of an appropriate rural site from which two important aspects can be extracted i.e. the minimization of landscape (e.g. topography, water bodies) and urban effects. It is also important to consider which land-cover type (e.g. rainforest, turf, desert) corresponds to a pre-urban environment. The land-cover type that is characteristic of the selected site where the reference station is to be installed would give different estimates of CO_2 concentration. This is highlighted by the study of Day et al. (2002) over turf and desert where different CO_2 concentration values and patterns were observed. In addition, this study also brings into question whether the choice of land-cover type (i.e. turf and desert) fits the notion of “rural” in order to be considered as representative of a pre-urban environment, hence good reference sites.

The issue of instrument sitting and exposure is a problem that is of more importance when considering fixed stations, rather than car traverses, for use in any urban climate study. Possibly, the only concern for car traverses is to ensure that the measured variable (e.g. CO_2 concentration, temperature) does not originate from perturbations created by the vehicle itself (Idso et al., 1998). Of primary concern to CO_2

concentration studies using fixed stations is the representativeness of the area represented by the stations. Fixed stations have a temporal advantage but have a spatial deficit. The challenge hence lies in trying to rectify this deficit which can be resolved by comparing the measurements at one location with measurements that might be observed elsewhere nearby through a series of short-term spatial sampling to assess the spatial representativeness of measurements made at the chosen site. This includes comparing measurements (1) within canyon and non-canyon settings, (2) from different land-uses/land-cover (e.g. urban versus sub-urban, urban versus industrial), and (3) at non-standard heights especially within urban canyons. These issues will be dealt with in the present thesis.

CHAPTER 3

– RESEARCH OBJECTIVES –

It is imperative that CO_2 research be conducted in tropical cities where studies of such nature are limited despite the fact that tropical cities are amongst the fastest growing in the world with disproportionally high population numbers. Several research questions can be identified.

First, there is a need to characterize the CO_2 concentration patterns over both urban and rural areas in tropical cities. Studies conducted in mid-latitude cities have shown the effect of winter and summer seasons on the level of CO_2 concentration. Tropical cities are characterized by year-long growing season with periodic cycle of wet and dry episodes i.e. monsoons. Effects of monsoonal disturbance and perennial growing cycle on CO_2 concentration remain unexplored. Additionally, existing studies have focused on concentration at either rural or urban site. One limitation is that it is difficult to conduct comparison at any given time. Simultaneous measurements of CO_2 concentration at both rural and urban sites will allow effective comparison on the patterns of CO_2 variability. At the same time, characterization of CO_2 concentration should involve measurements of CO_2 concentration in all types of urban land-uses e.g. industrial, residential, and not just merely urban-rural comparison. This will allow a better representation of the spatial variability of CO_2 concentration and help identify the role of anthropogenic contribution.

Second, the existence of the urban CO_2 dome needs to be researched. Henninger and Kuttler (2004) are doubtful about the progressive increase in CO_2 concentration from rural to urban areas, or otherwise known as the urban CO_2 dome phenomenon. The CO_2 concentration in a city is influenced by a variety of factors related to sources, sinks and dispersion of CO_2 which are regulated by traffic activities and heterogeneous city structure.

Third, methodological challenges in CO_2 research need to be addressed. There are only a few studies which measure the spatial variability within rural and urban sites. For example, are measurements made within urban canyons representative of those made in non-canyon settings (e.g. open space)?

Fourth, the relationship between CO_2 concentration and climate variables such as rainfall and wind direction needs to be explored. Past studies have shown that CO_2 concentration at a given site is a function of wind speed and wind direction. No data is available to study the effect of rainfall, however. Unlike solid pollutants (e.g. aerosols) which are washed away upon rain events, CO_2 is a gas and the effect of rainfall on the level of its concentration is unknown.

The specific research objectives of the present thesis are summarized as follows:

1. To explore the seasonality of CO_2 concentration in the tropical context, which is characterized by the absence of pronounced annual vegetation cycle, by investigating the temporal patterns of CO_2 concentration in Singapore over different scales (diurnal, monthly and seasonal);

2. To investigate the spatial variability of CO_2 concentration across different urban land-use types (heavy industrial, light industrial, low-rise high-density residential, low-rise low density residential, high-rise residential and city-centre) including investigating intra-urban and -rural differences as well as vertical variation of CO_2 concentration within an urban canyon;

3. To explore the relationship between CO_2 concentration and meteorological variables such as rain and wind speed/direction.

CHAPTER 4

– METHODOLOGY –

Different sets of methodologies are employed in order to effectively meet the objectives of the present study. Three techniques are used - fixed stations, localized spatial sampling ("mobile" station) and car traverses. This chapter begins with a brief description of the climatology of Singapore and classification of seasons followed by detailed descriptions of instrumentation, fieldwork sites, calibration techniques and data analysis procedures in subsequent sections. A summary of instrumentation used is provided in Table 4.1.

Table 4.1: List of instruments used at the various locations.

Variable / Instrument / Height	**Location**		
	Fixed Rural Station	**Fixed Urban Station**	**Mobile Station / Car Traverse**
CO_2	Model: LI-840 LI-COR Biosciences Serial: HGA 0237	Model: LI-840 LI-COR Biosciences Serial: HGA 0369	Model: LI-820 LI-COR Biosciences Serial: CGA 764
H_2O			-
T	Model: HMP45C Campbell Scientific, Inc Serial: X3920004	Model: HMP45C Campbell Scientific, Inc Serial: U3650049	Model: HMP45C Campbell Scientific, Inc Serial: X3920002
RH			
Solar Radiation	Model: Q-7.1 Campbell Scientific, Inc	-	-
Rainfall	Model: TB4-L Campbell Scientific, Inc	-	-
Wind Speed & Direction	Model: 034B-L Campbell Scientific, Inc	-	-
Air Sampling Pump	Model: BD LaMotte	Model: BD LaMotte	Model: BD LaMotte
Datalogger	CR10X Campbell Scientific, Inc	CR510 Campbell Scientific, Inc	CR510 Campbell Scientific, Inc
Height of Sensor	All sensors (except rainfall) at 2 m above ground level	All sensors at 3.5 m above ground level	All sensors at 2 m above ground level

Note: CO_2 - CO_2 concentration (ppm), H_2O - H_2O concentration (ppt), T - Temperature (°C) , RH - Relative humidity (%)

4.1 CLIMATE OF SINGAPORE

Singapore's climate is characterized by uniform daily average temperature and pressure, high humidity and abundant rainfall, owing to its geographic location being near the equator (Latitude 1.5 deg N and Longitude 104 deg E). The diurnal course of air temperature is small and ranges from 23 - 26 °C (minimum) and 31 - 34 °C (maximum). Rainfall is generally high throughout the year with a peak in December and a minimum in July (National Environment Agency of Singapore, 2002). Seasonal variation of rainfall is uneven over the country as a whole with the eastern parts of the island receiving more rainfall during the northeast monsoon whereas during the southwest monsoon, the situation is reversed (Foong, 1992). Figure 4.1 shows the climograph of mean monthly temperature and total rainfall of Singapore for the period 1872 - 1988.

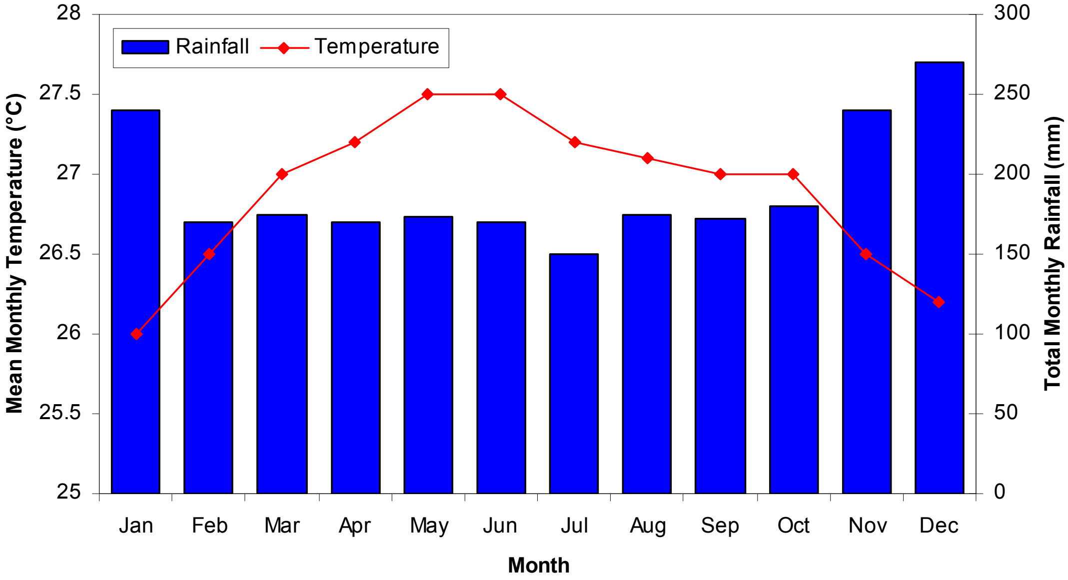

Figure 4.1: Climograph of monthly mean temperature and total rainfall for Singapore for the period 1872 - 1988 measured at Paya Lebar Airbase (01°27'37" N, 103°54'34" E; 20 m above mean sea level). Source: Chow and Roth (2006)

Figure 4.2 shows the ensemble net radiation for June and December observed at the rural station located in northwestern part of Singapore (cf. Fig. 4.6) to compare the difference in net radiation received in months near the summer and winter solstices. Net radiation is less in December because the Sun's angle is lower and due to higher coverage by clouds associated with the prevailing monsoon season i.e. Northeast monsoon.

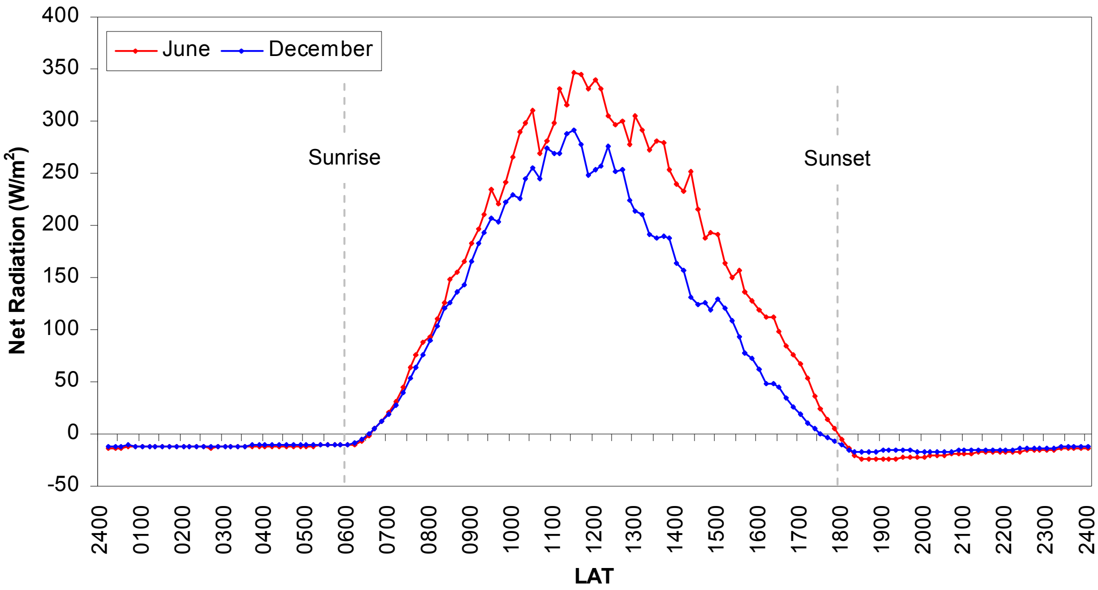

Figure 4.2: Ensemble net radiation for the months of June and December 2006 taken at a rural site in the northwestern part of Singapore. Refer to Fig. 4.6 for location of site. LAT - Local Apparent Time

Singapore has two main seasons: the Northeast (NE) monsoon and the Southwest (SW) monsoon separated by two short inter-monsoon (INT) periods. As the name suggests, the monsoon periods are brought about by the change in dominant wind direction which blows from the northeast and southwest, respectively. Although the start and end of the monsoons are not well-defined and vary from year to year, the common periods of their occurrence are December - March (NE monsoon) and May - September (SW monsoon). Important characteristics of Singapore's seasonal cycle are given in Table 4.2.

Table 4.2: Characteristics of Singapore's seasonal cycle. Source: National Environment Agency, Singapore (2002)

Season	Characteristics
NE Monsoon	Northeast winds prevail, sometimes reaching 20 km/h. Cloudy conditions in December and January with frequent afternoon showers. Spells of widespread moderate to heavy rain occur lasting from 1 to 3 days at a stretch. Relatively drier in February till early March. Also generally windy with wind speeds sometimes reaching 30 to 40 km/h in the months of January and February.
(INT-Monsoon Period) Pre-southwest	Light and variable winds with afternoon and early evening showers often with thunder.
SW Monsoon	Southeast/southwest winds. Isolated to scattered late morning and early afternoon showers. Early morning 'Sumatra' line squalls are common. Hazy periods.
(INT-Monsoon Period) Pre-northeast	Light and variable winds. Sea breezes in afternoon. Scattered showers with thunder in the late afternoon and early evening.

4.1.1 CLASSIFICATION OF SEASONS FOR PRESENT STUDY

While climographs such as Figure 4.1 do show periods of wet and dry episodes, it is insufficient to use them as the only source to classify seasons for use in the present study. The primary determinant of monsoons is wind direction. Other variables such as cloud cover and rainfall are arguably the entailing effects of the change in wind direction. It makes sense to use wind direction as an additional indicator to distinguish between seasons.

Wind direction data was observed at the fixed rural station (cf. Section 4.3; Fig. 4.6). Data, based on raw 10-minute values, available from June 2006 - April 2007 were extracted to show the monthly frequency of wind direction from the four main directions i.e. northeast (0 - 90 °), southeast (91 - 180 °), southwest (181 - 270 °) and northwest (271 - 360 °). From Table 4.3, it can be seen that the months of June - September experience a high frequency of wind blowing from the southwest. From January - March, much of the wind blows from the northeast direction. In December, wind is still variable with 31 % of the winds blowing from the southwest, and 27 % from the northeast.

However, observations have shown that December usually marks the start of the NE monsoon (Chow and Roth, 2006). Hence it makes sense to classify December as a NE monsoon month. Additionally, rainfall observations at the rural site show that December records the highest total rainfall (Figure 4.3). Likewise, December's high wind speed and low temperature records are consistent with the characteristics of NE monsoon as described in Table 4.2. This supports the case for December being a NE monsoon month. Variable winds which characterize October, November, April (and possibly May) suggest the occurrence of the two inter-monsoon periods. Classification of seasons used in this study is hence based on these wind frequency trends and is consistent with the classification adopted in Chow and Roth (2006) except for the timing of seasons, which in the present study, begins a month later. Since the period of the fieldwork spans from June 2006 – January 2007, observation of CO_2 concentration for the NE monsoon consists of data from only two months – December and January – instead of four months which would theoretically include February and March. Although data used in this thesis spans till January, the observations are still ongoing as this thesis is being written with the hope of obtaining a full yearly cycle for future analysis.

Table 4.3: Monthly frequency (%) of wind direction based on raw 10-minute data observed at a rural site (cf. Figs. 4.6 and 4.7) in Singapore from June 2006 – April 2007.

	Jun	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**
Northeast (0-90°)	4	1	1	2	8	17	27	38	44	30	23	-
Southeast (91 - 180°)	23	32	29	26	31	25	21	21	31	26	25	-
Southwest (181 - 270°)	51	50	53	50	44	39	31	21	16	29	36	-
Northwest (271 - 360°)	22	17	17	22	17	19	21	20	9	15	16	-
Classification	|--------	SW Monsoon		---------|	INT Monsoon		|--------	NE Monsoon		---------|	INT Monsoon	

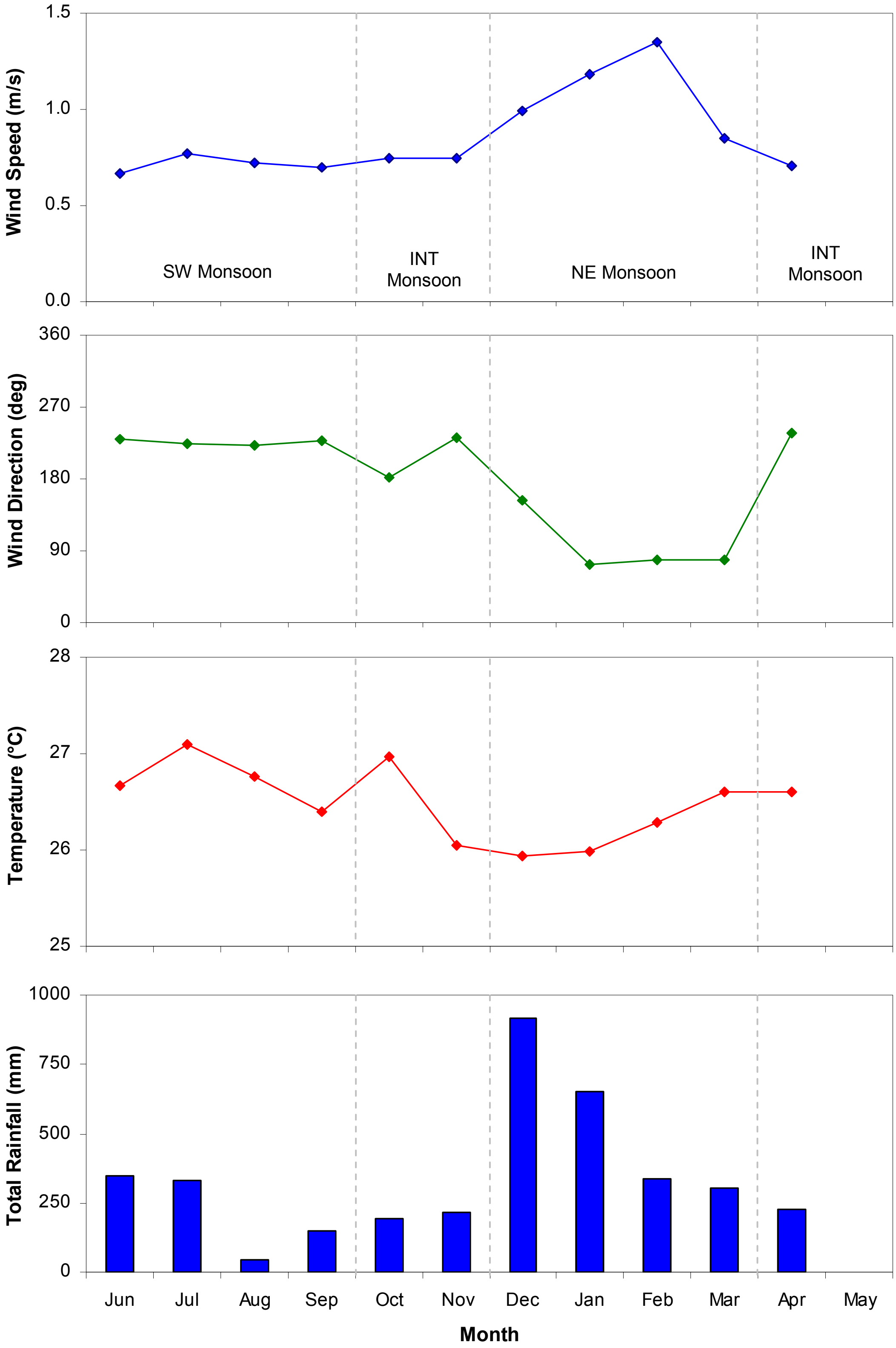

Figure 4.3: Monthly variation of selected variables observed at the fixed rural site in Singapore from June 2006 - April 2007. Refer to Fig. 4.6 for location of site. Note that observation period used in current study is from June 2006 – January 2007.

4.2 URBAN SITE

A fixed monitoring station was installed within an urban canyon at Bideford Road at the heart of Singapore's city-centre near Orchard Road (Fig. 4.4). The reason for choosing this location is because it has been used in past for a UHI study by Chow and Roth (2006). This facilitated permission sought since contacts with the authorities have already been established. The canyon is served by a 2-lane roadway which connects to the main road, Bideford Road Main. The activities in the buildings (z = 25 – 40 m, where z refers to height above ground level) flanking the canyon are service-oriented (e.g. service apartments, hotel, shopping mall, and an educational institute). Traffic feeds the multi-storey parking lots that are available at the ground level of these buildings. Vegetation characteristics included isolated trees (z = 5m) and several small isolated grass patches (10 - 20 m^2) (Chow and Roth, 2006). Vegetation fraction derived from a 100 m radius of the sensor is about 5 % (mainly roadside trees).

The sensors are mounted at the end of a 2 m long boom attached to one of the pillars of the 25 m high Grand Cairnhill Somerset Residences building (Fig. 4.5). The station consists of an environmental enclosure, a closed-path infra-red CO_2/H_2O gas analyzer, an air sampling pump which draws in air at a rate of 0.85 liter per minute, a temperature/humidity probe and a datalogger (Table 4.1). The instruments are powered by a 12V DC battery which is charged continuously using a battery charger which draws in power from a nearby AC supply. The measured variables are sampled every 10 seconds and averaged over 10 minutes. While there is no consensus on the optimal height of sensors in a narrow urban canyon setting as far as observations of CO_2 is concerned, a standard height of 2 m as recommended by the World Meteorological Organization (WMO) is always desirable (Oke, 2004). However, this was not possible for the present study since obstruction to pedestrians and fear of vandalism posed real concerns. In addition, studies have shown that there is no significant difference between measurements at the standard height and at a much higher level (e.g. Berry and Colls, 1990a; Vogt et al., 2006). With these factors in consideration, CO_2/H_2O and temperature/humidity sensor inlets are located at 3.5 m above a narrow strip of pedestrian walkway. Data was downloaded every fortnight onto a laptop. The Gelman filter for the CO_2/H_2O gas analyzer was replaced every 3 months.

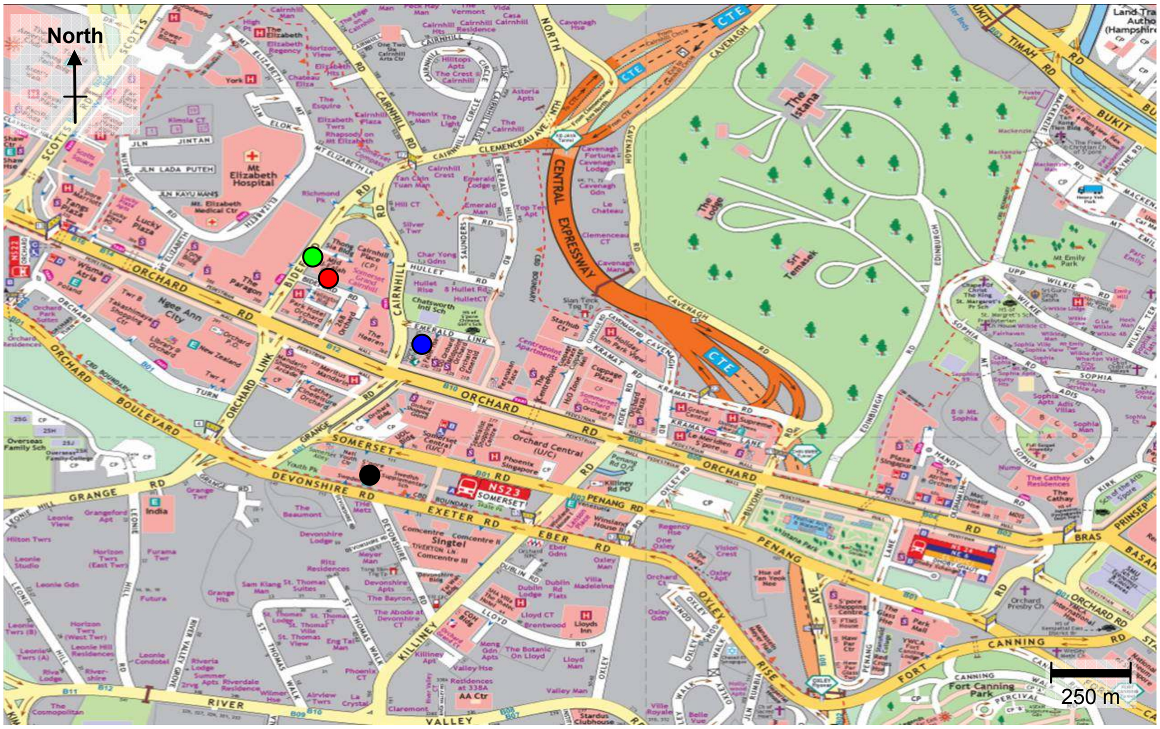

Figure 4.4: Location of urban station (indicated by red dot). Blue and green dots show the locations of the two intra-urban spatial sampling sites at Cairnhill Road and Bideford Road Main, respectively. Ancillary climate data was obtained from a meteorological station at the Singapore Power building (1°18'01.5" N, 103°50'14.0" E) (black dot). Map source: Map reproduced with permission from Mighty Minds Publishing Pte Ltd (2007).

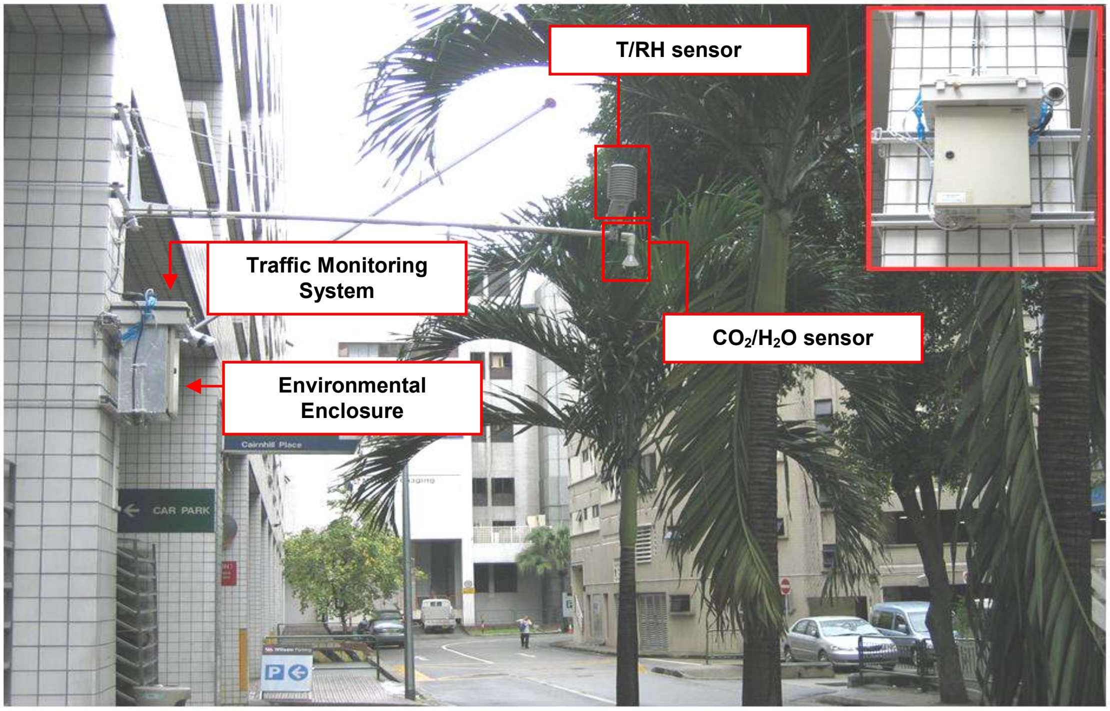

Figure 4.5: Set up of the main urban station at Bideford Road (1°25'27.18" N, 103°43'51.98" E). Inset shows close-up view of traffic monitoring system (camera on the right) and environmental enclosure.

4.3 RURAL SITE

In CO_2 concentration studies and likewise for UHI studies, the identification of a suitable representative rural site is crucial in the computation of the magnitude of CO_2 enhancement. The definition of what rural is poses several problems. In Singapore's context where pre-urban natural landscape has gone through various transformations from primary rainforest to plantations, not much extensive greenspace remains. Hence rural is defined as a predominantly naturally vegetated area in which the influence of urbanization and anthropogenic activities are kept at a minimum. While there remain areas in Singapore which fit this description, they are generally very small. The largest potentially appropriate rural area is the catchment area cum nature reserve located in the center of the island and an area in the northwest which is used as a military training ground and for small-scale agricultural activities near Lim Chu Kang. The presence of reservoirs and hills in the central catchment area reduces the potential of the area as a good approximation of rural, in accordance to Lowry's (1977) framework. Also, the long term nature of the study necessitates the availability of electrical power supply which is not available in the central catchment area.

A preliminary site recce at Lim Chu Kang was done prior to the start of the fieldwork. Several "ideal" sites were identified but due to the need of power supply and of the concern for security of the instruments, a site within the premises of the British Broadcasting Corporation (BBC) Far Eastern Relay Station at Kranji, in the northwestern part of Singapore was selected (Fig. 4.6). Vegetation of the area is characterized by tall dipterocarp trees of 10 – 15 m in height. Vegetation fraction within a 100 m radius of the sensor is about 80 %. The rural station sits in the middle of a grass-covered open space. The nearest obstacles are within 30 m north and south of the sensor in the form of a 3 m building and 10 m trees, respectively (Fig. 4.7). There is only one building (~ 5 m) within 100 m of the sensor. One important characteristics of the site is its proximity to the Kranji Reservoir about 400 m at its closest distance. Depending on the wind direction, this may affect the strength of CO_2 concentration.

The set-up at the rural site is similar to the one at the urban site. Main difference is that the monitoring station sits on a tripod with sensors located at 2 m above the ground (Fig. 4.7). Apart from a closed-path infra-red CO_2/H_2O gas analyzer and temperature/humidity probe, additional instruments used at the site include a rain gauge, net radiometer, and a wind speed and wind direction sensor (cf. Table 4.1). The reason for mounting the wind speed and wind direction sensors at 2 m above the ground level as opposed to the 10 m height recommended by the WMO is due to the lack of resources to mount the sensors at 10 m. Given the relatively open surroundings, a height of 2 m can provide useful approximation of synoptic wind conditions similar to measurements at 10 m. The instruments are connected to a datalogger, powered by a 12V DC battery which is continuously charged using a battery charger which draws in power from the AC supply located 20 m from the instrument tripod. The variables are sampled every 10 seconds and averaged over 10 minutes. This excludes rainfall data which is totalized at 10 minute intervals. Data was downloaded every fortnight onto a laptop. Gelman filter for the CO_2/H_2O gas analyzer was replaced every 3 months.

Figure 4.6: Location of rural station (indicated by red dot) at BBC Far Eastern Relay Station near Lim Chu Kang. Green areas are predominantly rural; grey areas on the right hand side are small industries and suburban housing. Map source: Map reproduced with permission from Mighty Minds Publishing Pte Ltd (2007)

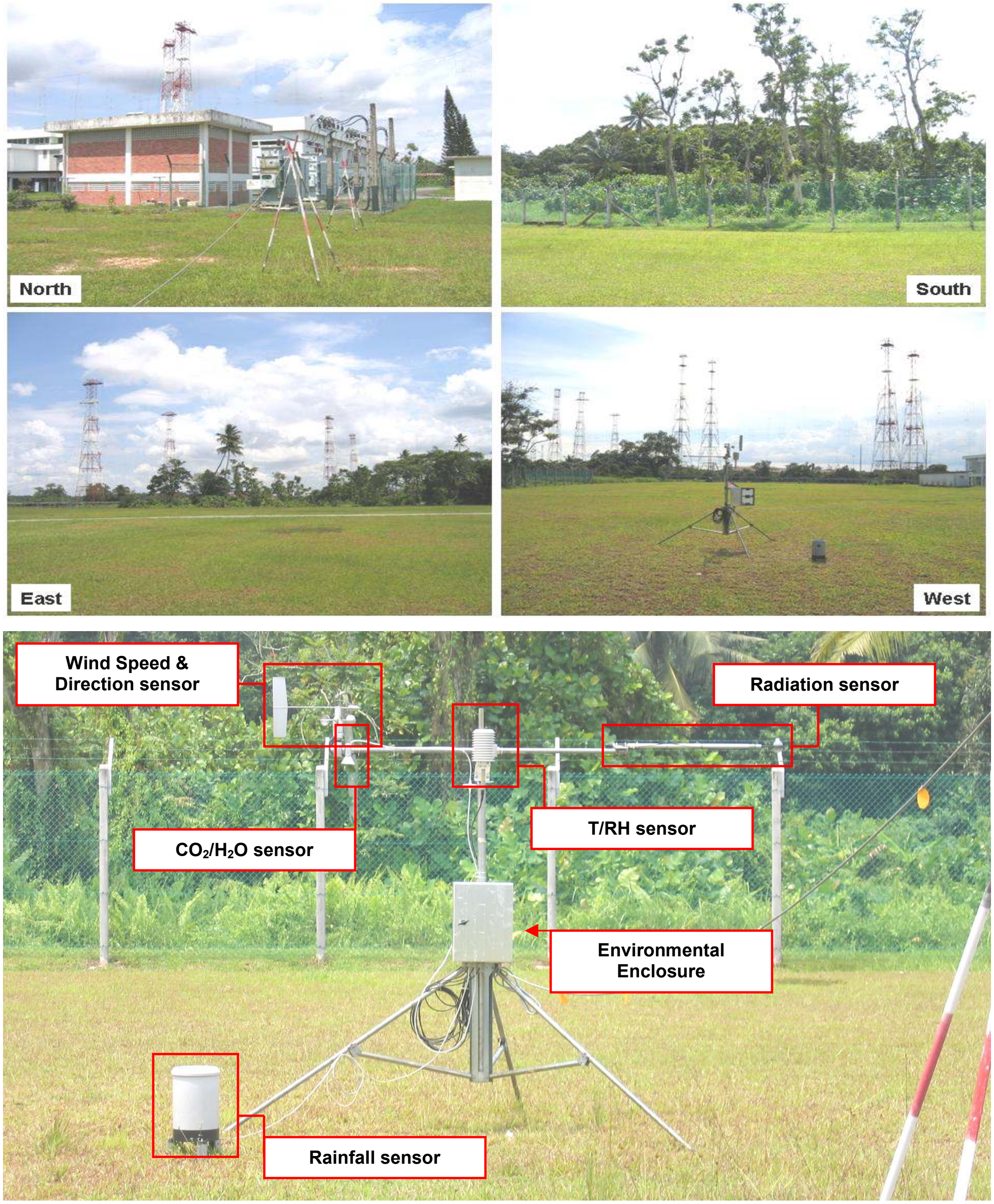

Figure 4.7: Set up at the rural reference site at BBC Far Eastern Relay Station (1°25’27.18” N, 103°43’51.98” E) and its surroundings at all cardinal directions.

4.4 SHORT–TERM LOCAL SPATIAL SAMPLING

Observation of CO_2 concentration at the rural and urban sites is supplemented with short-term spatial sampling lasting eight days using a mobile station. The purpose of the spatial sampling was to study the small-scale spatial variability of CO_2 concentration across different land-use types, including any variability that may arise within urban and rural sites due to different immediate site characteristics (e.g. canyon geometry, vegetation density).

Spatial sampling has been conducted in urban land-use types most commonly found in Singapore. They are heavy industrial, low-rise low-density residential, high-rise residential and low-rise high-density residential (Figs. 4.8 - 4.11). In addition, to assess the representativeness of the rural and urban long-term fixed sites, local spatial sampling has been conducted within each environment for a period of eight days. At the urban site, the first intra-urban sampling site (Cairnhill Road, Fig. 4.12) was located in a small open area next to Orchard Road which is the main commercial road in the city-centre. The second site (Bideford Road Main, Fig. 4.13) was located near Orchard Road, 20 m away from the main urban station. Vegetation type and density are the only differences between the two rural spatial sampling sites (Figs. 4.14 and 4.15). Table 4.4 provides a description of the characteristics of sampling sites, and observation periods. Locations and spatial distribution of all sampling sites are provided in Figure 4.16.

The instruments used for the mobile station consisted of a closed-path infra-red CO_2 gas analyzer and a temperature/humidity probe connected to a datalogger (Table 4.1). The sensor inlets were located at a height of 2 m supported by a make-shift instrument stand. At some sites (Hougang and Bideford Road Main), due to security and safety reasons, sensors inlets were attached to either a lamppost or a traffic signboard at a height of 3 m. Sensors were powered by two 12V 28Ah DC batteries, charged using a solar panel. Variables were sampled at 10 sec intervals and averaged over 10 minutes.

Figure 4.8: Heavy industrial site at Shipyard Crescent (1°18’01.91” N, 103°41’15.03” E) with views towards all cardinal directions.

Figure 4.9: Low-rise low-density residential site at Portsdown Road (1°17’53.28” N, 103°47’41.09” E) with views towards all cardinal directions.

Figure 4.10: High-rise residential at Hougang (1°22’02.25” N, 103°53’49.81” E). Inset shows close-up view of sensor attached to lamp post.

Figure 4.11: Low-rise high-density residential at Telok Kurau (1°18’51.87” N, 103°54’39.04” E) with views towards all cardinal directions.

Figure 4.12: Intra-urban sampling site 1 at Cairnhill Road (1°18’06.98” N, 103°50’16.01” E) with views towards all cardinal directions. Refer to Fig. 4.4 for location of the sampling site with respect to the main urban site.

Figure 4.13: Intra-urban sampling site 2 at Bideford Road Main (1°18’12.76” N, 103°50’10.47” E). Inset shows close-up of sensors attached to back of traffic signboard. Refer to Fig. 4.4 for location of the sampling site with respect to the main urban site.

Figure 4.14: Intra-rural sampling site I at Murai Farmway (1°23’04.88” N, 103°41’45.71” E) with views towards all cardinal directions. Refer to Fig. 4.16 for location of the sampling site with respect to the main rural site.

Figure 4.15: Intra-rural sampling site II at Lim Chu Kang AgriBioPark (1°25’42.42” N, 103°42’10.09” E) with views towards all cardinal directions. Refer to Fig. 4.16 for location of the sampling site with respect to the main rural site.

Table 4.4: Characteristics of sites used and observation periods for spatial sampling

Land Use Type (Location)	Period	Characteristics	Remarks
URBAN LAND-USE SPATIAL SAMPLING			
Heavy Industrial (Shipyard Crescent)	25 Sep – 3 Oct 2006	Small open space, short grass. 30 m from pier. Surrounded by heavy industries (oil refineries). Vegetation fraction = 40 % (short grass)	Fig. 4.8
Low-Rise Low-Density Residential (Portsdown Road)	3 – 10 Oct 2006	Short grass and sparse vegetation. Detached "black and white" houses. Vegetation fraction = 90 % (mixture of short grass and trees)	Fig. 4.9
High-Rise Residential (Hougang)	23 – 30 Oct 2006	Urban canyon surrounded by 40 – 50 m high apartment blocks. Vegetation fraction = 30 % (roadside trees and urban park)	Fig. 4.10
Low-Rise Low-Density Residential (Telok Kurau)	8 – 16 Jan 2007	Open field with sparse trees. 2 – 3 storey high buildings (6 – 9 m). Vegetation fraction = 35 % (mixture of roadside trees and football field)	Fig. 4.11
INTRA-URBAN SPATIAL SAMPLING			
Intra-Urban I (Cairnhill Road)	22 – 30 Dec 2006	Short grass at sampling site. Near major road junction. Vegetation fraction = 40 % (30 % roadside trees and 10 % short grass)	Fig. 4.12
Intra-Urban II (Bideford Road Main)	30 Dec – 7 Jan 2007	Wide urban canyon served by a 3-lane road with 20 – 25 m high buildings on both sides of road. Vegetation fraction = 10 % (roadside trees)	Fig. 4.13
INTRA-RURAL SPATIAL SAMPLING			
Intra-Rural I (Murai Farmway)	5 – 13 Jul 2006	Enclosed-space with tall grass and shrubs. Dense trees within 5 m radius of station. Vegetation fraction = 95 % (mixture of tall grass, trees and shrub)	Fig. 4.14
Intra-Rural II (Lim Chu Kang AgriBio Park)	16 – 24 Jul 2006	Open space with tall grass and shrubs. Dense trees to the East of station. Vegetation fraction = 75 % (mixture of tall grass, trees and shrub)	Fig. 4.15

Note: Vegetation fraction computed within 100 m radius of sensor

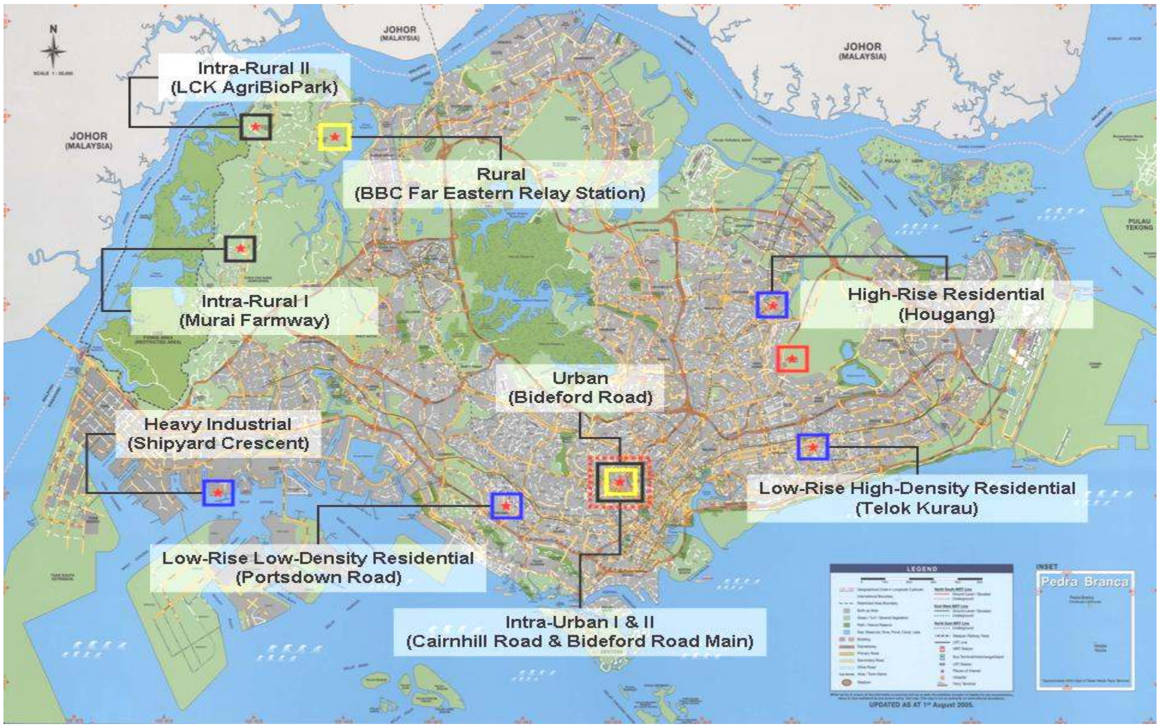

Figure 4.16: Locations of the two long-term fixed sites (yellow) and four short-term urban sampling sites (blue). Locations to assess the representativeness of fixed sites are given in black. Ancillary climate data are obtained from meteorological stations at Paya Lebar Airbase (solid red) and Singapore Power building (dotted red) (see Fig. 4.4 for subset city map). Map source: Map reproduced with permission from Mighty Minds Publishing Pte Ltd (2007).

4.5 CAR TRAVERSES

In order to investigate the spatial variation or the existence of an urban CO_2 dome in more detail, car traverses were conducted on 11, 13 and 15 February 2007 at pre-dawn (0300 – 0445 hrs) and midday (1130 – 1300 hrs). In total, five runs (two at pre-dawn, three at midday) were completed, traversing different land-use types comprising rural (Lim Chu Kang), city-centre (Orchard Road), high-rise residential (Bukit Batok), low-rise high-density residential (Sixth Avenue), low-rise low-density residential (Portsdown Road), heavy industrial (Jurong Industrial Estate) and light industrial (Sungai Kadut Industrial Estate) areas (Fig. 4.17). The traverse route has been carefully selected so that the total time taken to complete it should take less than 2 hrs to minimize temporal changes of climate variables during the traverse. Instrumentation used for the traverse involved the same sensors used for the spatial sampling (cf. Table 4.1). Sensor inlets were mounted on the left side of the vehicle at 2 m above the ground (Fig. 4.17, inset). Variables are sampled every second and averaged over 3 seconds. The high-resolution averaging is necessary since each land-use type takes on average 2 – 3 minutes to traverse.

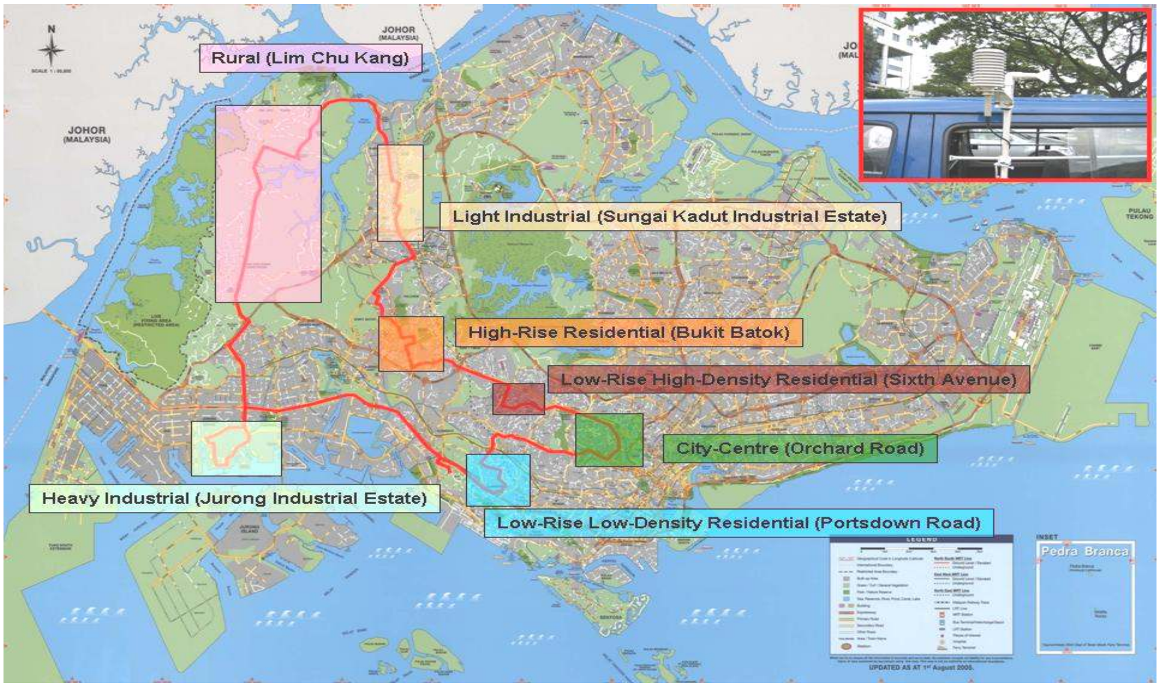

Figure 4.17: Traverse route to investigate the spatial variability of CO_2 concentration. Inset shows the sensor on the van used for the traverse. Map source: Map reproduced with permission from Mighty Minds Publishing Pte Ltd (2007).

4.6 VERTICAL VARIATION

A comparison between CO_2 concentrations measured simultaneously at 3.5 m at the urban station and above the rooftop at the same location was done from 31 January – 5 February 2007 (Fig. 4.18). Moriwaki et al. (2006) and Vogt et al. (2006) observed no significant difference between CO_2 concentrations measured at different heights within the urban canyon (cf. Section 2.4). Factors which explain the low variability of CO_2 concentrations at different heights in the two studies include the nature of their respective canyons (e.g. geometry) and emission sources (e.g. traffic load, ventilating fans). Instrumentation used was the same as the spatial sampling / car traverse. The set-up consists of CO_2 sensor inlet and temperature/humidity probe installed at 2 m above local rooftop and extending 0.5 m into the canyon (Fig. 4.18, inset).

Figure 4.18: Location of canyon and rooftop sensors. Rooftop sensor inlets protrude 0.5 m away from the building wall into the canyon. Inset shows set up used for the rooftop measurement.

4.7 TRAFFIC COUNT

The CO_2 concentration observation at the urban site is supplemented by a 20-day traffic count from 22 December 2006 – 11 January 2007 to study the influence of traffic on the CO_2 concentration within the canyon. This is done by having a night-vision closed-circuit camera and a digital video recorder system which conducts 24-hr traffic surveillance (Fig. 4.5, inset). Traffic data is then manually counted on a television screen using a hand tally. The traffic monitoring period in the canyon coincides with the two intra-urban sampling periods at Cairnhill Road (22 – 30 December 2007) and at Bideford Road Main (30 December 2006 – 7 January 2007). In addition, automated traffic count at 10-minute resolution from October – January was obtained from the Intelligent Transport System of the Singapore Land Transport Authority to highlight the nature of traffic in the city-centre, particularly during periods where the CO_2 observations at Cairnhill Road and Bideford Road Main were conducted.

4.8 CALIBRATION AND DATA QUALITY CONTROL

Inter-comparison of all CO_2 sensors and temperature/humidity probes was conducted before (24 April – 17 May 2006) and after (5 – 8 Feb 2007) the 8-month observation period from June 2006 – January 2007 to ensure that any drift in the sensors can be corrected before the final analysis of the data. The inter-comparison procedure involves setting up the CO_2 sensors inlets and temperature/humidity probes side-by-side with each other outdoors at a height of 2m. For the pre-fieldwork calibration, the inter-comparison was conducted at the Department of Geography instrument test site. For the post-fieldwork calibration, measurements at the urban site were stopped and sensors were brought over to the main rural site for inter-comparison together with the sensor used for mobile measurements. The post-fieldwork calibration was kept relatively short so that observations at the urban site can resume as quickly as possible to obtain data beyond the 8-month period used in this thesis for future analysis.

In the case of the CO_2 sensor, the one installed at the urban station was used as the reference for the others because it is the newest sensor with the most recent factory calibration. To simplify calculation procedures, the urban station temperature/relative humidity sensor was also used as a reference for the sensor installed at the other sites. Only relative drift during the observation period between sensors was corrected for since no absolute calibration was possible. Corrections applied to sensors at the rural and mobile stations was derived by first finding the average percentage drift per week calculated from the difference between pre-fieldwork (week 0) and post-fieldwork (week 36) calibration phases. Table 4.5 shows that the CO_2 sensor at the rural station needed to be adjusted in respect to the reference by between 3.830 % (week 0) and -3.641 %

(week 36) corresponding to 15.136 ppm and -12.634 ppm, respectively. This means that over the course of the observation period, the sensor has progressively moved from being systematically lower than the reference sensor to being systematically higher. The sensor used for the spatial sampling need to be adjusted by between -2.015 % (week 0) to 4.215 % (week 36) corresponding to -7.984 ppm and 14.629 ppm, respectively. The temperature sensors showed very good agreement with each other and insignificant relative drift over time.

Table 4.5: Overall drift in sensors used for rural and mobile stations during the 35-week observation period from June 2006 – January 2007.

Station	Sensor	Serial No.	Total Drift		Remarks
			Percentage Difference	Raw Difference	
Urban	LI-840 [CO_2]	HGA-0369	-	-	Reference sensor
Rural	LI-840 [CO_2]	HGA-0237	7.47 %	27.77 ppm	Week 0 : 3.830 % (15.136 ppm) Week 36: -3.641 % (-12.634 ppm) Drift per week: 0.213 % (0.793 ppm)
Mobile	LI-820 [CO_2]	CFA-764	-6.23 %	-22.61 ppm	Week 0 : -2.015 % (-7.984 ppm) Week 36: 4.215 % (14.629 ppm) Drift per week: -0.78 % (-0.646 ppm)
Urban	LI-840 [H_2O]	HGA-0369	-	-	Reference sensor
Rural	LI-840 [H_2O]	HGA-0237	11.41 %	1.61 ppt	Week 0 : 4.728 % (0.150 ppt) Week 36: -6.682 % (-1.463 ppt) Drift per week: 0.326 % (0.046 ppt)
Mobile	-	-	-	-	Only CO_2
Urban	HMP45C [Temperature]	U3650049	-	-	Reference sensor
Rural	HMP45C [Temperature]	X3920004	-0.000412 %	0.023 °C	Week 0 : 0.020 % (0.570 °C) Week 36: 0.021 % (0.547 °C) Drift per week: -0.000012 % (0.000668 °C)
Mobile	HMP45C [Temperature]	X3920002	-0.000412 %	0.023 °C	Week 0 : 0.020 % (0.570 °C) Week 36: 0.021 % (0.547 °C) Drift per week: -0.000012 % (0.000668 °C)
Urban	HMP45C [R.Humidity]	U3650049	-	-	Reference sensor
Rural	HMP45C [R.Humidity]	X3920004	1.29 %	0.96 %	Week 0 : 0.819 % (0.618 %) Week 36: -0.473 % (-0.340 %) Drift per week: 0.037 % (0.02736 %)
Mobile	HMP45C [R.Humidity]	X3920002	4.80 %	-3.20 %	Week 0 : -1.550 % (0.878 %) Week 36: 3.253 % (2.320 %) Drift per week: -0.137 % (-0.09137 %)

It is inevitable that data loss due to instrument failure or maintenance will happen. Table 4.6 presents the periods of data loss throughout the observation period. The table excludes regular maintenance such as replacement of radiometer desiccant and Gelman filter which only took a short time (< 2 minutes). Periods of data-loss are excluded in the data analysis.

Table 4.6: Periods of data-loss between June 2006 – January 2007.

Period	Days	Station	Variables Affected	Remarks
2 June @ 1600 hrs – 4 June @ 1450 hrs	1.9	Rural	All	CR10X error
19 June @ 1240 hrs – 20 June @ 1700 hrs	1.1	Rural	All	CR10X error
14 July @ 1650 hrs – 16 July @ 1420 hrs	1.8	Rural	All	CR10X error
31 July @ 1210 hrs – 2 August @ 1530 hrs	2.1	Rural	All	CR10X error
17 August @ 1320 hrs – 30 August @ 1350 hrs	13	Rural	All	CR10X error
18 September @ 1650 – 25 September @ 1410 hrs	6.8	Rural	All	CR10X error
10 October @ 1200 – 1220 hrs	0.01	Rural	All	Maintenance
5 July 2006 @ 1430 – 1500 hrs	0.02	Rural	Net Radiation	Maintenance
17 January 2007 @ 1330 – 1430 hrs	0.04	Rural	Net Radiation	Maintenance

The time format used in the present study is Local Apparent Time (LAT). This gives a more precise indicator of the position of the Sun at any given time. LAT for Singapore was calculated in accordance to Oke (1987) and is generally one hour behind Local Time (LT) or +7 hrs GMT. Sunrise and sunset times throughout the observation period was computed using the data services facility from the U.S. Naval Observatory's (2007) website. Calculations show that sunrise occurs between 0646 – 0706 hrs LT while sunset occurs between 1849 – 1916 hrs LT throughout the 8-month observation period. Given the small range, sunrise and sunset times were standardized at 0700 hrs and 1900 hrs LT, respectively. Hence in this study, sunrise and sunset times are given as 0600 hrs and 1800 hrs LAT, respectively.

4.9 DATA ANALYSIS PROCEDURES

This section describes the data analysis procedures using built-in functions in Microsoft Excel and pertains specifically to how averages are computed and descriptive statistics (e.g. mean, maximum and minimum) are derived (Section 4.9.1). The computation of mean wind direction is described in Section 4.9.2. Correlation and significance tests (Section 4.9.3) are performed on wind direction, wind speed, traffic load, rainfall and vegetation fraction to investigate the effects of these variables on CO_2 concentration using the Pearson Product-Moment Correlation Coefficient and test statistic, t (i.e. t-test).

4.9.1 ENSEMBLE AVERAGING

Data analysis procedures used in the study involves computing the diurnal cycle for monthly, 8-month and seasonal ensemble averages based on the raw 10-min data. Monthly ensembles are calculated by averaging the data at each time-stamp (e.g. 0010 hrs, 0020 hrs, 0030 hrs) for all days in the month. The procedure is repeated for subsequent months. This gives the monthly-stratified diurnal variation of the variable (e.g. Figs. 5.3 and 5.4). Following this procedure, the 8-month ensemble is derived by averaging the monthly-stratified diurnal data at each time stamp (e.g. Figure 5.1). Similarly, the seasonal ensemble is derived by averaging the monthly-stratified diurnal data at each time stamp according to their respective seasonal classification as described in Section 4.1.1 (e.g. Figure 5.8). Where periods of data-loss are concerned, the same averaging procedure is done with remaining data-points. Descriptive statistics like mean, maximum and minimum are derived from the respective ensemble diurnal data. Due to the nature of the data analysis, the statistics used in the study will reflect the mean of the mean, mean maximum and mean minimum values (e.g. Tables 5.1 – 5.3).

4.9.2 WIND DIRECTION

The mean wind direction is determined by frequency analysis based on 90 ° sectors. Wind direction is averaged at each time-stamp for all days in the month to give the monthly-stratified diurnal variation of wind direction. The averaging at each time-stamp is based on the dominant wind direction derived from frequency analysis of wind direction data from all four sectors (0 – 90 °, 91 – 180 °, 181 – 270 ° and 271 – 360 °). For example, if at 0100 hrs, 88 % of the wind originates from the 91 - 180 ° sector, the average wind direction at that time-stamp i.e. 0100 hrs will reflect the average value of all wind direction samples within this sector. The computation of mean monthly wind direction follows the same procedure. The frequency of wind direction for each sector is computed from the monthly-stratified diurnal data to determine the dominant wind direction for the month. Once the dominant wind direction has been determined, the average wind direction for the month is computed by averaging the all values within the sector (Table 6.1). For example, if within the monthly-stratified diurnal ensemble of wind direction 60 % of the wind originates from the 0 - 90 ° sector, the average wind direction for the month will reflect the average value of all samples within this sector i.e. 0 - 90 °. The average wind direction analysis is sub-divided into all-day, daytime (0600 - 1750 hrs), and nighttime (1800 – 0550 hrs) cases.

4.9.3 CORRELATION AND STATISTICAL SIGNIFICANCE

The analysis of data in this study involves finding the relationship between two variables (e.g. CO_2 concentration and wind direction). The strength of the correlation, r, is determined using Pearson Product-Moment Correlation Coefficient which is expressed as:

$$r = \frac{N\Sigma xy - (\Sigma x)(\Sigma y)}{\sqrt{\left([N\Sigma x^2 - (\Sigma x)^2]\,[\mathrm{N}\Sigma y^2 - (\Sigma y)^2] \right)}}$$

where N = sample size and x and y are variables 1 and 2, respectively. Statistical test on the significance of the correlation is conducted at p = 0.05 (where p = level of significance) using one-tailed test statistic, t, expressed as:

$$t = \frac{r}{\sqrt{\left([1 - r^2] / [N - 2] \right)}}$$

where r = correlation coefficient, N = sample size, and N - 2 = degrees of freedom, df. The significance of the correlation is then compared against the Critical Values of the t Distribution, t_c. The strength of correlation is statistically significant if $t > t_c$ for a given df where p = 0.05 evaluated with a one-tailed test.

CHAPTER 5

– RESULTS –

This chapter presents results from the 8-month observation period. It addresses the objectives of the study as set out in Chapter 3. First, patterns of CO_2 concentration over Singapore will be discussed over diurnal, monthly and seasonal time scales, respectively (Sections 5.1 - 5.3). Second, the spatial variability of CO_2 concentration over different land-use types will be discussed (Section 5.4). Third, results of car traverses will be presented to assess the nature of the urban CO_2 enhancement (dome) (Section 5.5). The chapter finishes with a discussion of the vertical variation of CO_2 concentration (Section 5.6).

5.1 DIURNAL VARIATION OF CO_2 CONCENTRATION

Figure 5.1 shows the diurnal variation of urban and rural CO_2 concentrations during the 8-month observation period measured at the two main sites (Fig. 4.16). It can be seen that there are distinct differences in the general pattern. Characteristics of CO_2 concentration at the rural site can be identified by the following features: (1) Low concentration throughout the day from 0900 - 1700 hrs with concentration reaching a minimum value of 353 ppm, (2) steady increase in concentration from 1700 – 0500 hrs with a maximum value of 455 ppm attained during pre-dawn hours, (3) rapid drop in concentration between 0630 – 0900 hrs, and (4) large diurnal amplitude of 103 ppm. The pattern is not repeated at the urban site which instead shows more irregularities. Four important characteristics can be noted: (1) Generally uniform concentration throughout the day with the lowest value (380 ppm) observed in the early morning hours, (2) presence of two concentration peaks at 1230 hrs (404 ppm) and at 1900 hrs (413 ppm), respectively, (3) decreasing concentration after 1900 hrs throughout the night and (4) small diurnal amplitude of 33 ppm.

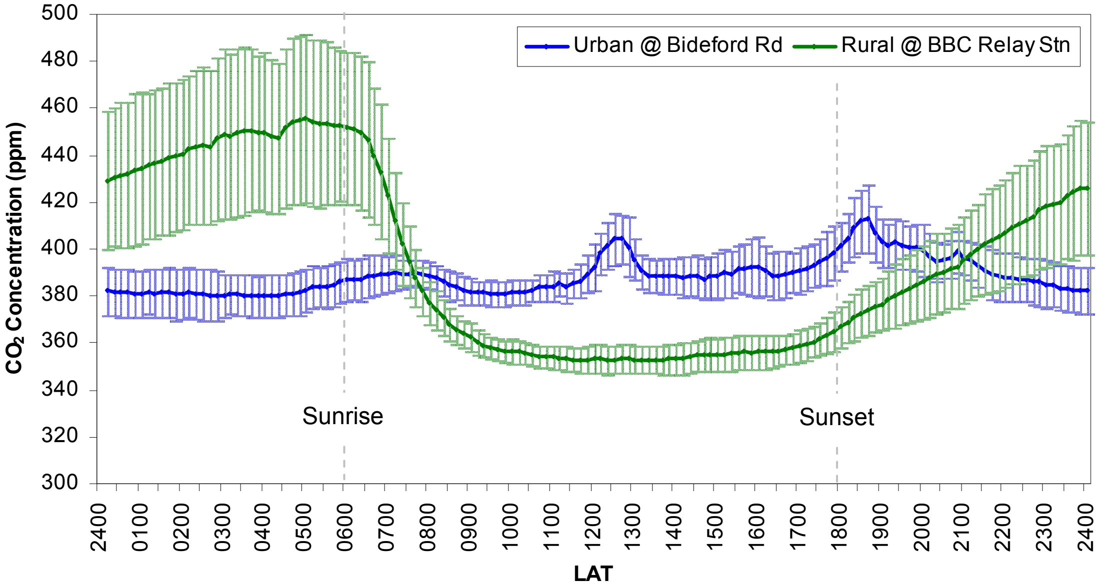

Figure 5.1: Diurnal variation (ensemble average) of urban and rural CO_2 concentrations from June 2006 - January 2007. Error bars indicate ±1 standard deviation.

Figure 5.2 shows CO_2 concentration difference between the urban and rural station, $\Delta CO_{2(urban-rural)}$, during the course of the fieldwork period. It shows the presence of an urban-induced CO_2 enhancement from 0730 - 2100 hrs with average enhancement of 28 ppm or 7 %. The two enhancement peaks correspond to two peaks observed in urban concentrations in Figure 5.1. At night, urban concentration is much lower (49 ppm or 13 %) compared to the rural value.

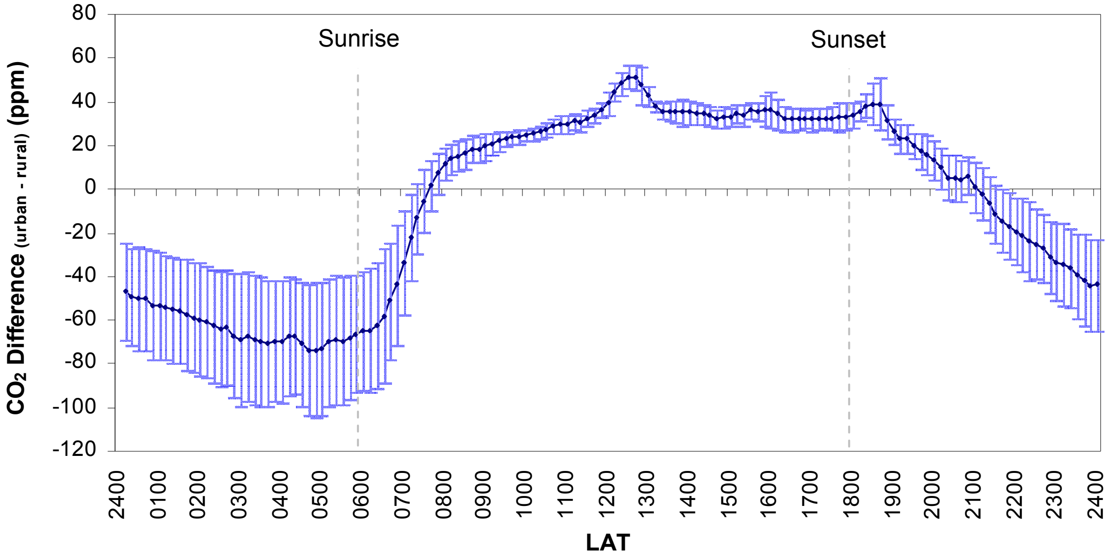

Figure 5.2: Diurnal variation of mean urban-rural CO_2 concentration difference, $\Delta CO_{2(urban\text{-}rural)}$, from June 2006 – January 2007. Error bars indicate ±1 standard deviation.

Results of the CO_2 concentration at the rural site are consistent with the findings of other studies conducted over rural environments (Tables 2.3 and 5.1). In terms of absolute values, there is a difference of approximately 55 ppm and 35 ppm for minimum and maximum CO_2 concentrations, respectively when compared to some of the studies (i.e. Cincinnati, Ithaca and Long Island) (Table 2.3). Greatest difference (80 ppm) in maximum concentration was seen when compared to Sutton Bonington while least difference (8 ppm) in minimum concentration was observed when compared to Sutton Bonington and Rondônia (Table 2.3). The pattern of CO_2 concentration at the rural site is typical of what one would expect of a naturally vegetated environment. In this respect, high concentration at night and low concentration during the day are due to the action of respiration (release) and photosynthesis (uptake) of CO_2, respectively. This contrasts with the urban site where the source of CO_2 is largely traffic and the absence or lack of CO_2 sinks in the form of vegetation suggests that CO_2 cannot be removed in the same way. Emitted CO_2 by vehicles during daytime increases the concentration relative to the rural value, whereas at night CO_2 emissions from vegetation are absent. This discussion ignores any meteorological effects but in part accounts for the less pronounced concentration pattern at the urban site. Table 5.1 compares concentrations at both sites. Interestingly, average concentration at the urban site is lower than at the rural site.

Table 5.1: Comparison of mean CO_2 concentration (ppm) values at the rural and urban sites in Singapore from June 2006 - January 2007. Vegetation fractions are 5 % and 80 % for urban and rural sites, respectively.

	Urban	**Rural**
Mean Maximum	413	455
Mean Minimum	380	353
Mean	389	394
Mean Diurnal Amplitude	33	103

Figures 5.3 and 5.4 show the diurnal variation of CO_2 concentration stratified by month at the urban and rural sites, respectively. While there exist several irregularities, the diurnal pattern for each month at the urban site conforms well to the characteristics of the 8-month ensemble pattern (Fig. 5.1) which includes the presence of two peaks and generally small variation throughout the day. At the rural site, similar consistency with the 8-month ensemble data exists with the exception of significant irregularities during the pre-dawn hours. At both sites, the overall shape of the concentration patterns remains the same from month to month but the absolute magnitudes decrease towards January. Monthly variation of CO_2 concentration will be discussed in greater detail in Section 5.2.

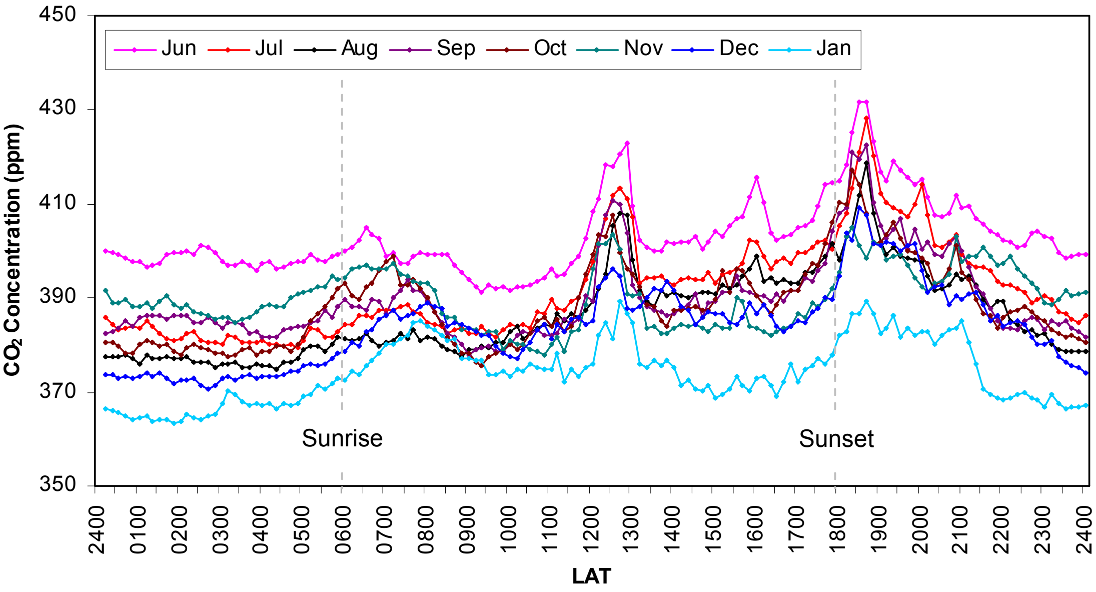

Figure 5.3: Monthly-stratified diurnal variation of CO_2 concentration at the urban site from June 2006 - January 2007.

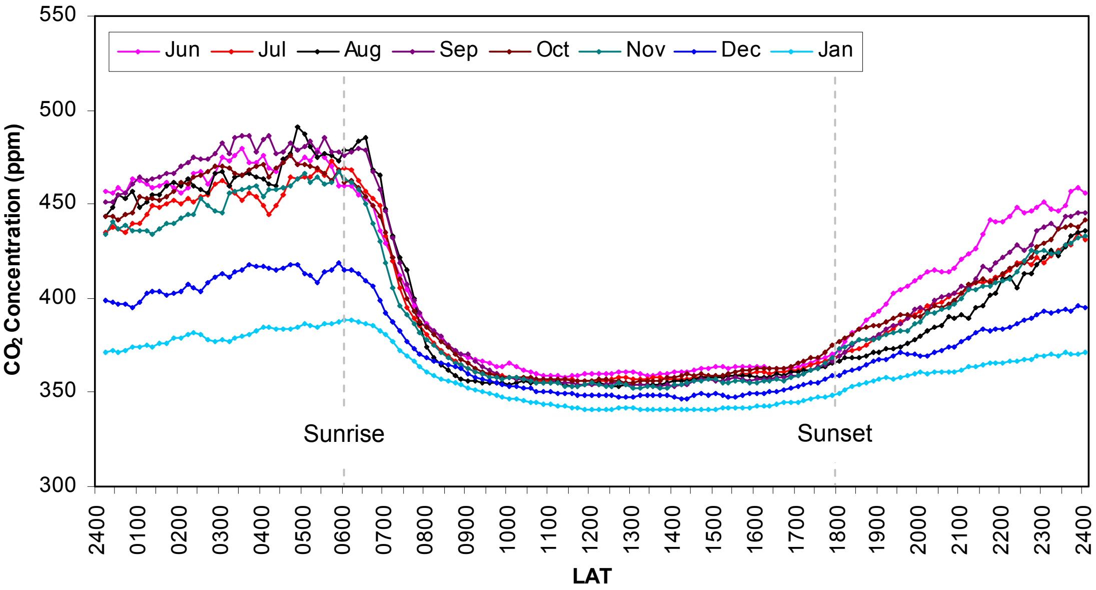

Figure 5.4: Monthly-stratified diurnal variation of CO_2 concentration at the rural site from June 2006 – January 2007

5.2 MONTHLY VARIATION OF CO_2 CONCENTRATION

Monthly variation of CO_2 concentration at the main urban and rural sites is given in Figures 5.5 and 5.6, respectively. Ensemble CO_2 concentration values are summarized in Table 5.2. In general, CO_2 concentration at the urban site shows a downward trend since the start of the observation period (Table 5.2). A similar trend exists at the rural site. Highest and lowest mean values for both sites are found in June 2006 (urban: 403 ppm, rural: 409 ppm) and January 2007 (urban: 374 ppm, rural: 361 ppm), respectively. Also noted is the variability in mean diurnal amplitude which is more prominent at the rural than at the urban site (Table 5.2). Variability is generally larger at the rural compared to the urban site (Fig. 5.6). The variability in standard deviation may be due to variation in the strength of emission sources and meteorological controls such as wind speed and direction. At the urban site, uniform standard deviation suggests that the strength of emission sources, which is largely from traffic, is consistent during each month. This implies that the number of vehicles at the urban site does not vary much between months. At the rural site, pattern of mean monthly standard deviation may reflect the respiratory-photosynthetic behavior of vegetation and soil micro-organisms.

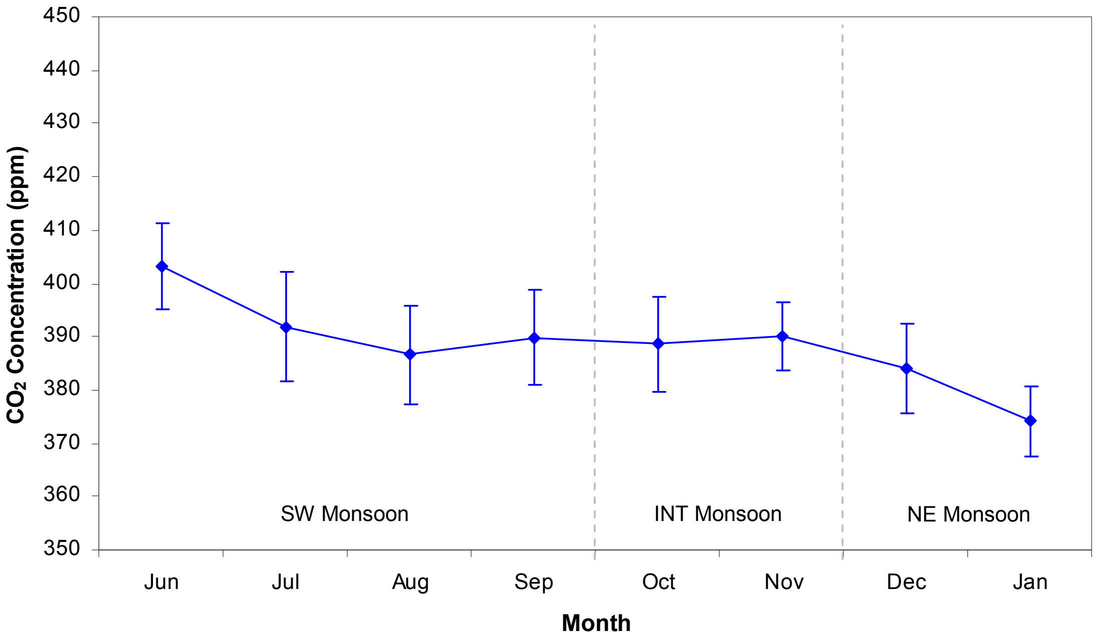

Figure 5.5: Mean monthly variation of CO_2 concentration at the main urban site from June 2006 – January 2007. Error bars indicate ±1 standard deviation.

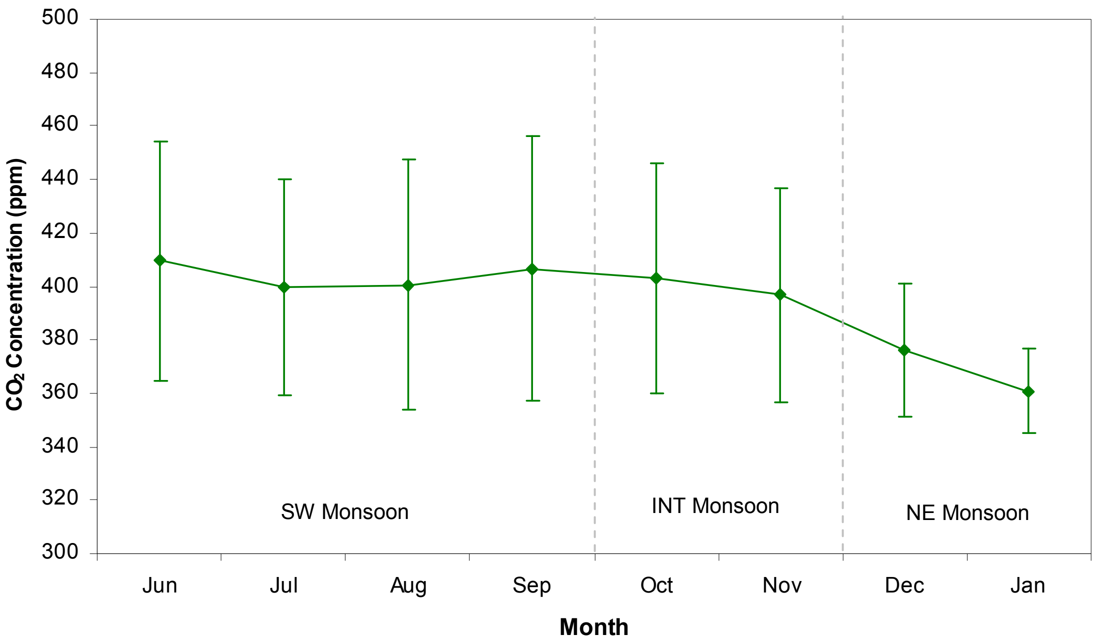

Figure 5.6: Mean monthly variation of CO_2 concentration at the main rural site from June 2006 - January 2007. Error bars indicate ±1 standard deviation.

Table 5.2: Monthly CO_2 concentration values (in ppm) at the urban and rural sites from June 2006 - January 2007. Values are ensemble 10-minute averages.

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Urban								
Mean Maximum	432	428	419	422	417	405	409	389
Mean Minimum	391	380	375	378	376	378	370	363
Mean	403	392	387	390	389	390	384	374
Mean Amplitude	40	49	44	45	41	27	39	26
Rural								
Mean Maximum	479	473	491	486	475	467	419	389
Mean Minimum	358	356	353	353	355	352	346	340
Mean	409	400	400	407	403	397	376	361
Mean Amplitude	121	117	138	133	120	115	73	48
Difference$_{(Urban - rural)}$								
Mean Maximum	-47	-45	-72	-64	-58	-62	-10	0
Mean Minimum	33	24	22	25	21	26	24	23
Mean	-6	-8	-13	-17	-14	-7	8	13

5.3 SEASONAL VARIATION OF CO_2 CONCENTRATION

Classification of monthly CO_2 concentration into seasonal categories gives a better picture on the influence of the SW, NE and inter-monsoon periods on the level of atmospheric CO_2 concentration (Fig. 5.7). Seasonal means are calculated by obtaining the average CO_2 concentration for the respective months as defined in Table 4.3. Statistics on ensemble mean, maximum and minimum values are given in Table 5.3.

During the SW monsoon, concentrations are higher at both sites. This can be seen in the ensemble mean maximum, minimum and average values where concentrations are higher than during the NE or the inter-monsoon periods (Table 5.3). One aspect worth noting is the variation in diurnal amplitude during different periods. At the urban site, the amplitude experiences a moderate decrease of 10 ppm (26 %) from 42 ppm during the SW to 31 ppm during the NE monsoon. The degree of change is greater at the rural site which sees a 50 % (61 ppm) drop in amplitude from 121 ppm during the SW to 60 ppm during the NE monsoons.

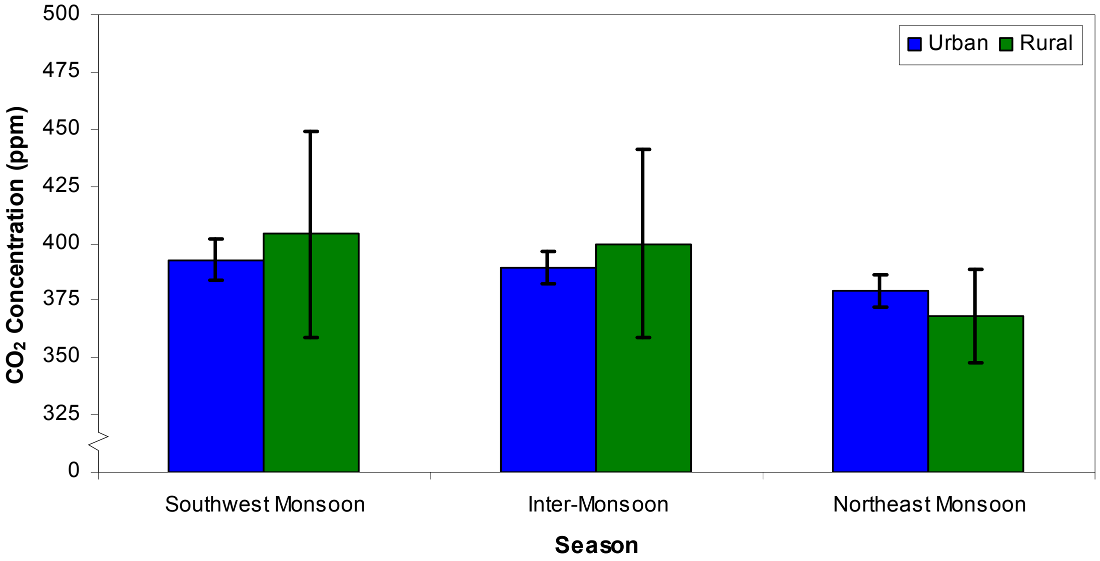

Figure 5.7: Mean seasonal variation of CO_2 concentration at the main rural and urban sites from June 2006 – January 2007. Error bars indicate ±1 standard deviation.

Table 5.3: Seasonal variation of CO_2 concentration (ppm) at the urban and rural sites. Seasons are classified as Southwest (June – September), inter-monsoon (October – November) and Northeast (December – January). Values are 10-minute ensemble averages.

	Urban			**Rural**		
	SW Monsoon	**Inter monsoon**	**NE Monsoon**	**SW Monsoon**	**Inter monsoon**	**NE Monsoon**
Mean Maximum	425	411	398	477	469	403
Mean Minimum	383	379	368	356	354	344
Mean	393	389	379	404	400	368
Mean Amplitude	42	32	31	121	115	60

Observation of seasonally-stratified diurnal patterns shows that CO_2 concentration pattern during the inter-monsoon period lie closer to the SW monsoon, making it difficult to distinguish between the influence of the SW and the inter-monsoon periods on the CO_2 concentration pattern (Figs. 5.8a, b). The pattern is more apparent at the rural site where CO_2 concentrations during the SW and inter-monsoon periods show no variability – average difference of 4 ppm – with daytime values (0800 - 1800 hrs) resembling an almost perfect fit (Fig. 5.8b). With regards to CO_2 enhancement (Fig. 5.8c), there is little difference in the percentage increase in the degree of enhancement during the various seasons. During the SW monsoon, the magnitude is 2 % (56 ppm) greater than during other periods (NE: 47 ppm or 14 %, inter-monsoon: 51 ppm or 14 %).

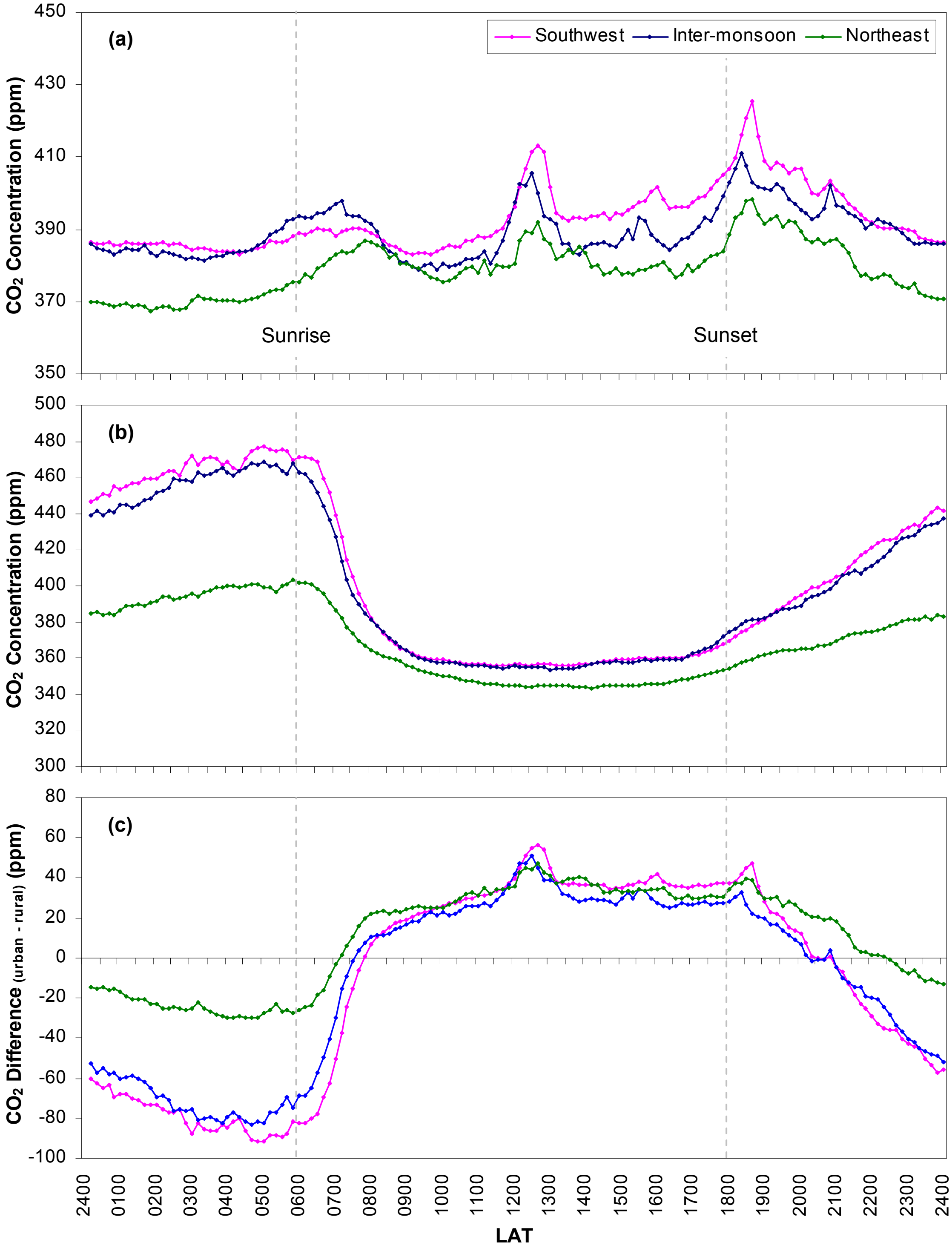

Figure 5.8: Diurnal variation of CO_2 concentration for different seasons at: (a) urban and (b) rural sites, and (c) magnitude of CO_2 enhancement from June 2006 - January 2007.

5.4 SPATIAL VARIABILITY OF CO_2 CONCENTRATION

Spatial sampling seeks to elucidate the variability of CO_2 concentration across different urban land-use types. Sampling was conducted over high-rise residential, low-rise low-density residential, low-rise high-density residential and heavy industrial areas as pointed out in Section 4.4. Additional sampling was conducted within urban and rural sites where the respective fixed stations were located to assess intra-urban and -rural variability. This data will be discussed first and will give insight on whether the CO_2 concentrations observed by the two fixed stations are representative of their respective environments.

5.4.1 INTRA–URBAN AND –RURAL VARIABILITY

Patterns of concentration observed at the rural site in comparison with the two intra-rural sampling sites at Murai Farmway and LCK AgriBioPark match closely to one another (Fig. 5.9). The data reveal little difference in minimum concentration but somewhat greater variability in maximum concentration observed at the three sites (Table 5.4). The rural site is 25 ppm lower compared to the site at Murai Farmway whereas compared to the LCK AgriBioPark site, it is 31 ppm higher. Average values for the three sites show that concentration at the rural site (396 ppm) is 12 ppm lower than concentration at Murai Farmway sampling site (408 ppm). On a separate observation period, concentration at the rural site (411 ppm) is 10 ppm higher than the concentration at the sampling site at LCK AgriBioPark (401 ppm). The study concludes that the selected reference site (BBC Relay Station) is representative of rural CO_2 concentration.

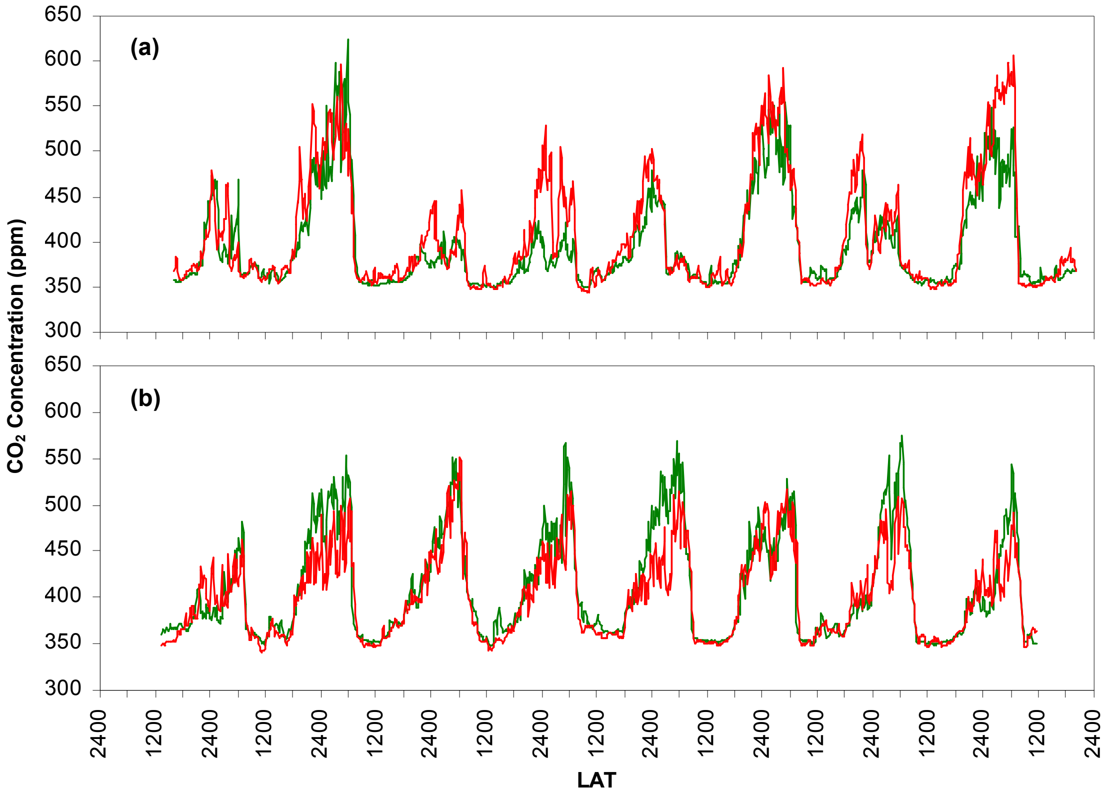

Figure 5.9: Patterns of CO_2 concentration from the two intra-rural sampling sites (red line) at: (a) Murai Farmway from 5 - 13 July 2006 and (b) LCK AgriBioPark from 16 - 24 July 2006 in comparison with the main rural site (green line).

Table 5.4: Variability of CO_2 concentration (ppm) at the two intra-rural sampling sites, in comparison with the main rural site (80 % vegetation fraction), from 5 - 13 July 2006 (Murai Farmway) and 16 - 24 July 2006 (LCK AgriBioPark). Values shown are ensemble 10-minute averages. Vegetation fractions for Murai Farmway and LCK AgriBioPark are 95 % and 75 %, respectively.

	Rural (BBC Relay Stn) (1)	**Mobile (Murai Farmway) (2)**	**(1) - (2)**	**Rural (BBC Relay Stn) (1)**	**Mobile (LCK AgriBioPark) (2)**	**(1) - (2)**
Mean Maximum	459	483	-25	518	487	31
Mean Minimum	357	355	2	354	352	2
Mean	396	408	-11	410	401	9

Patterns of CO_2 concentration for the two intra-urban spatial sampling sites at Cairnhill Road and at Bideford Road Main throughout the respective observation period are given in Figure 5.10. At the main urban site, average concentration is about 10 ppm higher than concentrations recorded at the two spatial sampling sites. Difference in maximum concentration observed is variable i.e. the urban site is 37 ppm and 14 ppm higher than at Cairnhill Road and at Bideford Road Main (Table 5.5). Nighttime minimum concentration usually agrees well across all the urban sites with the main urban site being higher by 5 ppm and 8 ppm, respectively. Note that the concentration peak which forms at the urban site circa 1200 – 1400 hrs coincides with Islamic prayer session every Friday (Fig. 5.10b). However, the peak was either not clearly visible on some Fridays (Fig. 5.10a and 5.11b). The rise in concentration, presumably contributed by both traffic and human respiration, is not considered a spike which would otherwise be omitted. Similar to the main rural site, CO_2 concentration measured at the urban reference site (Bideford Road) can be considered as representative of CO_2 concentration in Singapore's city-centre.

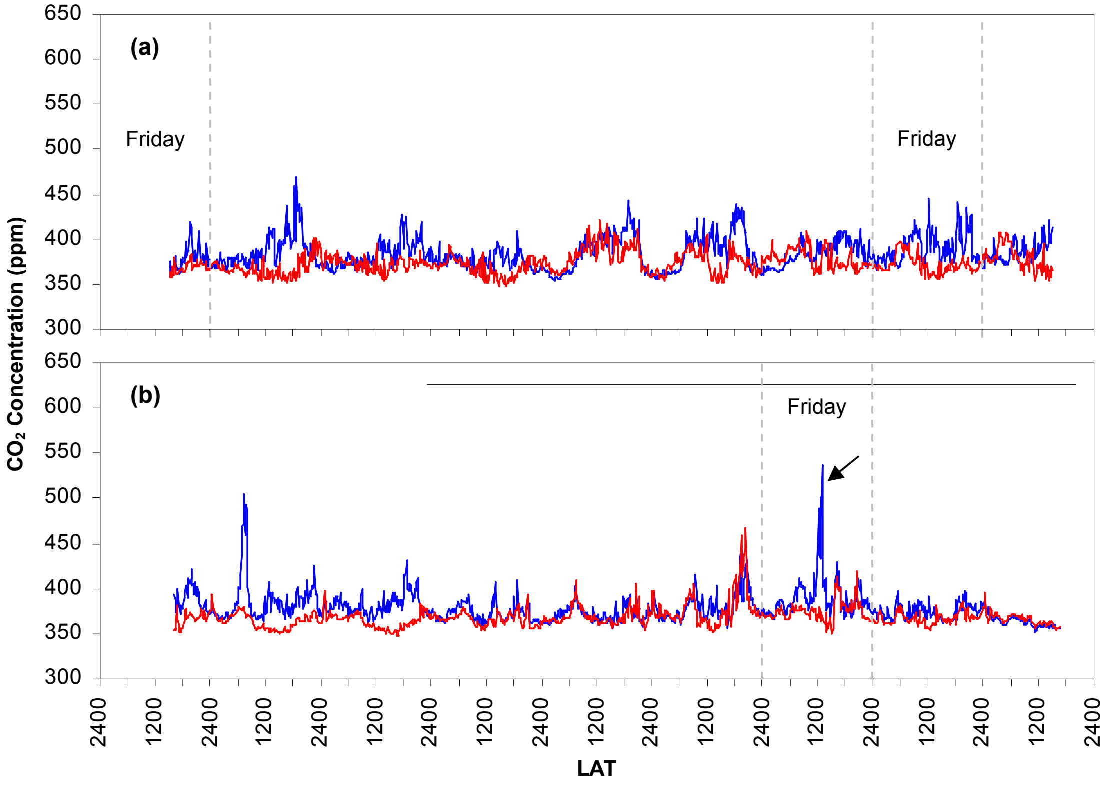

Figure 5.10: Patterns of CO_2 concentration from the two intra-urban sampling sites (red line) at: (a) Cairnhill Road from 22 – 30 December 2006 and (b) Bideford Road Main from 30 December 2006 – 7 January 2007 in comparison with the main urban site (blue line). Peak in concentration (indicated by arrow) coincides with Islamic prayer session from 1200 – 1400 hrs.

Table 5.5: Variability of CO_2 concentration (ppm) at the two intra-urban sampling sites in comparison with the main urban site (5 % vegetation fraction) from 22 – 30 December 2006 (Cairnhill Road) and 30 December – 7 January 2007 (Bideford Road Main). Values are ensemble 10-minute averages. Values for Bideford Road are inclusive of Friday peaks (1200 – 1400 hrs). Vegetation fractions for Cairnhill Road and Bideford Road Main are 40 % and 10 %, respectively.

	Urban (Bideford Rd) (1)	Mobile (Cairnhill Rd) (2)	(1) - (2)	Urban (Bideford Rd) (1)	Mobile (Bideford Rd Main) (2)	(1) - (2)
Mean Maximum	420	383	37	399	385	14
Mean Minimum	367	362	5	366	358	8
Mean	384	373	11	379	368	10

5.4.2 SPATIAL VARIABILITY OF CO_2 CONCENTRATION ACROSS DIFFERENT URBAN LAND– USE TYPES

Spatial sampling at four urban land-use types (heavy industrial, high-rise residential, low-rise low-density residential and low-rise high-density residential) was conducted for a period of eight days using a mobile station between 25 September 2006 – 16 January 2007. The patterns of CO_2 concentration over the duration of the sampling period are depicted in Figure 5.11. In general, maximum, minimum and average concentrations at the main urban site are always higher than those observed at the sampling sites. Considering mean and maximum CO_2 concentrations, the smallest difference is observed at the high-rise residential site (Hougang) and the highest difference at the heavy industrial site (Shipyard Cresent) (Table 5.6). Minimum CO_2 concentrations at the four sites reveal a consistent difference of about 10 – 13 ppm with respect to the main urban site. Difference in concentration between the main urban and the inter-urban sampling sites suggest the influence of urbanization and anthropogenic CO_2 emissions are different from site to site.

Statistics in Table 5.6 show that the high-rise residential site bears closest resemblance to the main urban site. This is followed by the low-rise high-density residential and low-rise low-density residential sites. The heavy industrial site on the other hand shows the largest difference. The results observed can be understood in terms of the amount of urbanization, and greenspace in the immediate vicinity of the respective sites. For example, highest CO_2 concentration at the high-rise residential site as compared to other sites may be due to a combination of sparse vegetation (isolated trees), small greenspaces, and canyon setting in addition to it being a carpark (hence higher traffic) (Fig 4.10). The correlation between vegetation fraction and CO_2 concentrations will be reviewed in Section 6.2. Observation also shows that low-rise low-density residential, low-rise high-density residential and to a lesser extent, the high-rise residential follow the rural CO_2 variation. This can be seen in the patterns of CO_2 concentration where daytime values are almost the same but early morning values are lower (Figs. 5.11b - 5.11d). This suggests that the capacity of these suburban land-uses for respiration is much lower due to the much lower vegetation cover than at the rural location. It is however surprising to see that the activities in the industrial site do not contribute to higher CO_2 concentration during daytime as expected despite being in the vicinity of CO_2-producing oil refinery industries (Fig. 5.11a). This issue will be addressed in Section 6.2

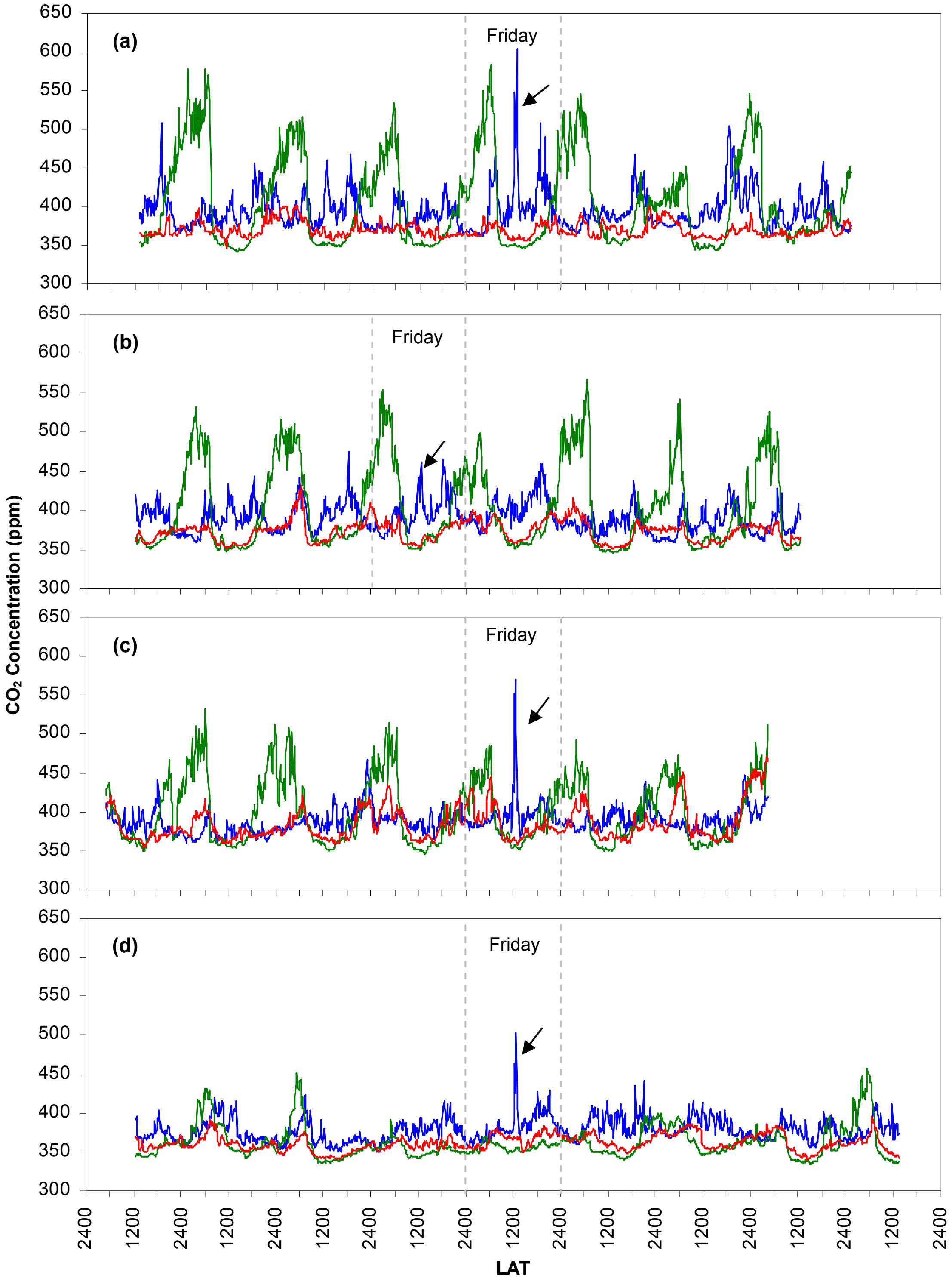

Figure 5.11: Patterns of CO_2 concentration from the four inter-urban sampling sites (red line) at: (a) Shipyard Crescent (heavy industrial) from 25 September - 3 October 2006, (b) Portsdown Road (low-rise low-density residential) from 3 - 10 October 2006, (c) Hougang (high-rise residential) from 23 - 30 October 2006 and (d) Telok Kurau (low-rise low-density residential) from 8 - 16 October 2007 in comparison with the main urban (blue line) and rural (green line) sites. Peak in concentration (indicated by arrow) coincides with Islamic prayer session from 1200 - 1400 hrs.

Table 5.6: Variability of CO_2 concentration (ppm) at four inter-urban sampling sites in comparison with the main urban and rural sites. Values indicated are ensemble 10-minute averages. Values at the urban main site are inclusive of Friday peak (1200 – 1400 hrs) values. Vegetation fractions for the four inter-urban sampling sites are 40 % (Shipyard Crescent), 90 % (Portsdown Road), 30 % (Hougang) and 35 % (Telok Kurau). Main urban and rural sites have vegetation fractions of 5 % and 80 %, respectively.

	Heavy Industrial @ Shipyard Crescent (25 September – 3 October 2006)					**Low-Rise Low-Density Residential @ Portsdown Road (3 – 10 October 2006)**				
	Urban (1)	**Rural (2)**	**Mobile (3)**	**(1) - (3)**	**(2) - (3)**	**Urban (1)**	**Rural (2)**	**Mobile (3)**	**(1) - (3)**	**(2) - (3)**
Mean Maximum	464	498	381	83	117	441	501	388	53	112
Mean Minimum	371	351	361	10	-10	369	352	357	13	-4
Mean	394	405	370	24	36	390	404	373	17	31

	High-Rise Residential @ Hougang (23 – 30 October 2006)					**Low-Rise High-Density Residential @ Telok Kurau (8 – 16 January 2007)**				
	Urban (1)	**Rural (2)**	**Mobile (3)**	**(1) - (3)**	**(2) - (3)**	**Urban (1)**	**Rural (2)**	**Mobile (3)**	**(1) - (3)**	**(2) - (3)**
Mean Maximum	414	474	421	-7	52	398	398	379	18	19
Mean Minimum	376	353	364	13	-11	362	344	351	11	-7
Mean	388	400	384	4	16	378	362	361	17	0

5.5 THE URBAN CO_2 ENHANCEMENT

Investigation of the urban CO_2 enhancement (dome) was conducted by means of car traverses at dawn (0300 – 0445 hrs) and midday (1130 – 1300 hrs) on 11, 13 and 15 February 2007. A total of two pre-dawn and three midday runs across different land-use types (Figure 4.17) were completed. Each land-use type takes on average 2 – 3 minutes to complete. Data for each land-use type are presented in Table 5.7 and Figures 5.12 and 5.13.

Table 5.7: Mean CO_2 concentration values (ppm) for each land-use type based on car traverses at midday (1130 - 1300 hrs) and at pre-dawn (0300 - 0445 hrs) on 11 February (Sunday), 13 February (Tuesday) and 15 February (Thursday) 2007. Mean CO_2 concentration for each land-use type is derived by averaging the individual 3-second values over the respective land-use type.

	Midday				**Pre-Dawn**		
	11 Feb	**13 Feb**	**15 Feb**	**Average**	**13 Feb**	**15 Feb**	**Average**
Low-Rise Low-Density Residential	348	345	359	350	356	362	359
City Centre	415	411	434	420	365	362	364
Low-Rise High-Density Residential	357	360	367	361	356	366	361
High-Rise Residential	349	353	350	351	358	356	357
Light Industrial	353	367	377	366	362	357	360
Rural	350	341	347	346	413	380	396
Heavy Industrial	352	375	393	373	368	358	363

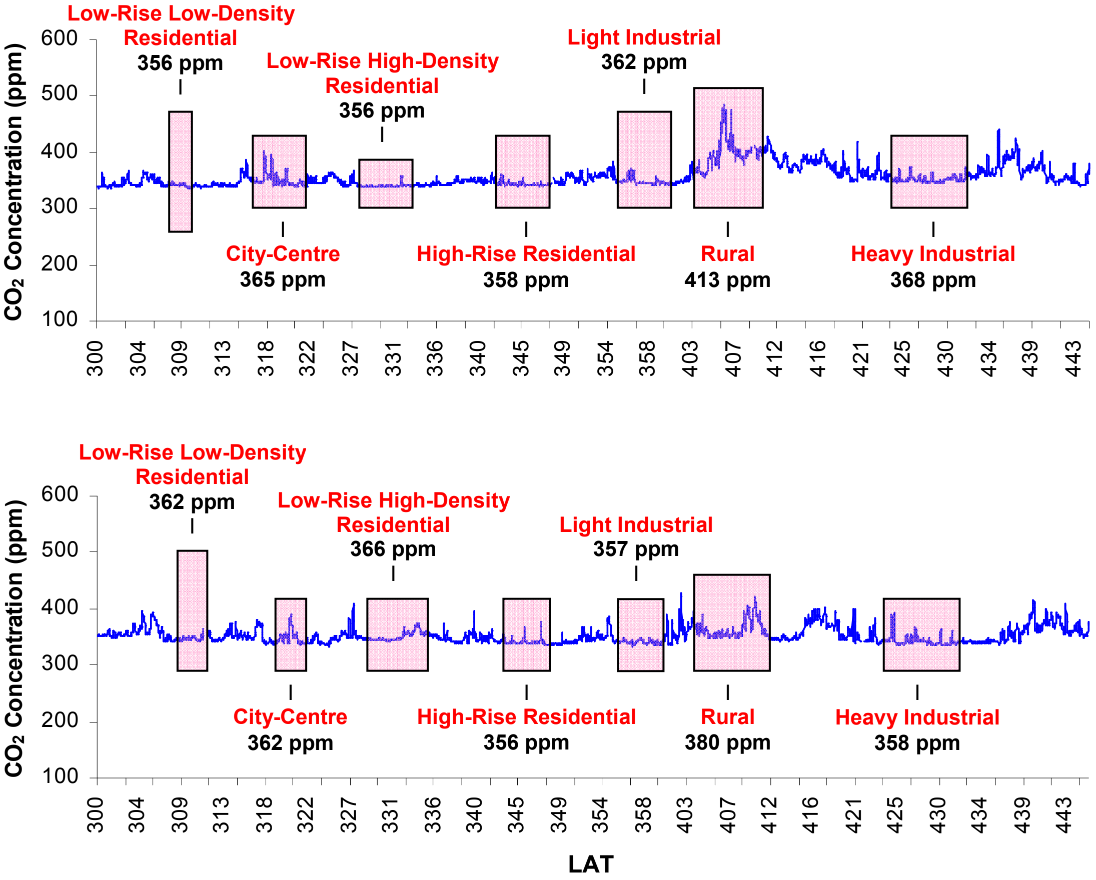

Figure 5.12: Variation of CO_2 concentration across different land-use types based on car traverses at pre-dawn (0300 - 0445 hrs) on 13 February (top) and 15 February 2007 (bottom). Blue line shows the individual 3-second CO_2 concentration values. Data shown are mean CO_2 concentration for each land-use type derived by averaging the individual 3-second values over the respective land-use type (indicated by boxes).

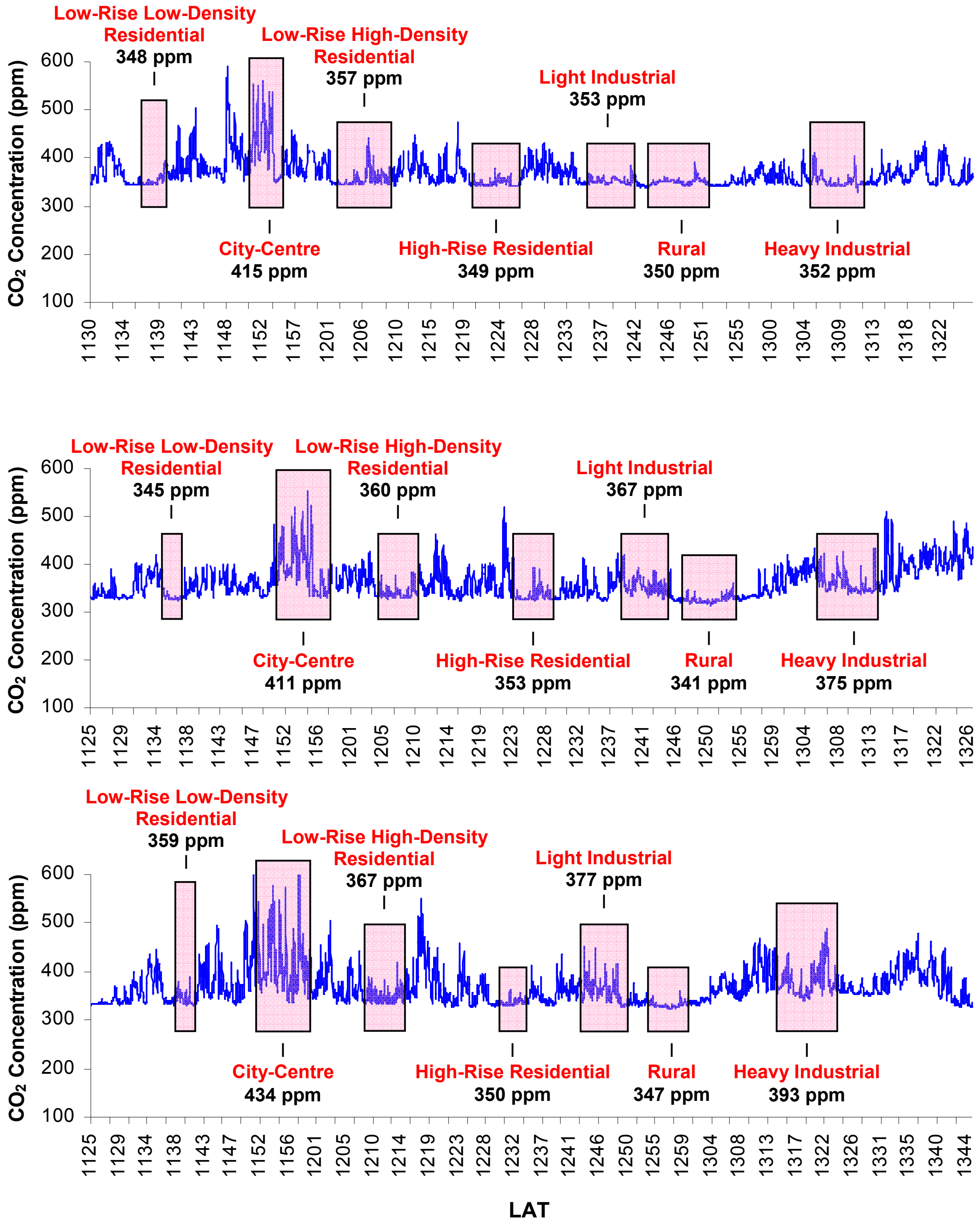

Figure 5.13: Variation of CO_2 concentration across different land-use types based on car traverses at midday (1130 - 1300 hrs) on 11 February (top), 13 February (middle), and 15 February 2007 (bottom). Blue line shows the individual 3-second CO_2 concentration values. Data shown are mean CO_2 concentration for each land-use type derived by averaging the individual 3-second values over the respective land-use type (indicated by boxes).

Results from the traverses conducted at pre-dawn show high concentration averaging 396 ppm over the rural area with values 33 - 37 ppm higher than other land-use types which all show similar concentrations (Fig. 5.12 and Table 5.7). The trend is reversed at midday which shows higher CO_2 concentration in the city-centre (mean: 420 ppm) which is on average 47 – 74 ppm higher than other land-use types (Fig. 5.13 and Table 5.7). Values in the heavy industrial area were second highest while the rural land-use showed the lowest concentrations as expected. In addition to the relatively strong midday urban enhancement (dome), there is a larger day-to-day variability for midday values (Table 5.7). No significant difference could be observed between weekend (11 February) and weekdays (13 and 15 February) CO_2 concentrations. Compared to studies conducted elsewhere, the intensity of CO_2 dome observed is smaller (Table 2.6) with the urban mean peak value only 74 ppm (21 %) greater than the rural baseline value. Results of the car traverses are consistent with the data from the spatial sampling which shows higher CO_2 concentration at the city-centre than at each sampling site during the respective observation period.

5.6 VERTICAL VARIATION OF CO_2 CONCENTRATION AT THE MAIN URBAN SITE

The site and elevation (3.5 m above ground level) of the main urban site have been selected to be representative of the canyon-layer environment. Short-term spatial sampling has been conducted to get an initial estimate of the potential variation of CO_2 concentration with height using an additional sensor located just above the top of the canyon (27 m above ground level) (Fig. 4.18).

Nighttime concentrations agree very well with each other whereas daytime values within the canyon are systematically larger (Fig. 5.14). This is similar to the findings by Vogt et al. (2006) who found decreasing concentration with height throughout the canyon and above (more so during the day than at night). The narrow and often shaded canyon at the present main urban site inhibits mixing of the canyon air during daytime and hence the CO_2 emitted near the canyon floor cannot easily be dispersed upwards. This may explain the larger difference in CO_2 concentration between the two heights. The well-matched CO_2 concentration patterns during nighttime may possibly be caused by effective mixing brought about by the warming of the surface, i.e. the UHI effect which transports CO_2 upwards and the downdraft of cool air from above. The well-matched patterns could also be due to the lack of traffic during nighttime. Lower traffic suggests lower CO_2 emissions hence there is low variability in concentration observed at the two heights.

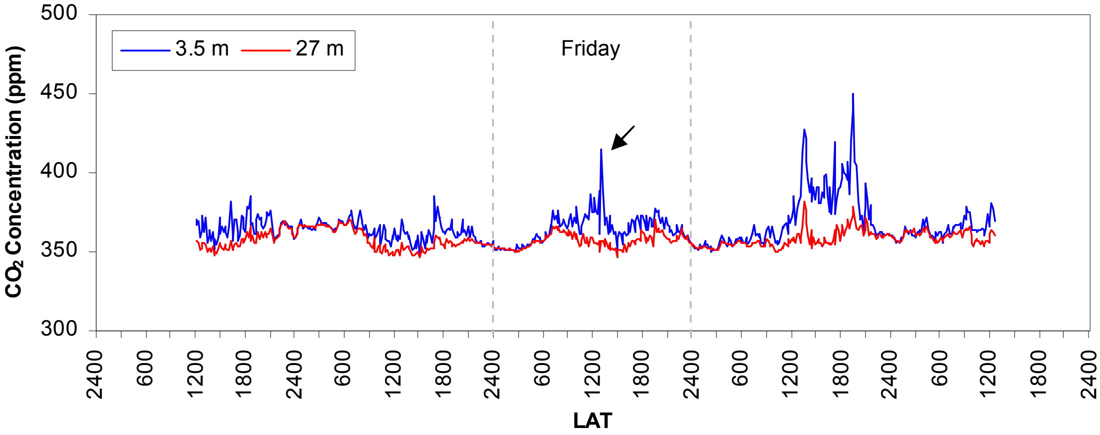

Figure 5.14: Comparison of CO_2 concentrations at 3.5 m and at 27 m at the main urban site from 31 January - 5 February 2007. Refer to Figure 4.18 for the locations of the two sensors. Peak in concentration (indicated by arrow) coincides with Islamic prayer session from 1200 – 1400 hrs.

CHAPTER 6

– DISCUSSION –

This chapter discusses the results presented in Chapter 5. Several questions need to be addressed, particularly the pattern of temporal variability of CO_2 concentration. Issues include why average CO_2 concentration is higher at the rural compared to the urban site during most of the observation period and why concentrations in December and January are lower than during other months. CO_2 concentration will be examined in relation to meteorological variables like wind speed and direction and rainfall. To explain the diurnal variability of concentration at the urban site, relationship between CO_2 concentration and traffic is sought. The spatial variability of CO_2 concentration amongst sampling sites will also be covered in this chapter. Finally, results from the present study will be compared with those from past studies.

6.1 TEMPORAL VARIABILITY OF CO_2 CONCENTRATION

Average CO_2 concentration is higher at the rural compared to the urban site during the months of June – November but lower in December and January (Table 5.2). In addition, the diurnal pattern of rural concentration shows significantly less pronounced variation in December and January (Fig. 5.4) particularly during nighttime. Classification of months into their respective seasons shows that the diurnal variability and absolute values of CO_2 concentration during the NE monsoon are significantly lower than during the SW or the inter-monsoon periods (Fig. 5.8). The diurnal variability and absolute values of CO_2 concentration during different months and seasons are therefore possibly affected by changes in wind direction.

Table 6.1 lists the frequency of wind direction derived from monthly-stratified diurnal ensemble for each month of the observation period as measured at the rural site (cf. Section 4.9.2). Wind direction frequency shows that in January, 69 % of the winds come from the northeast. This contrasts with June when 91 % of the winds come from the southwest. Statistics for remaining months are also included in the table. Overall, much of the winds throughout the observation period come from the southwest except for October and December where the wind direction is highly variable. Wind direction during nighttime shows a higher frequency of winds originating from the southwest for all months except January. This differs from the daytime case where the dominant wind direction is from the southwest (June – September), southeast (October – November) and northeast (December – January).

Table 6.1: Frequency of all-day, daytime and nighttime wind direction (%) derived from monthly-stratified diurnal ensemble of wind direction for each month measured at the rural site from June 2006 – January 2007.

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
All-day								
Northeast	0	0	0	0	0	9	39	69
Southeast	6	19	23	24	44	25	10	5
Southwest	91	74	67	72	54	62	41	15
Northwest	3	7	10	4	2	4	10	11
Daytime								
Northeast	0	0	0	0	0	18	57	69
Southeast	11	24	22	39	65	50	14	4
Southwest	88	75	75	58	33	26	15	6
Northwest	1	1	3	3	2	6	14	21
Nighttime								
Northeast	0	0	0	0	0	0	21	70
Southeast	0	15	24	10	24	0	7	4
Southwest	94	72	60	86	74	97	66	25
Northwest	6	13	16	4	3	3	6	1

The hypothesis is that during the SW monsoon, anthropogenic CO_2 from industrial areas southwest of the rural site gets transported up north consequently increasing the CO_2 concentration observed at the rural site. This is apparent for the case in June – September where higher CO_2 concentrations are observed. In December and January, upon the change in prevailing wind direction, the import of pristine air from the

Straits of Johor, north of the rural site, reduces the CO_2 concentration, hence lower CO_2 concentrations in December and January. If this hypothesis is true, then the relationship between CO_2 concentration and wind direction would be apparent.

Correlating wind direction and CO_2 concentration for each month reveals a relationship between the two variables (Fig. 6.1). Monthly mean CO_2 concentration and wind direction show that during the SW monsoon (June – September), high CO_2 concentration ranging 407 – 409 ppm is observed when winds are from the southwest (Fig. 6.1a). In January, due to the change in wind direction which now comes from the northeast, CO_2 concentration exhibits a much lower value of 361 ppm. The inter-monsoon period (October – November) reveals a pattern similar to that of the SW monsoon i.e. high concentration ranging 397 – 403 ppm corresponding to winds from the southwest during the same period of time. During nighttime, high CO_2 concentration during the months of June – November is observed when winds are from the southwest (Fig. 6.1b). December experiences lower CO_2 concentration than June – November despite winds originating from the same direction. The daytime case for all months except December sees a much lower CO_2 concentration despite winds originating from the same direction as the nighttime case (Fig. 6.1c). This can be understood by the assimilative action of plants which take in CO_2 during the day. Based on these observations, it is possible that changes in wind direction bring about different CO_2 concentration values observed. However, it only forms part of the explanation since it cannot account for the much lower nighttime concentration in December, compared to June – November, despite winds from the southwest (Fig. 6.1b). The strength of the correlation between mean monthly CO_2 concentration and wind direction as determined by the Pearson Product-Moment Correlation Coefficient shows strong positive correlation for nighttime (r = 0.79), all-day (r = 0.92) and daytime (r = 0.92) cases. In addition, results of t-test show statistically significant relationship ($t > t_c$) between CO_2

concentration and wind direction with t = 3.20 (nighttime), 5.74 (all-day), and 5.61 (daytime) where t_c = 1.94 and p < 0.05.

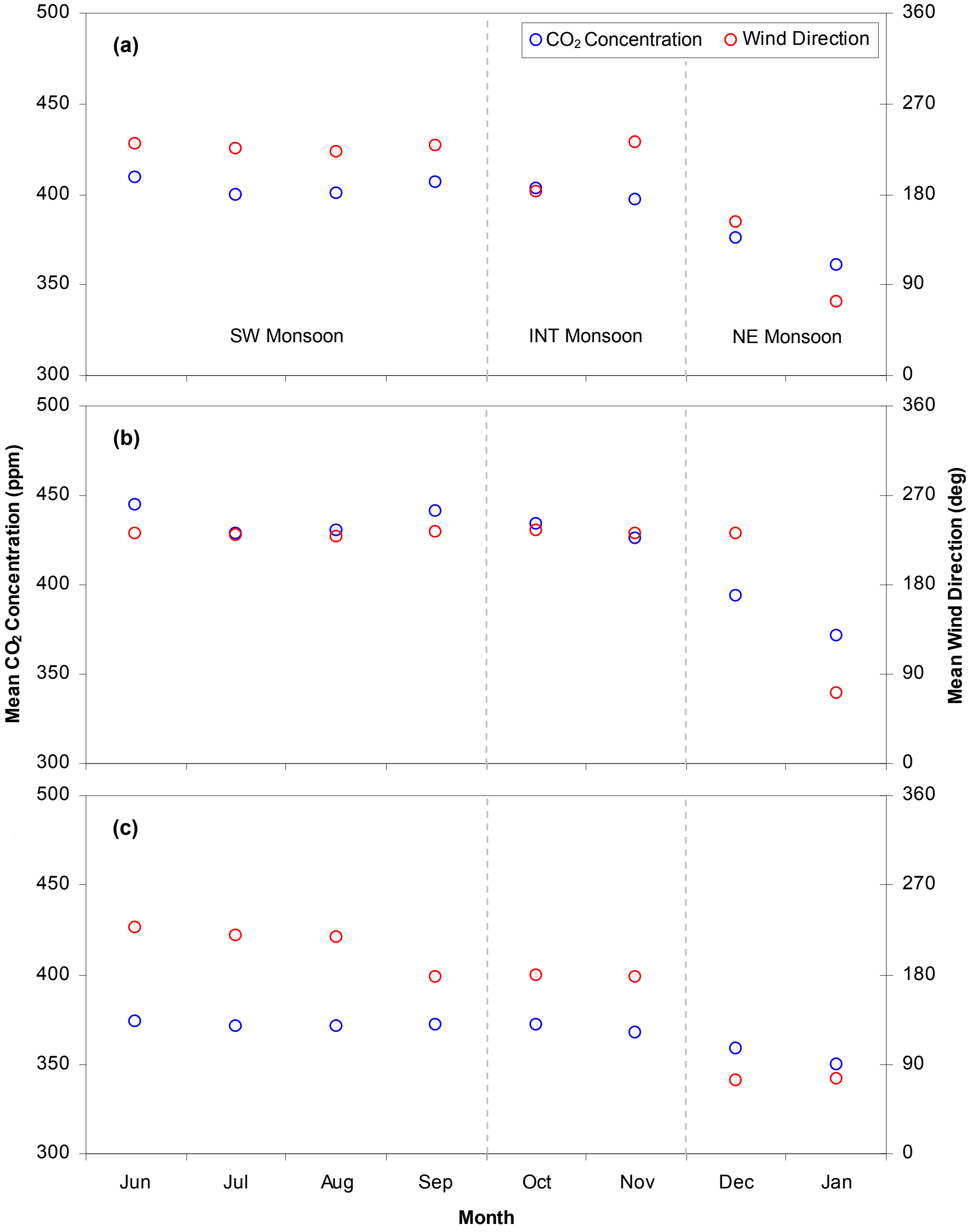

Figure 6.1: Mean CO_2 concentration and wind direction observed at the main rural site for (a) all-day, (b) nighttime and (c) daytime cases from June 2006 - January 2007.

The dispersive capability of the atmosphere increases with increasing wind speed which may therefore affect the level of CO_2 concentration. Table 6.2 shows the mean all-day, nighttime and daytime wind speeds for all months during the observation period as measured at the main rural site. It is evident that December and January are marked by higher wind speeds compared to the other months, a feature that is characteristic of the NE monsoon (Table 4.2). Analysis of wind speed and CO_2 concentration indicates higher CO_2 concentrations when wind speeds are low (Fig. 6.2a). The case of December which shows lower CO_2 nighttime concentration than June – November despite the same wind direction (Fig. 6.1b) may be supported by the higher wind speed in December which promotes CO_2 dispersion, hence lowering its nocturnal CO_2 concentration (Fig. 6.2b). Analysis of correlation between the mean monthly data-set for the two variables show a strong negative relationship where r = -0.99 (daytime), -0.98 (nighttime), and -0.99 (all-day). However, results of t-test show a statistically insignificant correlation ($t < t_c$) with t = -15.12 (daytime), -13.05 (nighttime) and - 17.56 (all-day) where t_c = 1.94, and $p > 0.05$. The discussion on the influence of wind speed and CO_2 concentration neglects any effects due to seasonal changes in vegetation which can still happen due to larger availability of moisture during the NE monsoon period.

Table 6.2: Mean all-day, daytime and nighttime wind speeds (m/s) observed at the main rural site from June 2006 – January 2007.

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Mean All-day	0.67	0.77	0.72	0.70	0.75	0.75	0.99	1.18
Mean Daytime	0.99	1.13	1.06	1.06	1.10	1.12	1.39	1.60
Mean Nighttime	0.35	0.41	0.38	0.34	0.40	0.38	0.60	0.77

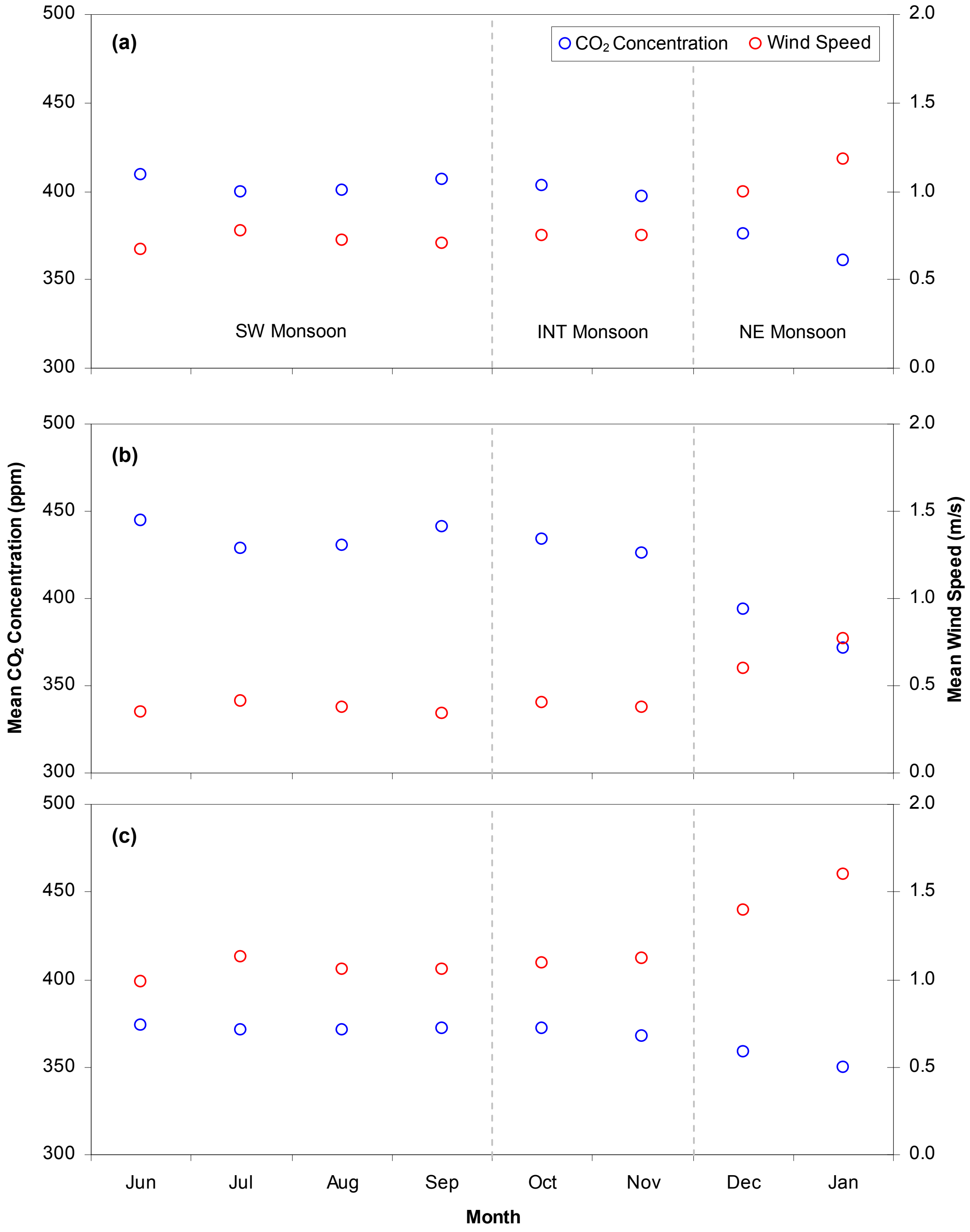

Figure 6.2: Mean CO_2 concentration and wind speed observed at the main rural site for (a) all-day, (b) nighttime and (c) daytime cases from June 2006 – January 2007.

Temporal variation of CO_2 concentration at the urban site can be discussed in terms of the absence of vegetation and contribution from traffic which forms the major anthropogenic source of CO_2 apart from human respiration. The lack of a pronounced daily cycle as shown in Figure 5.1 is due to the absence of respiration-assimilation activities of vegetation and soil micro-organism. CO_2 at the urban site originates largely from traffic sources. The lack of natural CO_2 sinks in the form of vegetation means that emitted CO_2 by traffic during the day is not absorbed. Consequently, the level of CO_2 concentration remains high throughout the day even at night. Past studies have reported a clear positive relationship between traffic load and CO_2 concentration (e.g. Takagi et al., 1998; Grutter, 2003; Gratani and Varone, 2005; Velasco et al., 2005; Vogt et al., 2006). However, traffic count conducted at the urban site does not show a similarly strong relationship with the diurnal pattern of CO_2 concentration (Fig. 6.3). This suggests that the pattern of CO_2 concentration at the urban site is possibly not caused by traffic alone and may indicate the influence of meteorological variables like wind speed, rain, atmospheric boundary layer height and larger scale mixing with background air in modulating the level of atmospheric CO_2 concentration.

Figure 6.3 shows the 19-day traffic count and CO_2 concentration ensemble data observed between 23 December 2006 and 11 January 2007. Note that 31 December forms a special case since the day coincides with New Year's Eve and a national holiday (*Hari Raya Haji*) in Singapore, in addition to it being a Sunday. It will be omitted from the ensemble data and will be used as a case study in later part in this section. The resultant CO_2 concentration pattern can be attributed to the evolution of the boundary layer throughout the day. The increase in boundary layer height results in decreasing concentration after sunrise despite increasing traffic volume. Concentration starts to increase again as traffic adds increasing amounts of CO_2 to the air in the canyon. Concentration remains high after sunset despite decreasing traffic volume possibly because of the evening collapse of the boundary layer and reduced mixing. The higher daytime and early evening CO_2 concentrations can probably be related to the higher traffic volume at these times. However, the two concentration peaks at 1200 - 1300 hrs and 1800 - 1900 hrs do not seem to be caused by traffic or meteorological factors alone. The relationship between the 19-day ensemble data for traffic load and CO_2 concentration (Fig. 6.3) is statistically significant (t = 8.30 > t_c =1.65, and $p < 0.05$) with r = 0.57.

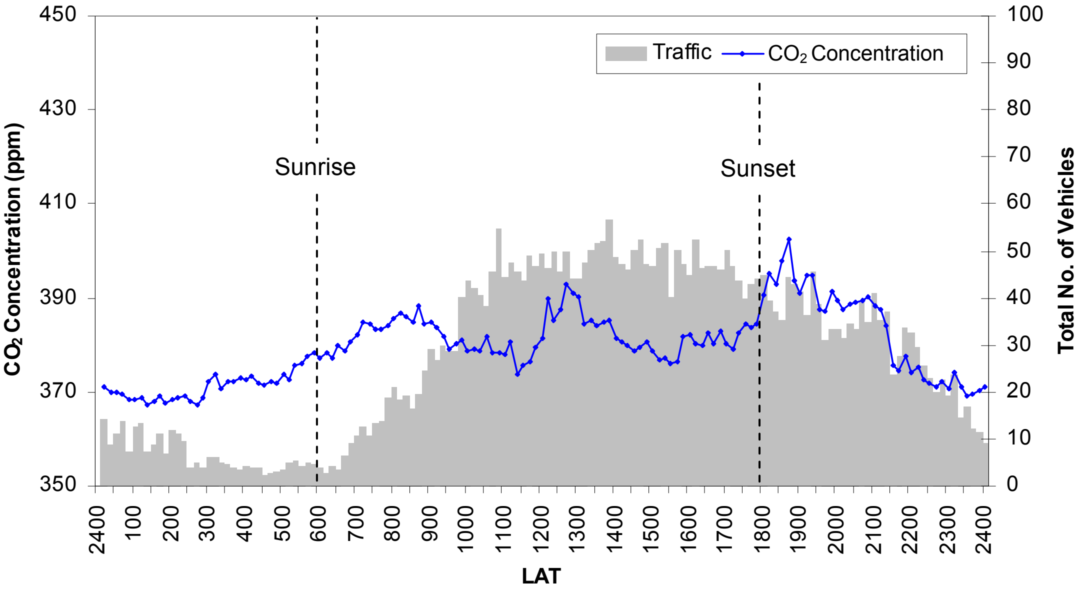

Figure 6.3: Number of vehicles and CO_2 concentration at the main urban site. Data are ensemble averages for 23 December 2006 – 11 January 2007 (excluding 31 December 2006).

There was, however, an instance when CO_2 concentration responded positively to a rise in traffic load. As shown in Figure 6.4, a clear positive relationship between CO_2 concentration and traffic can be seen from 0630 - 0730 hrs on 31 December 2006 which was a national holiday. The rise in traffic coincided with the special Islamic prayer during that time. During this time, the height of the boundary layer is shallow and associated mixing and turbulent activities are less intense. Following the rise in traffic at 0630 hrs, air within the urban canyon traps CO_2 near the ground, restricting its vertical transport and dispersion. Consequently, high concentration of up to 500 ppm is observed. Thereafter when traffic picks up again at around 1000 hrs, the increase in boundary layer and turbulence result in relatively low concentration. The lag between peak in traffic at

0630 hrs and CO_2 concentration may not be due to the sole influence of traffic and may reflect the additional CO_2 contribution by human respiration.

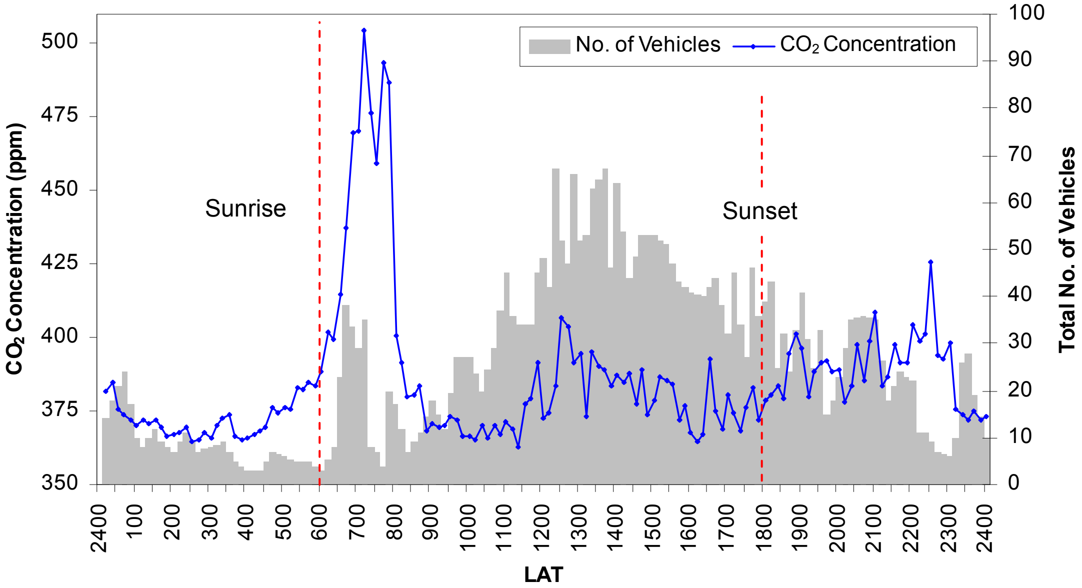

Figure 6.4: Correlation between traffic and CO_2 concentration observed on Sunday 31 December 2006, corresponding to a public holiday. The sudden rise in traffic load from 0630 - 0730 hrs coincides with the special Islamic prayers.

Traffic patterns do not vary much between weekdays, weekends and public holidays (apart from 31 December 2006) during the observation period from 23 December 2006 - 11 January 2007. Although traffic during weekends is generally higher than during weekdays, there are cases where weekday traffic is as high as weekend traffic (Fig. 6.5). Likewise, traffic during public holidays is as high as weekday traffic. This contrasts with the patterns of traffic observed in mid-latitude cities which indicate higher traffic during weekdays and lower traffic during weekends (e.g. Idso et al., 1998). Figure 6.5 shows the relationship between total number of vehicles and its corresponding average CO_2 concentration as observed at the urban site between 23 December 2006 - 11 January 2007 at midday (1130 - 1330 hrs) when the primary peak in CO_2 concentration is observed. The relationship does not suggest a clear correlation (r =

0.46) between midday traffic load and its corresponding CO_2 concentration although the correlation is statistically significant ($t = 2.17 > t_c = 1.73$, and $p < 0.05$).

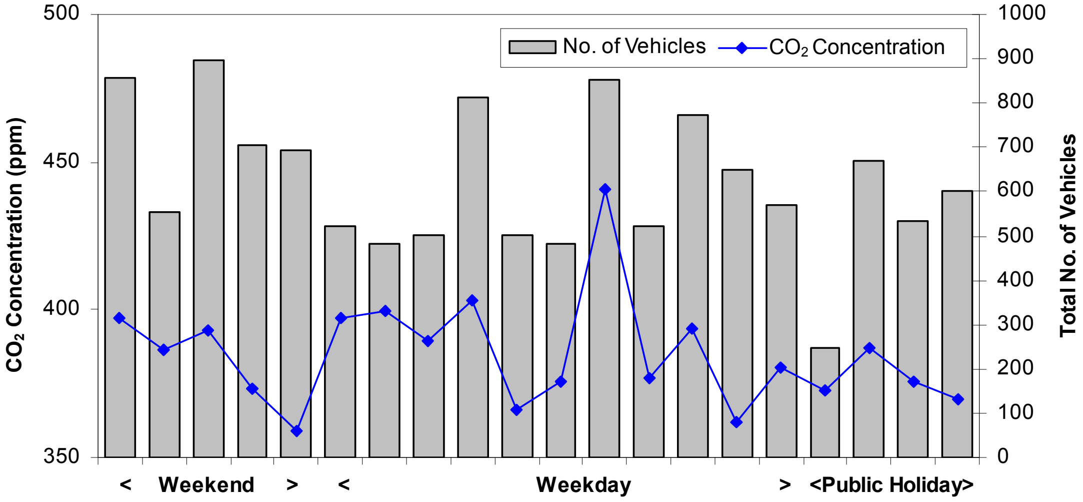

Figure 6.5: Traffic and midday (1130 - 1330 hrs) CO_2 concentration during weekdays, weekends and public holidays observed at the main urban site from 23 December 2006 - 11 January 2007.

The variation in monthly CO_2 concentration at the urban site, in addition to its systematically lower mean values than at the rural site during the months of June - November as shown in Table 5.2, can partly be explained by the contamination of CO_2 at the rural site during the SW monsoon which raises its concentration. This makes the average CO_2 concentration value at the urban site lower in comparison. Traffic count alone does not explain the difference in monthly CO_2 concentration at the main urban site since traffic load in the canyon is generally high irrespective of weekday/weekend/public holiday during the observation period from 23 December 2006 - 11 January 2007 (Fig. 6.5). It is therefore necessary to consider the influence of rain and wind speed on controlling the level of CO_2 concentration. Rain reduces the mixing volume of the air while wind speed indicates the dispersive capability of CO_2. Their influence as such may provide an explanation for the monthly variation of urban CO_2 concentration in Table 5.2.

Secondary rainfall data at hourly intervals was obtained from station 79 managed by the Meteorological Services Division of the National Environment Agency of Singapore. The station is located on at the top of the Singapore Power building and is approximately 0.35 km (linear distance) from the main urban site (see Figs. 4.4 and 4.16). The rainfall data shows highest rainfall during the NE monsoon period i.e. December and January. This is consistent with the observed rainfall at the rural site (Fig. 4.4). Rainfall conditions during the SW monsoon are short, less intense and less frequent (averaging 15 rainy days per month or 199 mm/month) whereas the NE monsoon is characterized by more frequent (20 rainy days on average or 686 mm/month), prolonged and intense rain. Figure 6.6 compares the monthly total rainfall and mean CO_2 concentration at the urban site. It can be seen that the drop in CO_2 concentration in December and January coincides with the heavy NE monsoon rainfall although no causable relationship can be found between the two. Correlating the mean monthly rainfall and CO_2 concentration at the rural and urban sites, the coefficient values show negative relationship where r = -0.78 and -0.59, respectively. No statistical significance of the correlation can be found. For the rural site, t = -3.03 while for the urban site, t = -1.80 where t_c = 1.94, and p > 0.05. The trend over the diurnal cycle (Fig. 6.7) does not provide a consistent picture on the influence of rain on CO_2 concentration as opposed to Figure 6.6.

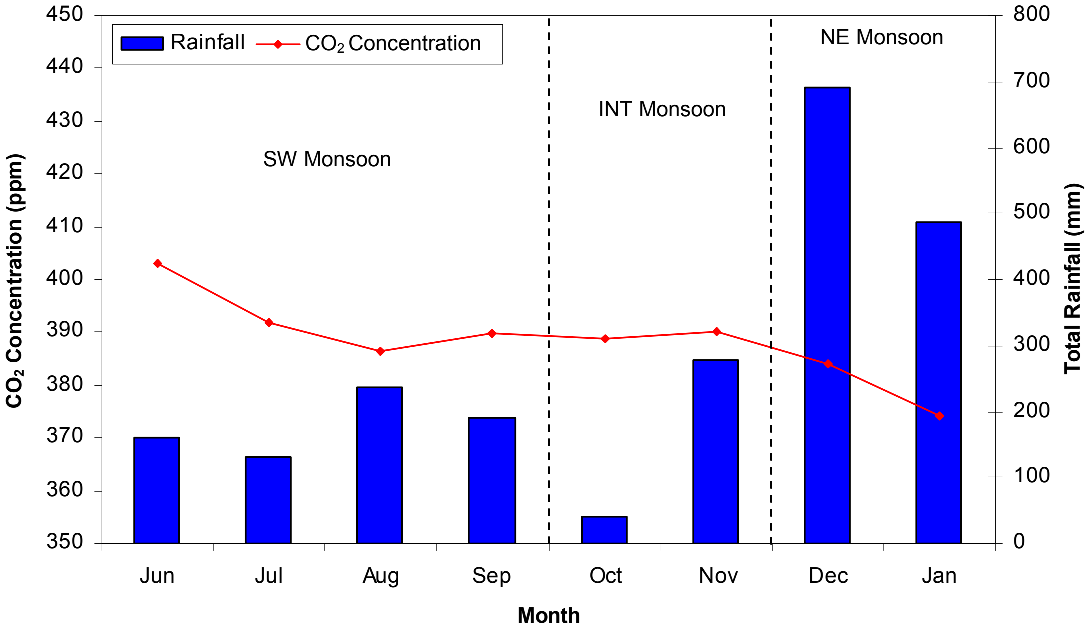

Figure 6.6: Mean CO_2 concentration and total rainfall at the main urban site for all months from June 2006 - January 2007. Rainfall data is obtained from a meteorological station located 0.35 km (linear distance) from the main urban station. Refer to Fig. 4.4 for location of meteorological station with respect to the main urban site.

Figure 6.7 illustrates the effect of rain on the level of urban CO_2 concentration over the diurnal course on 9 January. CO_2 concentration pattern based on 8 January is provided to typify a non-rain situation. It can be seen that the incidence of rain from 1000 - 1600 hrs does not reduce the level of CO_2 concentration. Instead, the concentration during the rain period is higher than during the non-rain period. In addition, the level of concentration remains low after the rain event. The observed result could be explained by the reduced mixing volume (i.e. lower boundary layer height) during rain event hence emitted CO_2 during the period gets trapped near the ground level and increases the concentration near the ground. However, analysis of all similar events throughout the observation period shows that the relationship as seen on 9 January is not readily reproducible.

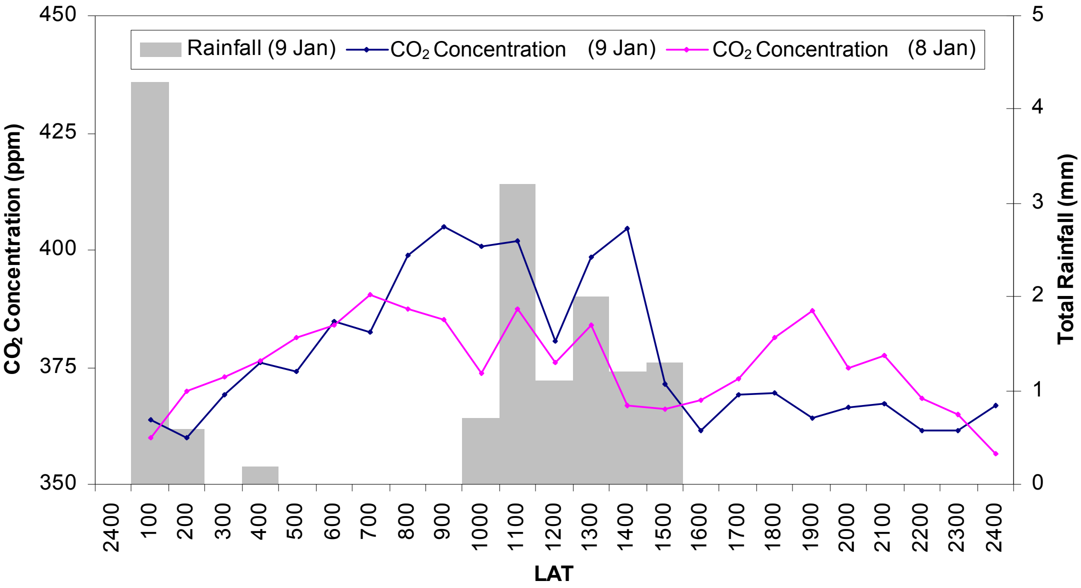

Figure 6.7: Effect of rain on CO_2 concentration at the urban site on 9 January 2007. The CO_2 concentration on 8 January 2007 is given to typify the pattern during a non-rain situation.

Strong winds during the NE monsoon may play a role in diluting the atmospheric CO_2 concentration. Comparison of mean monthly CO_2 concentration data observed at the main urban site with mean wind speed data observed at the main rural site also show that high wind speed is associated with low CO_2 concentration (Fig. 6.8). The present study did not measure urban wind speed and direction because observations would not have been representative of “urban”. In addition, while wind speed data from the rural site approximates the synoptic climatology of Singapore and is not truly representative of conditions within urban canyons, it still provides an approximation of wind behavior in the canyon. Certainly, the strength of wind speed decreases due to friction from the rough urban surface. This has been confirmed, for example, by Vogt et al. (2006) who observed four times lower wind speed in the urban canyon than above the canyon. Wind speed data from the rural site indicate that NE monsoon winds are stronger than winds in other months. Using Vogt et al.’s observation as a guide, this would mean that the approximated wind speed in the canyon is low but mixing is still sufficient to disperse CO_2 after experiencing the fictional slow-down. At the urban site, mixing with background air may not effective during daytime as shown in Figure 5.14 where there is a difference in CO_2 concentrations at the surface (3.5 m) and at higher level (27 m) from 0600 - 1900 hrs. At night, the negligible difference in concentration may suggest effective mixing brought about by the warming of the surface and downdraft of cool air from above the canyon.

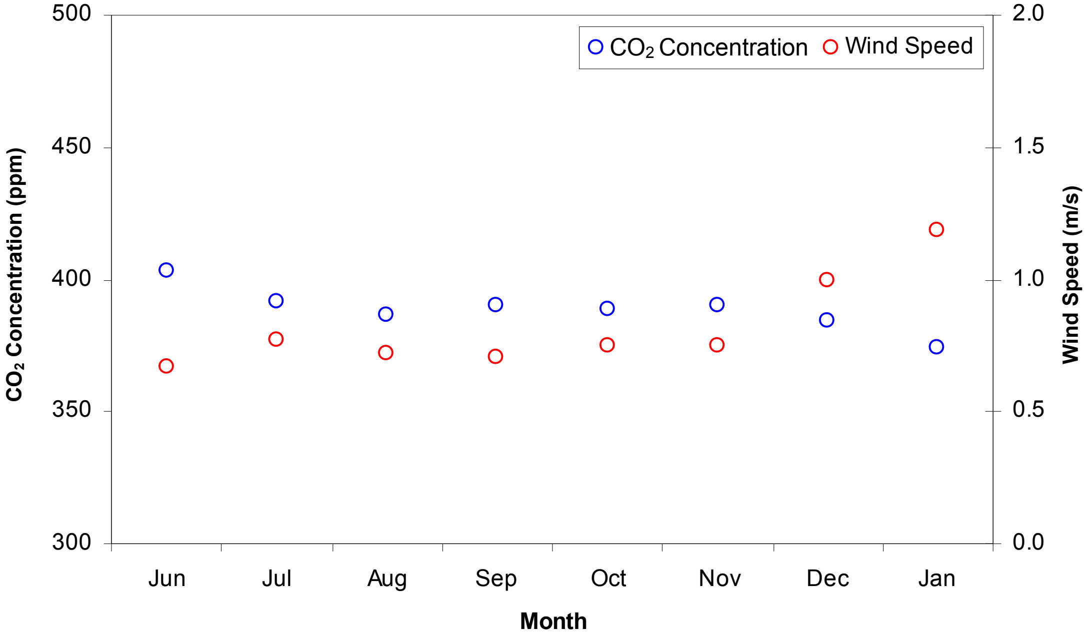

Figure 6.8: Mean monthly CO_2 concentration observed at the main urban site and mean wind speed observed at the rural site from June 2006 - January 2007.

6.2 SPATIAL VARIABILITY OF CO_2 CONCENTRATION

Results from spatial sampling indicate large variability in mean maximum (range: -25 - 83 ppm) but less in minimum concentrations (range: 2 - 13 ppm) observed at the four urban land-use types and at the two intra-rural sampling sites (Tables 5.4 and 5.6). The two intra-urban sampling sites also show large variation in mean maximum (range: 14 - 37 ppm) but less in minimum concentrations (range: 5 - 8 ppm) (Table 5.5). These observations reflect the diversity of urban and rural areas in terms of anthropogenic and biogenic activities such as emissions of CO_2 from traffic and respiration, respectively. At the two intra-rural sampling sites, the role of high vegetation density is apparent in contributing to the observed nighttime maximum CO_2 concentration. Additionally, wind speed may play a role in regulating the strength of daytime CO_2 concentration which differs from site to site.

At the urban site, the two intra-urban sites exhibit higher maximum concentrations than the main urban site. This is due to the proximity of these sites to a trunk road (Bideford Road Main) and major road intersection (Cairnhill Road) which are characterized by high traffic loads. At Cairnhill Road, average daily traffic count obtained from Land Transport Authority's Intelligent Transport System amounts to 58,991 vehicles while Bideford Road Main experiences on average 64,005 vehicles daily. This contrasts with the number of vehicles within the urban canyon at main urban site which averages only 3,960 vehicles per day based on manual traffic count. At night the main urban site shows a higher minimum CO_2 concentration than the two intra-urban sites. This may be explained by the lesser dispersion of CO_2 at the main site due its higher H/W ratio which reduces ventilation.

The large difference (83 ppm) between mean maximum concentrations observed at the heavy industrial sampling site and the main urban site (Table 5.6) may be explained by several factors. First, the proximity of the sampling site to open water suggests the influence of fresh maritime air which would lower its concentration. Second, there is limited amount of road traffic activities surrounding the sampling site. This means that the capacity for vehicular-based CO_2 emissions to increase the level of CO_2 concentration at the site is low. Third, the well-mixed nature of the air at the industrial site disperses the CO_2 emitted from the tall chimneys. Resultantly, the sensor did not record an increase in daytime concentration despite the ongoing industrial activities. Correlation between mean CO_2 concentrations (see Tables 5.1, 5.4 - 5.6) and vegetation fraction at all sites show weak correlation between the two variables (r = 0.52). Statistically, the significance of correlation is low with $t = 1.72 < t_c = 1.86$ where $p > 0.05$.

6.3 COMPARISON WITH MID-LATITUDE CITIES

Comparing the present results with studies conducted in mid-latitude cities, the following conclusions could be made. First, urban CO_2 concentration observed in Singapore is similar to those found in other cities (Table 6.3). At the urban site, mean maximum and minimum concentration values of 413 ppm and 380 ppm are consistent with observations from other cities. The diurnal amplitude (33 ppm) also fits well with the results from other cities. However, the urban mean maximum and minimum values occur during daytime and at night, respectively, hence remain contrary to the findings in other studies which report pre-dawn maxima and daytime minima (e.g. Reid and Steyn, 1997; Grimmond et al., 2002; Velasco et al., 2005; Vogt et al., 2006; Moriwaki et al., 2006). The observation at the rural site which records a large diurnal amplitude (103 ppm), high maximum (455 ppm) and low minimum (353 ppm) CO_2 concentrations is also similar to other studies (Table 6.4).

Table 6.3: Comparison of CO_2 concentration (ppm) values over urban areas from past observations and present study.

Location & Reference	Nagoya (Japan)	Vancouver (Canada)	Phoenix (USA)	Chicago (USA)	Kuwait City (Kuwait)	Mexico City (Mexico)	Kugahara (Japan)	Basel (Switzerland)	Singapore
	Aikawa et al. (1995)	Reid and Steyn (1997)	Idso et al. (2002)	Grimmond et al. (2002)	Nasrallah et al. (2003)	Velasco et al. (2005)	Moriwaki et al. (2006)	Vogt et al. (2006)	present study
Mean Maximum	385	387	424 – 490	405	371	421	444	423	413
Mean Minimum	366	361	391	370	368	375	406	362	380
Mean Diurnal Amplitude	19	26	33 – 99	35	3	46	38	61	33

Notes: (a) Values from Idso et al. (2002) are seasonal; (b) Values from Nasrallah et al. (2003) are annual variation.

Table 6.4: Comparison of CO_2 concentration (ppm) values over rural areas from past observations and present study.

Location & Reference	Cincinnati, Ohio (USA)	Ithaca, New York (USA)	Long Island, New York (USA)	Sutton Bonington, Nottingham (UK)	Rondônia, (Brazil)	Singapore
	Clarke (1969)	Allen Jr. (1971)	Woodwell et al. (1973)	Berry and Colls (1990a)	Culf et al. (1997)	present study
Mean Maximum (Nighttime)	422	350 – 500	> 500	376	486	455
Mean Minimum (Daytime)	297	< 300	290 – 300	345	360	353
Mean Diurnal	322	325 – 400	395 – 400	360	423	394
Mean Diurnal Amplitude	125	100 – 200	210 – 200	31	126	103

Note: Daytime minimum and nighttime maximum CO_2 concentrations in Woodwell et al. (1973) are lowest and highest observed values, respectively.

Second, there is still a large variability in seasonal variation of mean urban CO_2 concentration between mid-latitude cities and the present study, indicating a general picture of seasonal variability has yet to be found (Table 6.5). Mid-latitude cities observe high mean urban CO_2 concentration during the cold/wet season (winter) compared to the hot/dry season (summer) (e.g. Berry and Colls, 1990a; Derwent et al., 1995; Idso et al., 2002; Pataki et al., 2003; Henninger and Kuttler, 2004; Gratani and Varone, 2005; Coutts et al., 2007; c.f. Table 6.5). However, the case for Singapore shows lower mean CO_2 concentration during the cold/wet season (NE monsoon). Seasonal variation of CO_2 concentration over rural areas from observations in mid-latitude cities indicates higher mean values during the hot/dry season (summer) (e.g. Clarke, 1969; Berry and Colls, 1990a) attributed to the higher CO_2 release rates from plant respiration during the season. The present study also shows higher mean rural concentration values during the hot/dry season (SW monsoon). However, it is difficult to attribute this finding to the assimilative-respiration pattern of vegetation and soil micro-organisms at the rural site alone since meteorological factors like wind speed and direction play a strong role in modulating the level of CO_2 concentration observed between seasons.

Table 6.5: Comparison of mean seasonal variation of CO_2 concentrations (ppm) over urban areas from past observations and present study. Parenthesis denotes percentage difference.

Location & Reference	Nottingham (UK)	London (UK)	Phoenix (USA)	Kuwait City (Kuwait)	Salt Lake City (USA)	Essen (Germany)	Rome (Italy)	Melbourne (Australia)	Singapore
	Berry and Colls (1990a)	Derwent at al. (1995)	Idso et al. (2002)	Nasrallah et al. (2003)	Pataki et al. (2003)	Henninger and Kuttler (2004)	Gratani and Varone (2005)	Coutts et al. (2007)	present study
Hot/Dry	355	417	409	370	375 – 400	393	388	364	393
Cold/Wet	366	427	441	369	390 – 480	415	463	370	379
Difference	12 (3 %)	10 (2 %)	32 (7 %)	1 (0.2 %)	15 – 80 (4 – 16 %)	22 (5 %)	75 (16 %)	7 (2 %)	13 (3 %)

Note: Data in Nasrallah et al. (2003) are annual variation.

Third, the magnitude of enhancement inside the CO_2 dome is smaller than most studies (Table 6.6). The degree of enhancement of the present study is similar to Rome, both in terms of percentage and the absolute value differences. The large magnitude of enhancement as observed in these studies is due the strength of emission sources (Widory and Javoy, 2005; Kèlomé et al., 2006), topography and prevailing local meteorological conditions (Idso et al., 2002) which favor the development of such a strong dome.

Table 6.6: Comparison of mean maximum CO_2 concentrations (ppm) measured in the city-centre with rural baseline value from past observations and present study. Values in parentheses are CO_2 enhancement expressed as percentages.

Location & Reference	Phoenix, Arizona (USA)	Rome (Italy)	Paris (France)	Cotonou (Benin)	Singapore
	Idso et al. (2001)	Gratani and Varone (2005)	Widory and Javoy (2005)	Kèlomé et al. (2006)	present study
Mean Maximum	529 (43 %) - Weekday 510 (38 %) - Weekend	477 (18 %)	542 (30 %)	650 (71 %)	420 (21 %)
Mean Rural Baseline	369	405	418	380	346
Absolute Difference	160 - Weekday 141 - Weekend	72	124	270	74

Note: Values in Widory and Javoy (2005) and Kèlomé et al. (2006) are maximum observed values.

CHAPTER 7

– SUMMARY & CONCLUSIONS –

In the past, the effect of urbanization on the local climate has been examined for major meteorological variables such as temperature, humidity, precipitation or air pollution. Studies involving measurements of CO_2 concentrations over cities are few but they find large temporal and spatial variability between observations so that it is difficult to construct a unique urban "picture". This chapter summarizes the important findings according to the objectives stated in Chapter 3. This is followed by a summary which compares the present study with those from mid-latitude cities. Directions where future research could take place are also highlighted.

7.1 SUMMARY OF PRESENT STUDY

The first objective of the study is to characterize the temporal patterns (diurnal, monthly and seasonal) of CO_2 concentration in Singapore. The variation of CO_2 concentration at the rural site over the diurnal course throughout the observation period conforms well to our understanding of the behavior of CO_2 in rural environments. Maximum and minimum concentrations occur at night and during the daytime, respectively corresponding to respiratory and photosynthetic activities of vegetation and soil micro-organisms. At the urban site, the pattern shows nighttime minimum and daytime maximum CO_2 concentrations, characterized by peaks at midday and in the later afternoon. Analysis of monthly CO_2 concentration shows more pronounced variation at the rural compared to the urban site with December and January exhibiting lowest CO_2 concentrations. The variation is believed to be due to the influence of wind direction from the southeast and high wind speed. At the urban site, diurnal amplitude is less and CO_2 concentration decreases between June – January. Meteorological conditions (e.g. wind speed and direction, boundary layer height and rainfall), the absence of vegetation and most importantly, CO_2 emissions from vehicles are responsible for the particular urban signature. On a seasonal scale, CO_2 concentration is lower during the NE monsoon than during the SW or inter-monsoon periods at both main sites. Throughout the observation period, average CO_2 concentration is higher at the rural than at the urban site during most months which maybe due to the input of additional anthropogenic CO_2 by the prevailing winds at the rural site.

The second objective seeks to investigate the spatial variability of CO_2 concentration over different urban land-use types including intra-urban and -rural variability. First, there exists variability in mean maximum, minimum and average CO_2 concentrations amongst the different urban land-use types with the heavy industrial and high-rise residential sites exhibiting the largest and least variability in concentration values, respectively. Second, the selection of urban and rural reference sites used in this study is representative of urban and rural environments. Although there exists quite a large variability in mean maximum CO_2 concentration, especially at the urban site which is due to site-specific characteristics like vegetation density and proximity to major roads, average CO_2 concentration values indicate low variability amongst sampling sites. Enhanced CO_2 concentration (dome) based on car traverses has been observed over the city-centre during midday. The intensity of the dome is slightly variable but nonetheless is higher than over other land-use types which included rural, industrial and residential. At pre-dawn, the urban CO_2 dome disappears and the rural area exhibits higher concentration, pointing to the contribution from respiration from vegetation and soil micro-organisms which is largely absent in the city-centre.

Third objective seeks to explore the relationship between meteorological variables like wind speed and direction, and rainfall. The correlation between CO_2 concentration and wind speed and direction is clear. The effect of rain on CO_2

concentration shows higher concentration during rain event. However, the relationship is not readily reproducible throughout the period of the observation.

7.2 COMPARISON WITH MID-LATITUDE CITIES – SUMMARY

Results of the present study are consistent with most findings from mid-latitude studies. Characteristics of urban CO_2 concentration are similar to those observed in past studies. These include the generally high concentration values throughout the day, low diurnal amplitude as compared to the rural reference, and the presence of traffic-induced concentration peaks. Contrary to most studies, the present study observed maximum and minimum concentration values during the day and at night respectively. Concentration at the rural site shows a better agreement when compared to mid-latitude studies in terms of mean nighttime maximum, daytime minimum and large diurnal amplitude values. Seasonal variation of CO_2 concentration in this study does not compare well with data from past studies which remain highly variable. In addition, a majority of these studies observe high CO_2 concentration during the cold/wet season i.e. winter. This contrasts with the present study which observed high values during the hot/dry season i.e. SW monsoon. The intensity of CO_2 enhancement (dome) of this study is smaller than observed by most studies. These studies remain exceptional cases since factors like topography and strength of emission sources play an important role in influencing the high level of CO_2 concentration.

7.3 FUTURE DIRECTIONS

There remain possible avenues where future research can be conducted following this study. First, measurements of CO_2 concentration at the urban site could be made alongside wind speed observations. CO_2 concentration has been shown in the present study to be modulated by wind speed. At the urban site, wind speed measurement was not available hence it is not known if its diurnal pattern of concentration was regulated by wind speed. Although wind speed measurement in urban canyon is not representative of the urban environment, it nonetheless may shed insight on the dispersive capability of the atmosphere within the canyon. Second, CO_2 concentration is largely determined by site-specific characteristics. While observation of CO_2 concentration within an urban canyon at the main urban site is representative of the urban environment, little is known if CO_2 in other urban canyons exhibit similar patterns and values as the site used in the present study or if concentrations in other canyons are representative of an urban environment. In this respect, the temporal and spatial behavior of CO_2 from canyon to canyon remains unknown and needs to be researched. Spatial sampling at various inter-urban land-use types could have been conducted simultaneously to provide better comparison between sites. Lastly, the relationship with rainfall could be further investigated to better understand the effect of rain on the level of CO_2 concentration.

CO_2 concentration in cities is largely contributed by anthropogenic sources originating from primarily the burning of fossil fuels for home/office heating and traffic usage. In the case of a tropical-equatorial city like Singapore, the source of CO_2 comes from largely traffic and the concentration has shown to be in a magnitude similar to those observed in mid-latitude cities. It is also necessary to have an emissions inventory for Singapore to supplement existing measurement-based CO_2 concentration studies so that areas with high CO_2 concentrations could be attributed to a particular emission source.

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