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Temporal and Spatial Variations in Ambient Air Quality during 1996–2009 in Bangkok, Thailand

Pornpun Watcharavitoon[1,3], Chia-Pin Chio[1], Chang-Chuan Chan[1,2*]

[1] *Institute of Occupational Medicine and Industrial Hygiene, College of Public Health, National Taiwan University, Room 722, No. 17, Xuzhou Road, Taipei City 100, Taiwan*
[2] *Global Health Center, College of Public Health, National Taiwan University, No. 17, Xuzhou Road, Taipei City 100, Taiwan*
[3] *School of Occupational Health and Safety, Institute of Medicine, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand*

ABSTRACT

The severe air pollution in Bangkok (BKK) is an important issue in Thailand. The Bangkok air quality and meteorological data used in this study were collected by the Pollution Control Department of the Ministry of Natural Resources and Environment, Thailand, during 1996–2009. Measurements of hourly air quality and meteorological data were derived from 10 residential and seven roadside sites. Pearson's chi-square cross tabulation statistics show that the 24-hour mean PM_{10} concentrations at both roadside and residential sites were to be significantly higher than the Thai National ambient air quality standards (NAAQS) and World Health Organization (WHO) guidelines. The daily 1-hour maximum O_3 ($O_{3\text{-}1hr}$) concentration was higher than the Thai NAAQS at both sites. However, the concentrations of 8-hour time-weighting average of CO (CO_{8hr}) were lower than the Thai NAAQS at both sites. The 24-hour average SO_2 concentration and the daily 1-hour mean concentration of NO_2 were higher than the WHO guidelines, but complied with the Thai NAAQS at both sites. A stepwise multiple linear regression model was used to analyze the significant factors affecting PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 levels at both sites, and the results showed a decreased association with meteorological parameters and an increased association with the area studied and seasons. In contrast, $O_{3\text{-}1hr}$ levels exhibited a decreased association with the area studied. This study found that traffic emissions are the major factor causing the spatial variation in air pollutants in BKK, Thailand, while the meteorological parameters might be the main factors that affect the temporal variations. Our findings show the heterogeneously spatiotemporal characteristics of air pollution in BKK, and can be used to help mitigate this problem.

Keywords: Bangkok; Temporal and spatial variations; Ambient air quality.

INTRODUCTION

The air quality in the Bangkok Metropolitan Region (BMR) is considered to be the worst area in Thailand (PCD, 2006, 2007, 2010). Air pollution in Bangkok (BKK) is mainly due to automobile and industry sources (Jinsart *et al.*, 2002; Chuersuwan *et al.*, 2008). The total number of vehicles registered to the Department of Land Transport (DLT) in 2007 was 5.57 million, and in 2009, it was 6.22 million (DLT, 2007, 2009). The road network in BKK has not been adequately expanded, which causes traffic jams and forces vehicles to move at slower speed. Road traffic was a significant source of air pollution in BKK, and the number of vehicles on the road was increasing every year. The DLT reported that the number of vehicles in the capital city in 2009 was nearly doubled (6,103,719 vs. 3,549,082) by comparing with that in 1996 (DLT, 2009). This had led to increase the particulate matter (PM) emissions into the ambient, especially those of smaller size particles (PM with aerodynamic diameter less than 10 microns or PM_{10}) emitted from the diesel engine-powered buses and trucks. The air pollution emitted from the roads was identified as a public health risk in BKK because the recorded level was consistently higher than the accepted standard (Ostro *et al.*, 1999; BMA, 2003, 2008). Traffic emissions were considered to be a major problem because the emissions contain many toxic substances, e.g., PM_{10}, CO, ozone (O_3), NO_x, SO_x, and aromatic hydrocarbons (Jinsart *et al.*, 2002; Kim Oanh and Zhang, 2004; Ruchirawat *et al.*, 2005; Chuersuwan *et al.*, 2008).

Systematic ambient air quality measurements in BKK, Thailand began in 1996 (Ostro *et al.*, 1999). Since September

* Corresponding author. Tel.: +886-2-3366-8082;
Fax: +886-2-2322-2362
E-mail address: ccchan@ntu.edu.tw

of 1996, the continuous air quality data were available for PM_{10}, CO, O_3, NO_2, and SO_2, as well as the supplementary meteorological parameters such as wind speed (WS), wind direction (WD), temperature, and relative humidity (RH). The monitoring data was automatically restored and recorded as database. The database was expected to meet the Thai National ambient air quality standards (NAAQS) of 2007 (Gazette, 2007). However, only few studies had discussed the long-term trends or spatiotemporal variations for air quality in BBK (Jinsart *et al.*, 2002; Kim Oanh and Zhang, 2004; Chuersuwan *et al.*, 2008).

Based on the evidence, the above-mentioned analyses were needed to be the bases for control strategies or other policies making by related authorities. The aims of this study were three fold: (1) to investigate the trends of air pollutants during 1996–2009, (2) to determine the temporal and spatial variations of the air quality data, and (3) to establish a stepwise multiple linear regression model to depict these data adopted from both residential and roadside sites in BKK.

MATERIALS AND METHODS

Descriptions of Locations and Seasons

Bangkok (BKK) is the capital city of Thailand and ranks 68th in size out of the country's 76 provinces with an area of 1,568 km^2. The city is split into 50 districts and 154 sub-districts. Currently, there are approximately 8,160,522 registered residents in BKK (DOPA, 2006). However, the actual number of people who stay in the city can reach 15 million. The BKK has a population density of 3,637 persons per km^2. Land use in BKK consists of 700 km^2 urbanised area, 379.0 km^2 of agricultural land (23.6% of the land), and 453.5 km^2 area for commercial, industrial and government uses (29.6% of the land). BKK is situated on the low flat plain of the Chao Phraya River, which extends to the Gulf of Thailand. BKK is located 13°45' north in latitude, and 100°31' east in longitude (Kim Oanh and Zhang, 2004; Chuersuwan *et al.*, 2008). The elevation is approximately 2.3 meters above sea level. The area surrounding BKK and the nearby provinces comprise a series of plains and river deltas that lead into the Bay of BKK approximately 30 km south of the city centre.

BKK has a tropical monsoon climate with two main seasons: wet or rainy and dry. The wet season extends from 16 May to 15 October. The dry season can be classified into two periods. The first period (16 October–15 February) is characterised by the mild weather of the winter monsoon and is known as the local winter. The second period (16 February–15 May) is known as the local summer and is extremely hot (Ostro *et al.*, 1999). Meteorological statistics from 1990–1999 show the annual average temperature of BKK to be 25–33°C, with an average WS of 1.3 m/s and a high RH year-round (Kim Oanh, 2004).

Air Quality and Meteorological Data

The BKK air quality and meteorological data used in this study were collected by the Pollution Control Department of the Ministry of Natural Resources and Environment, Bangkok, Thailand, from 1996 to 2009 (PCD, 2010). Hourly-based air pollution and meteorological data were collected from 17 air-monitoring stations, which included 10 ambient-residential and 7 ambient-roadside sites (Fig. 1). Detail information for selected sites was also shown in Fig. 1. Residential sites are the representative sites for residential areas, where are densely populated areas with a population of more than 50,000 persons. The residential monitoring sites are located approximately 100 m to 2 km far from a major road. However, the roadside sites are defined as closing to a major road approximately 10–50 m.

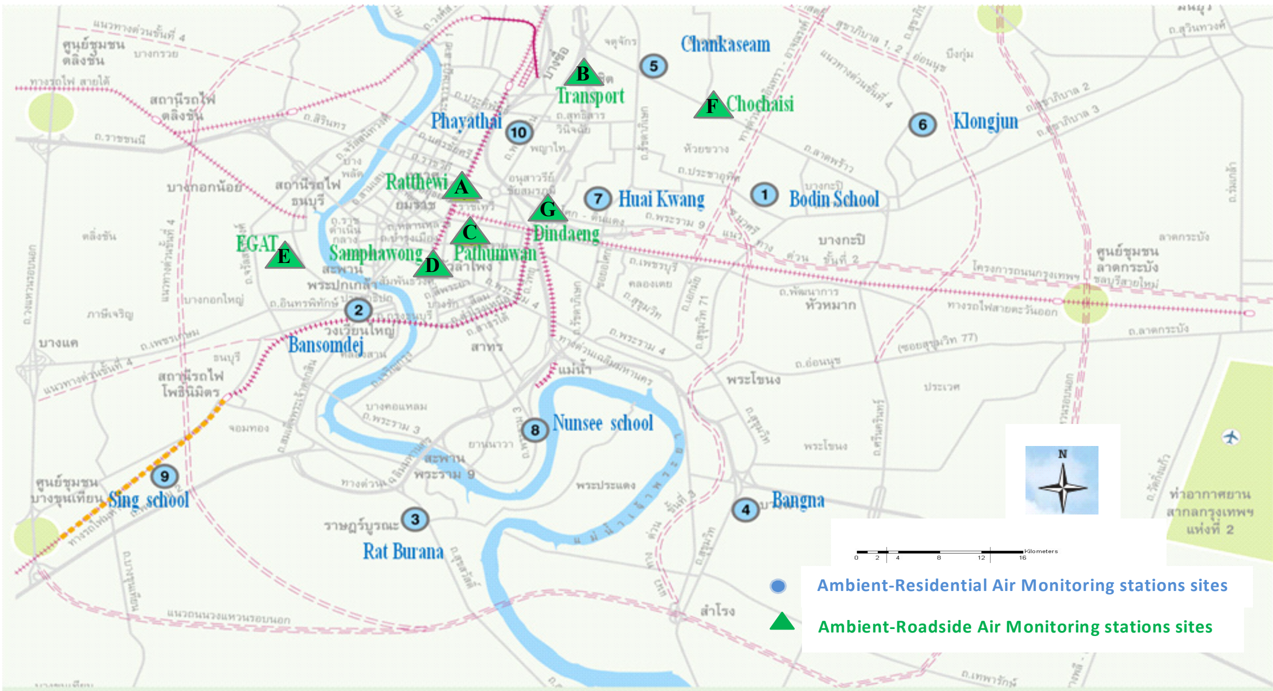
PM_{10}, CO, O_3, NO_2, SO_2, temperature, RH, WS, and WD are monitored using Beta Ray absorption, non-dispersive infrared detection, ultraviolet (UV) absorption photometry, chemiluminescence, UV-fluorescence, a thermistor, a thin-film capacitor, a cup propeller, and potentiometer wind vanes, respectively. These instruments are connected to a data logger that transmits the hourly average values from a modem to a central computer situated in the building of the station. The instruments are calibrated every month. For NO_2 (USEPA Federal Reference Method RFNA-0691-082), measured by using chemiluminescence monitors equipped with molybdenum/photolytic convertors, within 10% uncertainty of measurements had been shown in the literature (Dunlea *et al.*, 2007; Steibacher *et al.*, 2007). In this study, we especially focused on eight-hour time-weighting average of CO (CO_{8hr}) and daily 1-hour maximum O_3 ($O_{3\text{-}1hr}$) because these two pollutants represent the severe conditions in rush hours and the potential damages to people in BKK.

Statistical Analysis

The SAS version 9.2 statistical software for windows (SAS Institute Inc., NC, USA) was used to conduct a descriptive analysis, and two independent sample *t*-tests were used to compare air pollution concentrations and meteorological parameters between roadside and residential sites. An one-way analysis of variance (ANOVA) test was used to compare spatial and temporal variations of pooled data of PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 between sites and seasons at roadside and residential sites in the BKK during 1996–2009. Pearson's chi-square (χ^2) cross tabulation statistic was used to test correlations between the reported values of PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 that exceeded the thresholds of the Thai NAAQS of 2007 (Gazette, 2007) and the WHO guidelines (WHO, 2005), with weekday and weekend days, seasons and areas studied. Additionally, this statistic was used to test the relationship between air pollutants in different areas and the correlations between air pollutants and meteorological factors. We also developed a stepwise multiple linear regression model to determine the associations among air pollution concentrations, meteorological factors, areas studied, and seasonal parameters at roadside and residential sites in BKK in 2009. The general regression model can be expressed as:

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{j=k+1}^{n} b_j Z_j + e \qquad (1)$$

where b_0 is the regression constant and b_i and b_j are the regression coefficients of continuous (X_i) and category (Z_j)



Full name of air quality station	Short name in Fig.1
Residential sites (N = 10)	
1. Badindecha (Sing Singhaseni) School	1. Bodin School
2. Bansomdejchaopraya Rajabhat University	2. Bansomdej
3. Rat Burana Post Office	3. Rat Burana
4. Thai Meteorological Department, Bangna	4. Bangna
5. Chandrakasem Rajabhat University	5. Chankaseam
6. Klongjun - National Housing Authority	6. Klongjun
7. Huaykwang - National Housing Authority Stadium	7. Huai Kwang
8. Nonsi Withaya School	8. Nunsee School
9.Singharaj Pittayakom School	9. Sing School
10. The Government Public Relations Department	10. Phayathai
Roadside sites (N = 7)	
A. Ministry of Science and Technology	A. Ratthewi
B. Land Transport Department	B. Transport
C. Chulalongkorn Hospital	C. Pathumwan
D. Odien Circle	D. Samphanwong
E. Thonburi Power Substation	E. EGAT
F. Chokechaisi Police Box	F. Chochai4
G. Dindaeng - National Housing Authority	G. Dindaeng

Fig. 1. Location of air monitoring stations in Bangkok and Bangkok capital city (Source: Modified from the Pollution Control Department and the Department of Environmental Quality Promotion, PCD (2006, 2007, 2010)).

variables, respectively. The values of the constants and the coefficients can be determined by using the least-squares method. Finally, *e* shown in the regression equation is the error term. The significance level of the constant and coefficients are statistically tested using the *t* distribution. A generally used measure of the goodness of fit of a linear model is r^2 (Akpinar *et al.*, 2008). PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 concentrations were considered to be the dependent variables, while the meteorological parameters, such as temperature, RH, and WS, were considered to be the independent and continuous variables. Our multiple linear regression model also take into account the spatial variations, such as roadside and residential (reference) sites, and temporal variations, such as the winter season, summer season, and rainy season (reference), as independent and category variables.

RESULTS AND DISCUSSION

Air Quality and Standards

The daily mean concentrations of PM_{10} at roadside and residential sites were found to be significantly higher than the Thai NAAQS since 2007 and the WHO guidelines since 2005 (Table 1). The daily maximum concentration of

Table 1. Number of exceedances WHO guideline and Thai daily standard of the five air pollutions monitored in workday (WKD) and weekend (WKE) classified by season and areas.

Air Pollutions	Roadside areas							Residential areas						
	Winter		Summer		Rainy		Overall	Winter		Summer		Rainy		Overall
	WKD	WKE	WKD	WKE	WKD	WKE		WKD	WKE	WKD	WKE	WKD	WKE	
PM_{10}24hr =50 μg/m^3 (G)	1066	433	620	253	1093	453	3918	870	350	300	118	409	169	2216
PM_{10}24hr =120 μg/m^3 (S)	196	79	33	15	85	35	443	88	34	7	0	9	5	143
CO_{8hr} = 9 ppm (S)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$O_{3\text{-}1hr}$ =100 ppb (S)	17	9	16	3	2	1	48	167	63	97	27	79	32	465
$NO_2$1hr =170 ppb (S)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$NO_2$1hr =106 ppb (G)	998	329	280	140	232	93	2072	451	97	60	17	45	25	695
$SO_2$24hr = 8 ppb (G)	475	210	261	127	489	224	1786	114	58	69	27	80	39	387
$SO_2$24hr = 120 ppb (S)	0	0	0	0	0	0	0	0	0	0	0	0	0	0

S and G in brackets represent standard and guideline level (WHO, 2005; Gazette, 2007).

$O_{3\text{-}1hr}$ was higher than the Thai NAAQS in both sites. Additionally, the daily mean concentrations of CO_{8hr} was lower than the Thai NAAQS in both sites and the daily mean concentration of NO_2 and SO_2 were higher than the WHO guidelines, but complied with Thai NAAQS in both sites. According to the WHO guidelines, the daily (24-hour) mean concentration threshold of PM_{10} was 50 μg/m^3. The overall recorded levels exceeded this threshold in 3918 of 4900 cases in roadside sites (80.0%) and in 2216 of 4889 cases in residential sites (45.3%) during 1996–2009. For NO_2, results also showed the whole records exceeded the threshold (WHO guideline: 106 ppb) in 2072 (42.3%) and 695 (14.2%) cases in roadside and residential sites, respectively. However, only 443 of 4900 (9.0%) cases and 143 of 4889 (2.9%) cases were confirmed to exceed the Thai NAAQS (120 μg/m^3) for roadside and residential sites, respectively. The daily one-hour mean concentration threshold of SO_2 was 8 ppb, which was exceeded in 1786 of 4892 cases in roadside sites (36.5%) and in 387 of 5114 cases in residential sites (7.6%). Jinsart *et al.* (2002) compared the daily average PM_{10} in BKK with the Thai NAAQS and showed that the PM_{10} exceedance rate during April 1997 to March 2000 from 27.3% declines to 10.5% for roadside sites and from 8.6% decreases to 2.7% for general sites, respectively. Jinsart *et al.* (2002) also indicated that the mass concentration ratio of $PM_{2.5}$ (PM with aerodynamic diameter less than 2.5 μm) to PM_{10} in high polluted area (0.8 ± 0.08) is higher than that in low-polluted area (0.65 ± 0.04). By comparing with previous study (Jinsart *et al.*, 2002), our data is longer (14 yrs. vs. 3 yrs.) and wider (17 sites vs. 8 sites) than previous study and shows more representative in BKK. We also provided the new WHO guideline and showed that more exceedance rates were considered.

The PM_{10}, $O_{3\text{-}1hr}$, and SO_2 levels that exceeded the threshold in weekday (WKD) and weekend (WKE) tests were cross-tabulated by season and location to investigate any differences. The cross tabulation tests for PM_{10}, $O_{3\text{-}1hr}$, and SO_2 exhibited a significant different with location (χ^2 = 586, df = 5, p < 0.0001; χ^2 = 513, df = 5, p < 0.0001; and χ^2 = 2173, df = 5, p < 0.0001, respectively), day of the week (χ^2 = 3.4, df = 5, p = 0.6442; χ^2 = 3.9, df = 5, p = 0.5634; and χ^2 = 1.5, df = 5, p = 0.9143, respectively), and season (χ^2 =1172, df = 10, p < 0.0001; χ^2 = 1026, df = 10, p < 0.0001; and χ^2 = 4346, df = 10, p < 0.0001, respectively) (data not shown). Thus, there existed significant difference for PM_{10}, $O_{3\text{-}1hr}$, and SO_2 (values exceed the threshold) by testing location and season factors. However, Khamdan *et al.* (2009) showed that there was a significant correlation between PM_{10} levels that exceeded the threshold and haze episodes, but that there were not significant differences with location and seasons. In roadside sites, the appearance of severe episodic air pollution events from PM_{10}, CO_{8hr}, NO_2, and SO_2 were associated with calm conditions (WS = 1.19 m/s), when air mass stagnation is favoured. Results also showed that there was no significant difference between WKD and WKE periods at roadside sites.

Spatial Trends

The spatial trends of the overall average concentrations of air pollution data from 7 roadside and 10 residential sites are shown in Fig. 2. Taking into account the overall average, results showed the coefficient of variations (CVs) of PM_{10} (Figs. 2(a) and 2(b)), CO_{8hr} (Figs. 2(c) and (d)), and NO_2 (Figs. 2(g) and (h)) in roadside sites were less than those in residential sites (34.7–42.4% vs. 41.8–50.2%) in BKK, whereas the CVs of $O_{3\text{-}1hr}$ (Figs. 2(e) and (f)) and SO_2 (Figs. 2(i) and (j)) had an inverse trend (50.6–53.2% vs. 39.2–47.7%). By seasonal comparisons, only PM_{10} (Figs. 2(a) and 2(b)) had higher concentrations and variations in winter season than summer and rainy seasons at both roadside and residential sites. The other pollutants, such as CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 (Figs. 2(c)–2(j)), indicated that they had an inverse trend (higher concentrations and lower variations in winter) at both sites. In BKK, the overall and seasonal averages of air pollutants at roadside sites higher than that at residential sites were summarized, yet the seasonal effects might be significant than spatial effect on inter-roadside and inter-residential sites air pollutants variations. More details for site-specific variations with higher spatial resolutions in BKK similar to the previous study (Kim Oanh and Zhang, 2004) did not discussed here. However, the different temporal variations in BKK were discussed later in this study.

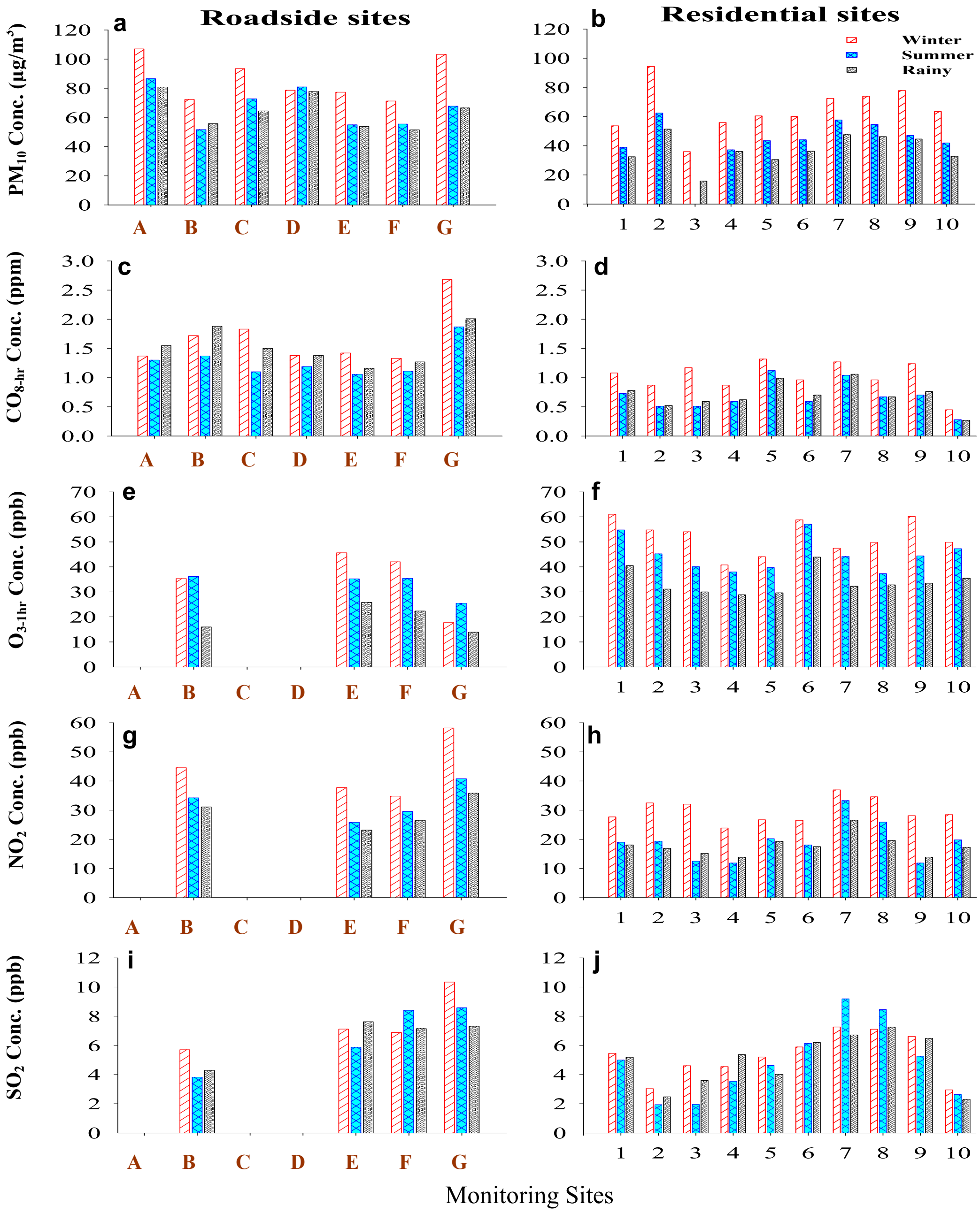


Fig. 2. The spatial distribution of average pollution concentrations between roadside and residential sites for (a, b) PM_{10}, (c, d) CO_{8hr}, (e, f) $O_{3\text{-}1hr}$, (g, h) NO_2, and (i, j) SO_2 in BKK during 1996–2009. (Definition of each site number has shown in Fig. 1. No data for $O_{3\text{-}1hr}$, NO_2, and SO_2 were monitored at roadside sites # 1, 3, and 4 in BKK during 1996–2009).

Long-Term Trends

Table 2 summarises the fourteen-year average and season-specific concentrations of air pollutants and meteorological parameters during 1996–2009 between roadside and residential sites. The overall average concentrations of PM_{10}, CO_{8hr}, NO_2, and SO_2 in roadside sites were higher than those in residential sites (74.5 ± 31.6 µg/m^3, 1.8 ± 0.7 ppm, 34.3 ± 11.9 ppb, and 7.7 ± 3.9 ppb vs. 55.0 ± 25.4 µg/m^3, 0.8 ± 0.4 ppm, 22.0 ± 9.2 ppb, and 5.1 ± 2.0 ppb). However, the overall average concentration of $O_{3\text{-}1hr}$ in roadside sites was lower than those in residential sites (37.6 ± 19.9 ppb vs. 61.0 ± 29.1 ppb). The overall average concentration of $O_{3\text{-}1hr}$ was lower than Thai NAAQS in both sites. The average concentrations of PM_{10}, CO_{8hr}, NO_2, and SO_2 in roadside and residential sites were comparable in magnitude to those previously reported by the PCD (PCD, 2007) for the same air monitoring sites. Since 1993, the Office of National Energy Policy has formulated a 10-year policy for fuel improvement (Thavisin, 2001); therefore, the level of air pollution is getting better.

Since 1996, the annual average concentrations of PM_{10}, CO_{8hr}, and SO_2 were decreased; however, the NO_2 and $O_{3\text{-}1hr}$ levels were slightly increased (Figs. 3(a) and (b)). Decreasing the NO_2 and $O_{3\text{-}1hr}$ levels is currently impractical because the Thai government promotes the use of gasohol fuel in cars and motorbikes. PM_{10} and CO_{8hr} levels at roadsides and residential sites were slightly increased compared to previous years (Fig. 3(a)) due to construction activities to improve road conditions in 2004, which resulted in traffic congestion in BKK, leading to the accumulation of air pollutants emitted from vehicles (PCD, 2006). Ozone is a secondary pollutant formed by this reaction between volatile organic compounds (VOCs) and nitrogen oxides in the presence of sunlight. There are many factors that make controlling the formation of ozone difficult in BKK. The various measures in place to reduce ozone levels do not reduce the amount of ozone down to the standard criteria. The main sources of ozone in the atmosphere were confirmed from VOCs produced by gas stations, motorcycles and 2-stroke motor tricycles, car spray paint garages, metal plating factories, electronics factories that use solvents for cleaning, and barbecue grills (CSD, 2008).

Additionally, the PCD measured the air pollution for gasohol cars and motorcycles during 2003–2004. The result of air quality tests from the five air measurement stations in BKK found that the THC levels decreased 5–25%, the CO levels decreased 15–30%, and the NO_x levels slightly increased. These results were consistent with those of a Brazilian study demonstrating that THC levels were reduced by 12%, CO levels were reduced by 32%, and NO_x levels slightly increased during the same period (PCD, 2007). The average of the air pollution concentrations and meteorological parameters were found to be significantly different between the studied sites ($p < 0.0001$), indicating that high traffic sites had higher air pollution levels than residential sites. Our results were similar with previous reports (Grivas *et al.*, 2004; Kim Oanh *et al.*, 2006; Chuersuwan *et al.*, 2008; Azmi *et al.*, 2010).

Seasonal Variations

In the winter, the average concentrations of PM_{10}, CO_{8hr}, NO_2, and SO_2 in roadside sites were higher than those in residential sites (90.1 ± 36.3 µg/m^3, 1.9 ± 0.8 ppm, 43.0 ± 12.2 ppb, and 8.4 ± 4.4 ppb vs. 71.7 ± 29.8 µg/m^3, 1.0 ± 0.4 ppm, 29.6 ± 9.7 ppb, and 5.4 ± 2.2 ppb). In contrast, the average concentrations of $O_{3\text{-}1hr}$, RH, and WS in roadside sites were lower than those in residential sites during winter seasons (48.0 ± 19.7 ppb, 66.4 ± 11.7%, and 1.1 ± 0.3 m/s vs. 71.7 ± 27.4 ppb, 70.8 ± 11.7%, and 1.3 ± 0.3 m/s). In the summer, the average concentrations of PM_{10}, CO_{8hr}, NO_2, and SO_2 and the average temperature in roadside sites were higher than those in residential sites (65.6 ± 24.2 µg/m^3, 1.6 ± 0.7 ppm, 30.9 ± 9.9 ppb, 7.4 ± 4.0 ppb, and 30.6 ± 1.6°C vs. 48.1 ± 16.8 µg/m^3, 0.7 ± 0.3 ppm, 18.4 ± 6.8 ppb, 4.9 ± 2.1 ppb, and 30.1 ± 1.5°C,). In contrast, the average monthly concentrations of $O_{3\text{-}1hr}$, RH, and WS in roadside sites were lower than those in residential sites (38.5 ± 20.4 ppb, 73.1 ± 10.5%, and 1.2 ± 0.3 m/s vs. 62.3 ± 30.3 ppb, 77.7 ± 10.3%, and 1.5 ± 0.3 m/s). In the rainy season, the average concentrations of PM_{10}, CO_{8hr}, NO_2, and SO_2 and the average temperature in roadside sites were higher than those in residential sites (67.4 ± 26.6 µg/m^3, 1.8 ± 0.6 ppm, 29.4 ± 8.5 ppb, 7.4 ± 3.2 ppb, and 29.6 ± 1.3°C vs. 45.8 ± 18.4 µg/m^3, 0.8 ± 0.3 ppm, 18.3 ± 5.7 ppb, 5.1 ± 1.7 ppb, and 29.2 ± 1.2°C). In contrast, the average monthly concentrations of $O_{3\text{-}1hr}$, RH, and WS in roadside sites were lower than those in residential sites (29.0 ± 15.3 ppb, 75.7 ± 10.6%, and 1.3 ± 0.4 m/s vs. 51.9 ± 26.5 ppb, 79.7 ± 9.8%, and 1.4 ± 0.3 m/s) (shown in Table 2).

An one-way ANOVA was applied to the data to elucidate temporal and spatial variations. Using a p-value of < 0.0001, the average concentrations of air pollutants and meteorology parameters during the three seasons at roadside and residential sites were found to differ significantly from each other. At the urban traffic areas, there was an intensive seasonal variability, with higher concentrations of PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 during the winter months. This finding is similar to that of previous studies (Tsai *et al.*, 2008; Juneng *et al.*, 2009; Azmi *et al.*, 2010; Rose *et al.*, 2011; Vlachogianni *et al.*, 2011).

Figs. 3(c) and 3(d) shows the average monthly concentrations of PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 during the 14-year monitored period. The concentrations of PM_{10}, CO_{8hr}, NO_2, and SO_2 exhibited the same seasonal pattern at roadside and residential sites, reaching maximum during the winter period and minimum during the rainy period. Note that during the dry season, a weak influence from the high-pressure ridge could be felt in BKK, which might reduce pollutant dispersion and cause a lack of rain scavenging (Kim Oanh *et al.*, 2006; Chuersuwan *et al.*, 2008). This pollutant variation was associated with the seasonal variation of the relevant meteorological dispersion, similar to the more common occurrence of stable and extremely stable low wind speed situations during the winter period (Vlachogianni *et al.*, 2011). The $O_{3\text{-}1hr}$ concentrations had a different seasonal pattern from the PM_{10}, CO_{8hr}, NO_2, and SO_2 concentrations. The maximum $O_{3\text{-}1hr}$ concentrations occurred during the winter, and a second peak occurred during the summer. The lowest $O_{3\text{-}1hr}$ concentrations occurred during the rainy

Table 2. Descriptive statistics of different air pollution and meteorology at roadside and residential sites in BKK during 1996–2009.

Variable	Roadside				Residential			
	Overall	Winter	Summer	Rainy	Overall	Winter	Summer	Rainy
	Mean ± SD (Min–Max)	Mean ± SD (Min–Max)	Mean ± SD (Min–Max)	Mean ± SD (Min–Max)	Mean ± SD (Min–Max)	Mean ± SD (Min–Max)	Mean ± SD (Min–Max)	Mean ± SD (Min–Max)
Air pollutants								
PM_{10} (μg/m^3)	74.5 ± 31.6 26.2–351.2	90.1 ± 36.3 29.6–351.2	65.6 ± 24.2 26.2–186.3	67.4 ± 26.6 27.9–223.4	55.0 ± 25.4 6.0–254.3	71.7 ± 29.8 6.0–254.3	48.1 ± 16.8 20.3–141.4	45.8 ± 18.4 18.8–184.4
CO_{8hr} (ppm)	1.8 ± 0.7 0.4–7.9	1.9 ± 0.8 0.4–7.9	1.6 ± 0.7 0.4–7.3	1.8 ± 0.6 0.5–5.2	0.8 ± 0.4 0.1–3.6	1.0 ± 0.4 0.3–3.6	0.7 ± 0.3 0.1–2.8	0.8 ± 0.3 0.2–2.4
$O_{3\text{-}1hr}$ (ppb)	37.6 ± 20.0 1.0–145.0	48.0 ± 19.7 3.0–137.0	38.5 ± 20.4 4.0–145.0	29.0 ± 15.3 1.0–106.0	61.0 ± 29.1 1.0–479.0	71.7 ± 27.4 15.0–221.0	62.3 ± 30.3 10.0–479.0	51.9 ± 26.5 1.0–370.0
NO_2 (ppb)	34.3 ± 11.9 0.5–107.6	43.0 ± 12.2 15.3–107.6	30.9 ± 9.9 13.6–72.3	29.4 ± 8.5 9.1–74.1	22.0 ± 9.2 3.2–68.5	29.6 ± 9.7 5.5–68.5	18.4 ± 6.8 3.2–50.0	18.3 ± 5.7 5.3–42.1
SO_2 (ppb)	7.7 ± 3.9 0.2–40.7	8.4 ± 4.4 0.7–40.7	7.4 ± 4.0 0.7–25.6	7.4 ± 3.2 0.2–25.4	5.1 ± 2.0 0.1–21.6	5.4 ± 2.2 0.0–21.6	4.9 ± 2.1 0.2–15.8	5.1 ± 1.7 0.5–14.6
Meteorology								
Temperature (°C)	29.4 ± 1.8 21.2–34.4	28.4 ± 1.9 21.2–32.4	30.6 ± 1.6 24.0–34.4	29.6 ± 1.3 24.8-33.2	29.0 ± 1.7 20.3–33.6	27.9 ± 1.8 20.2–32.1	30.1 ± 1.5 23.4–33.6	29.2 ± 1.2 25.0–32.6
RH (%)	72.0 ± 11.7 35.7–100.0	66.4 ± 11.7 38.6–99.4	73.1 ± 10.5 35.7–99.9	75.7 ± 10.6 44.1–100.0	76.3 ± 11.3 40.2–99.6	70.8 ± 11.7 41.0–99.2	77.7 ± 10.3 40.2–99.6	79.7 ± 9.8 53.6–99.5
WS (m/s)	1.2 ± 0.4 0.4–2.9	1.1 ± 0.3 0.4–2.8	1.2 ± 0.3 0.5–2.8	1.3 ± 0.4 0.5–2.9	1.4 ± 0.3 0.6–2.8	1.3 ± 0.3 0.6–2.7	1.4 ± 0.3 0.7–2.8	1.4 ± 0.3 0.6–2.6

Abbreviation: RH: relative humidity; WS: wind speed.

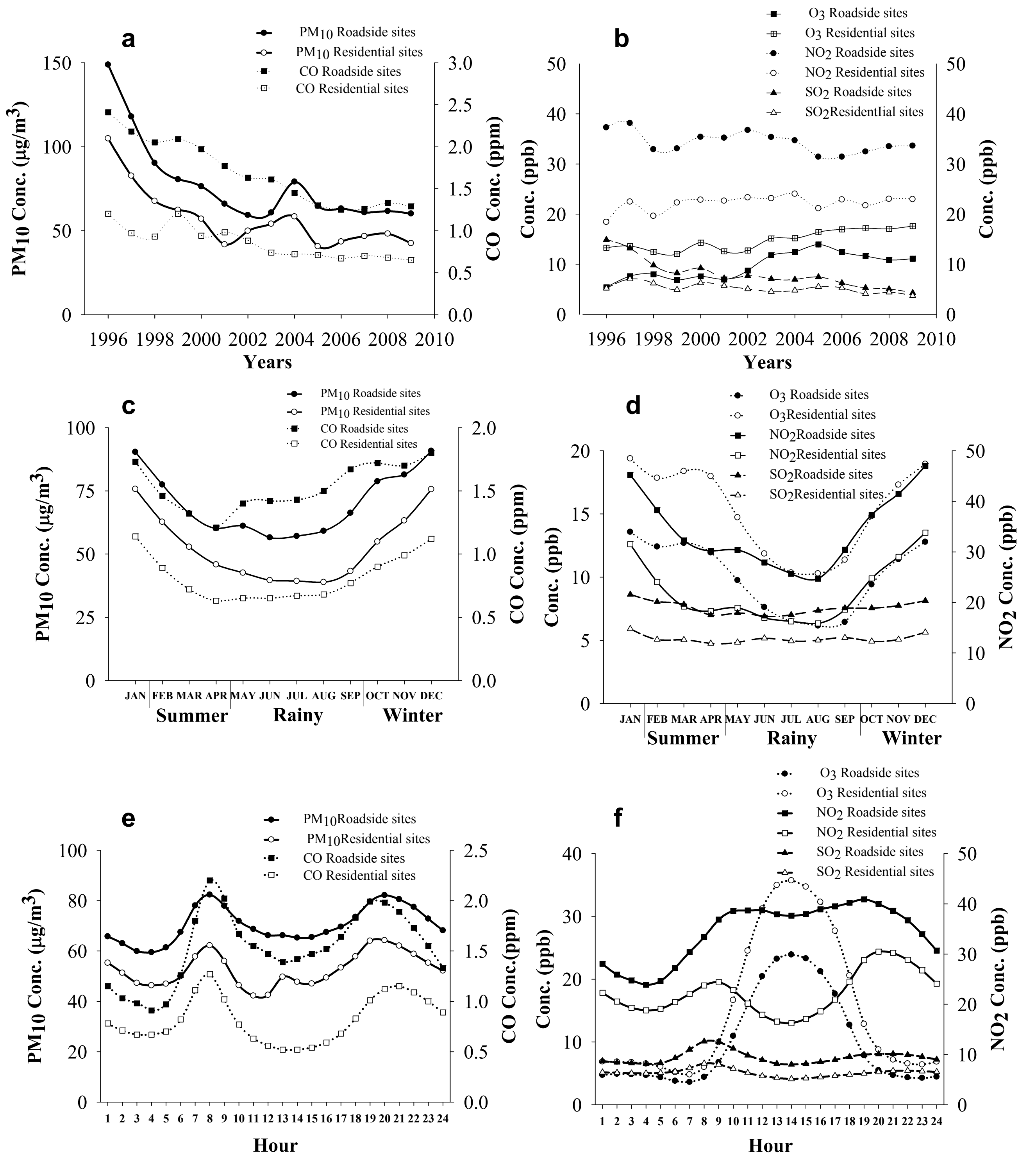


Fig. 3. The annual (a, b), seasonal (c, d), and diurnal (e, f) trends of PM_{10}, $CO_{8\text{-hr}}$, $O_{3\text{-1hr}}$, NO_2, and SO_2 concentrations in both roadside and residential sites in BKK during 1996–2009.

season at both roadside and residential sites due to the influence of sunlight on photochemical reactions.

Diurnal Variations

Figs. 3(e) and 3(f) shows that the daily concentration variations of PM_{10}, CO_{8hr}, NO_2, and SO_2 in roadside sites are higher than those in residential sites, which is the opposite of the ozone variations. The diurnal patterns of PM_{10}, CO_{8hr}, and NO_2 display double peaks occurring during the morning rush hour traffic peak around 07:00 to 09:00 and during the evening rush hour after 19:00 in both sites. In contrast, the peak ozone concentration occurred 14:00 in the afternoon, in accordance with the diurnal cycle of solar radiation. This is because sunlight is the most important factor affecting the photochemical reactions that produce ozone. These results did not reflect the results of the other gases. The temperature inversion emerging near the road surface at night also helped to augment and prolong the evening peaks, which persisted until the traffic flow subsided late at night, causing the pollutant concentrations to decrease accordingly.

Moreover, atmospheric stability and WS factors influencing PM_{10}, CO_{8hr}, NO_2, and SO_2 concentrations were likely to exhibit spatial and temporal variations. For instance, local contributions around roadside sites accounted for approximately one-third of the contributions in residential sites, most likely from high traffic and surrounding activities. The recorded daily means of air pollution concentrations were found to differ significantly between roadside and residential sites ($p < 0.0001$), indicating that, in addition to the negative influence of prevailing regional meteorological conditions, traffic emission patterns affected the entire area (Grivas *et al.*, 2004; Tsai *et al.*, 2008; Kim Oanh *et al.*, 2009; Azmi *et al.*, 2010; Genc *et al.*, 2010; Vlachogianni *et al.*, 2011). Moderate correlations were found between PM_{10} in roadside sites and PM_{10} and NO_2 in residential sites ($r = 0.403$, $p < 0.0001$ and $r = 0.308$, $p < 0.0001$, respectively), indicating the importance of direct road traffic emissions. Generally, there were lower correlations from frequently reported results for monitoring networks spanning over a large area as the distance between stations increases (Grivas *et al.*, 2004).

Correlations between Air Pollutants and Meteorological Factors

The correlations between air pollutants and meteorological parameters are shown in Table 3. All air pollutants were negatively correlated with WS because suspended air pollutants were accumulated during lower WS and diluted/ removed during higher WS (Grivas *et al.*, 2004; Kim Oanh *et al.*, 2009). Data showed that PM_{10} was positively correlated with NO_2 and CO_{8hr} ($r = 0.73$, $p < 0.0001$ and $r = 0.64$, $p < 0.0001$, respectively) and moderately correlated with SO_2 ($r = 0.54$, $p < 0.0001$). However, PM_{10} was negatively correlated with WS ($r = –0.44$, $p < 0.0001$). In addition, CO_{8hr} and NO_2 were strongly correlated ($r = 0.66$, $p < 0.0001$) indicating that a major source of their emissions came from vehicles (Grivas *et al.*, 2004; Azmi *et al.*, 2010).

Regression Models

The stepwise multiple linear regression models were used to find the factors that affected air pollution in BKK. The regression models for air pollutants with meteorological, area, and seasonal variables in 2009 were showed in Table 4. The regression analysis was conducted on significant factors affecting PM_{10}, NO_2, and SO_2 levels, including the areas studied, season, RH, temperature, and WS. Temperature was not a significant factor affecting $O_{3\text{-}1hr}$, while RH and season were not significant factors affecting CO_{8hr} levels. The coefficient of determination (r^2) for PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2 and SO_2 was 0.54, 0.68, 0.51, 0.64, and 0.22, respectively. The regression models for PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, and NO_2 decreased moderately with decreasing WS, temperature, and RH. On the other hand, there was a weak association between SO_2 concentrations and meteorological parameters, similar to a previous finding (Akpinar *et al.*, 2008).

Air pollution concentrations decreased with increasing WS and circulation of airflow because pollutants dilute through dispersion when WS is higher. The volume and dilution of air pollution were controlled by WS and WD. Moreover, RH is inversely related to air pollution because it controls the absorption rate of air pollutants. The coefficients

Table 3. Pearson's correlation coefficients between air pollution and meteorological parameters in BKK during 1996–2009.

Parameter	PM_{10}	CO	NO_2	SO_2	O_3	RH	Temp	WS
PM_{10}	1							
CO	0.64	1						
NO_2	0.73	0.66	1					
SO_2	0.54	0.58	0.43	1				
O_3	0.13	–0.25	0.21	–0.11	1			
RH	–0.06	0.06	–0.29	0.13	–0.28	1		
Temp	–0.19	–0.04	–0.28	0.05	0.14	–0.06	1	
WS	–0.44	–0.45	–0.49	–0.25	–0.07	–0.13	–0.23	1

All correlations of air pollution and meteorological parameters are significant at the < 0.0001 level (two-tailed).

Table 4. Regression model of air pollution concentrations, with a regression coefficient for meteorological conditions, the areas studied, and seasonal parameters in BKK in 2009.

	Intercept	RH (%)	Temp. (°C)	WS (m/s)	Roadside areas	Winter season	Summer season	r^2
PM_{10}, (μg/m^3)	172.41	–0.81	–1.26	–30.62	4.41	10.68	2.68	0.54
CO_{8hr}, (ppm)	1.77	NS	–0.02	–0.45	0.67	NS	NS	0.68
$O_{3\text{-}1hr}$, (ppb)	189.20	–0.92	NS	–50.81	–40.93	10.02	10.25	0.51
NO_2, (ppb)	108.35	–0.40	–1.05	–22.67	2.60	7.87	2.94	0.64
SO_2, (ppb)	7.48	–0.02	NS	–1.70	NS	0.31	–0.38	0.22

NS = Parameter is excluded from the model due to not significant.

of the season dummy variable indicated higher concentrations of PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2 and SO_2 during the winter and summer seasons, using the rainy season as a reference. Further, the coefficients of the areas studied dummy variable indicated higher concentrations of PM_{10}, CO_{8hr}, NO_2, and SO_2 in roadside sites, using residential sites as a reference. The inverse was found for $O_{3\text{-}1hr}$. It is demonstrated by both spatial and temporal variations in the PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2 and SO_2 models. There were marked significant effects of seasonal, temporal, and meteorological factors on air pollution concentrations, and the findings were similar to previous studies (Kim Oanh *et al.*, 2009; Genc *et al.*, 2010; Rose *et al.*, 2011). Fig. 4 shows the daily-basis predicted and monitoring data of PM_{10} and $O_{3\text{-}1hr}$ concentrations at both roadside and residential sites in BKK in 2009. Results showed that the prediction performances in PM_{10} and ozone at residential sites were better than that at roadside sites in 2009 (PM_{10}: $r^2 = 0.58$ vs. $r^2 = 0.37$; $O_{3\text{-}1hr}$: $r^2 = 0.45$ vs. $r^2 = 0.43$). However, the predicted model might not performed very well and still needed to improve with adding more detail affecting factors such as land-use, vehicle density, distance to monitoring site, seasonality, and so on. Further, if the resources were allowable, a GIS-based land-use regression model (Liu *et al.*, 2009; Chen *et al.*, 2012) might be applied for predicting the air quality in BKK.

Weekday-Weekend Variations and Potential Ozone Estimates

Table 5 shows the weekday (WKD) and weekend (WKE) variations at both roadside and residential sites in different seasons in BKK during 1996–2009. All the five pollutants including PM_{10}, CO_{8hr}, $O_{3\text{-}1hr}$, NO_2, and SO_2 did not show the significantly different between WKD and WKE durations at both roadside and residential sites for overall and single season. Table 5 only indicated that the air pollutants influenced by season change and location variables. For ozone, the phenomenon was differed from previous studies in India (Debaje and Kakade, 2006) and Japan (Sadanaga *et al.*, 2012). Lontati *et al.* (2006) had compared the fine PM data during WKD and WKE periods in Milan, Italy, and showed that the traffic emissions played a significant role to influence the PM sizes and concentrations at residential, traffic, and suburban sites during different seasons. Additionally, one study in Taipei, Taiwan (Chang and Lee, 2007), polled five monitoring sites and showed that the WKD-WKE variations of air pollutants were not significant different. However, our findings were not consistent with the Milan study but that in Taipei study.

Potential ozone or oxidant ($O_x = O_3 + NO_2$) (Kley *et al.*, 1994; Chou *et al.*, 2006) estimates distributions between roadside and residential sites in BKK during 1996–2009 are described in Table 6. For annual trends of O_x, there existed peaks for roadside sites in 2003–2004 and that for residential sites in 2008–2009. Overall, the annual O_x estimates at roadside sites were larger than that at residential sites but not significant. By monthly comparisons, they showed a peak occurred from November to January (next year) at both sites. The average differences between these two kinds of sites ranged from 5.9 ppb (in August) to 11.3 ppb (in February). By comparing with one study in Tokyo,

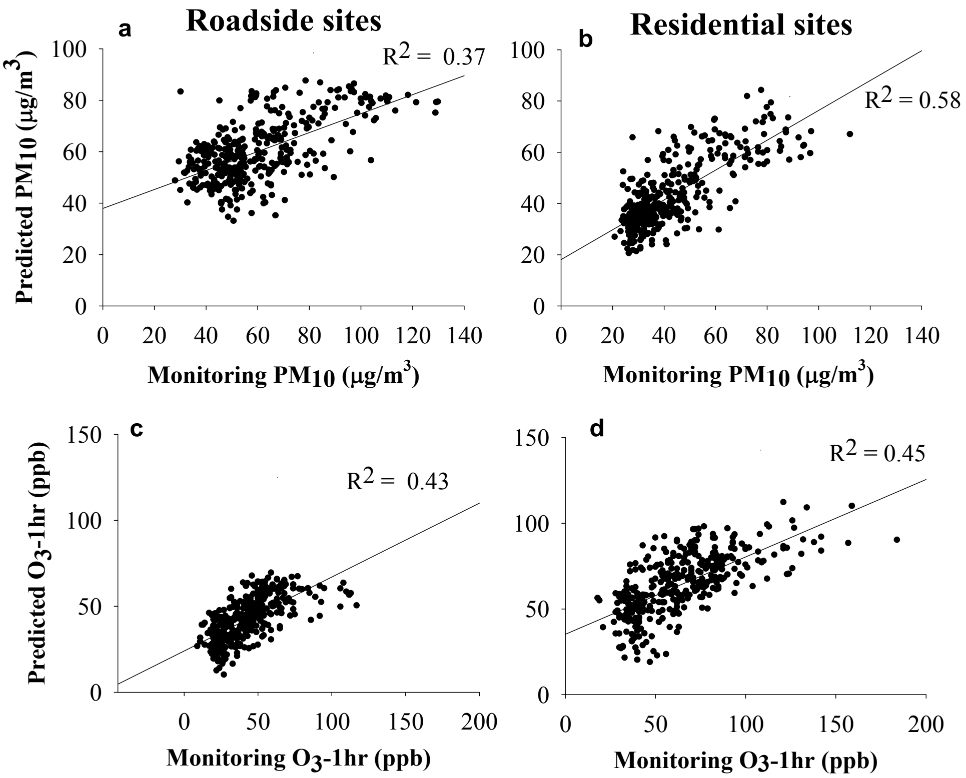


Fig. 4. Scatter plot showing the predicted and monitoring data of (a, b) PM_{10} and (c, d) $O_{3\text{-}1hr}$ concentrations at both roadside and residential sites in BKK in 2009.

Table 5. Weekday and weekend variations at both roadside and residential sites in different seasons in BKK during 1996–2009.

	Air Pollutants				
	PM_{10} (μg/m^3)	CO_{8hr} (ppm)	$O_{3\text{-}1hr}$ (ppb)	NO_2 (ppb)	SO_2 (ppb)
Roadside sites					
Overall					
WKD	74.3 ± 32.1	1.8 ± 0.7	37.6 ± 20.0	34.2 ± 12.2	7.7 ± 3.9
WKE	74.0 ± 30.5	1.7 ± 0.6	37.7 ± 19.7	34.5 ± 11.3	7.9 ± 3.8
Winter					
WKD	89.9 ± 37.1	1.9 ± 0.8	47.8 ± 19.7	42.8 ± 12.6	8.4 ± 4.5
WKE	90.5 ± 34.3	1.8 ± 0.7	48.5 ± 19.5	43.3 ± 11.2	8.4 ± 4.2
Summer					
WKD	65.5 ± 24.2	1.6 ± 0.7	38.8 ± 20.8	30.8 ± 10.2	7.2 ± 4.0
WKE	65.9 ± 24.0	1.6 ± 0.6	37.6 ± 19.5	31.1 ± 9.0	7.7 ± 4.0
Rainy					
WKD	67.3 ± 26.9	1.8 ± 0.6	28.9 ± 15.3	29.3 ± 8.7	7.4 ± 3.2
WKE	67.8 ± 25.6	1.7 ± 0.6	29.2 ± 15.3	29.4 ± 8.0	7.6 ± 3.1
Residential sites					
Overall					
WKD	54.9 ± 25.8	0.8 ± 0.4	61.1 ± 29.4	22.0 ± 9.3	5.1 ± 2.0
WKE	55.1 ± 24.4	0.8 ± 0.4	60.8 ± 28.3	22.1 ± 8.9	5.3 ± 2.1
Winter					
WKD	71.7 ± 30.5	1.0 ± 0.4	71.8 ± 27.9	29.5 ± 9.8	5.4 ± 2.1
WKE	71.6 ± 28.1	1.0 ± 0.4	71.6 ± 26.1	29.8 ± 9.2	5.6 ± 2.5
Summer					
WKD	48.2 ± 17.3	0.7 ± 0.3	63.2 ± 32.0	18.4 ± 7.0	4.8 ± 2.1
WKE	47.9 ± 15.5	0.7 ± 0.3	59.8 ± 25.5	18.4 ± 6.3	4.9 ± 2.1
Rainy					
WKD	45.6 ± 18.4	0.8 ± 0.3	51.5 ± 25.5	18.3 ± 5.8	5.0 ± 1.7
WKE	46.4 ± 18.4	0.7 ± 0.3	53.0 ± 28.9	18.3 ± 5.5	5.2 ± 1.7

Abbreviation: WKD: weekday; WKE: weekend.

Japan (Sadanaga *et al.*, 2012), the O_x production (Here defined as $O_x = O_3 + NO_2 - 0.1\ NO_x$) in annual variation between study sites (urban and suburban) was little. The seasonal change was the major dominant factor for O_x production. In addition, the diurnal trends at both sites were similar and showed that peak duration occurred from 12:00 to 17:00 everyday. In the peak duration, however, the O_x estimates at roadside sites had higher than that at residential sites (54.1–58.0 ppb vs. 42.2–44.2 ppb) but not significant which due to the higher variations shown at both sites.

CONCLUSIONS

With the exception of $O_{3\text{-}1hr}$, the annual averages of PM_{10}, CO, NO_2, and SO_2 concentrations in roadside sites were higher than those in residential sites in BKK. In winter, all the air pollutants concentrations were higher than those during summer and rainy seasons. Interestingly, there were no differences between weekday and weekend durations for the same site category and season in our observations. Furthermore, we proposed stepwise multiple linear regression models with meteorological, spatial, and temporal factors to five air pollutants at both roadside and residential sites in 2009. Results also showed good performances with r^2 ranged between 0.51 and 0.68 except SO_2. Compared with the standard in Thailand and guideline by WHO, the severe impacts caused by air pollutants should be noticed and concerned. Since 1993, however, the levels of air pollutions in BKK have decreased because the improvement of air quality have been included, by the national government, in the policy on the protection of public health, which was formulated in accordance with the National Economic and Social Development Plan (Kunchornrat *et al.*, 2008; Vichit-Vadakan and Vajanapoom, 2011). Our findings showed the heterogeneously spatiotemporal characteristics in BKK and supported the future improving direction of air pollution control.

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Table 6. Potential ozone (O_x) estimates distributions between roadside and residential sites in BKK during 1996–2009.

Roadside sites						Residential sites					
Annual		Monthly		Diurnal		Annual		Monthly		Diurnal	
1996	41.3 ± 23.1	Jan	54.9 ± 28.3	1	31.0 ± 17.3	1996	25.4 ± 19.2	Jan	45.9 ± 25.7	1	26.7 ± 15.9
1997	44.3 ± 25.1	Feb	47.5 ± 27.0	2	29.2 ± 16.1	1997	30.5 ± 21.7	Feb	36.2 ± 24.8	2	24.9 ± 14.8
1998	32.6 ± 25.1	Mar	42.1 ± 24.8	3	28.0 ± 15.2	1998	27.5 ± 20.1	Mar	32.2 ± 22.2	3	23.7 ± 13.9
1999	23.8 ± 22.8	Apr	40.5 ± 22.8	4	27.1 ± 14.5	1999	26.1 ± 20.5	Apr	31.4 ± 20.5	4	23.1 ± 13.3
2000	40.5 ± 25.8	May	37.4 ± 21.3	5	27.5 ± 14.2	2000	32.4 ± 21.8	May	29.5 ± 18.4	5	22.9 ± 13.0
2001	41.1 ± 23.9	Jun	33.9 ± 18.3	6	29.2 ± 15.1	2001	31.0 ± 21.1	Jun	25.4 ± 15.2	6	23.5 ± 12.8
2002	43.8 ± 23.3	Jul	31.2 ± 15.7	7	31.8 ± 17.0	2002	33.3 ± 20.4	Jul	23.9 ± 14.4	7	24.7 ± 13.1
2003	46.5 ± 23.8	Aug	29.4 ± 15.7	8	35.5 ± 18.3	2003	35.5 ± 22.7	Aug	23.5 ± 14.2	8	27.3 ± 13.8
2004	46.6 ± 24.7	Sep	34.6 ± 20.8	9	41.1 ± 20.3	2004	35.1 ± 22.5	Sep	27.0 ± 17.2	9	31.2 ± 16.5
2005	44.4 ± 23.2	Oct	43.9 ± 23.2	10	46.7 ± 22.8	2005	33.7 ± 19.3	Oct	35.6 ± 20.1	10	35.1 ± 19.7
2006	43.2 ± 22.7	Nov	49.8 ± 25.0	11	51.5 ± 24.2	2006	36.0 ± 21.2	Nov	42.4 ± 21.7	11	38.9 ± 22.6
2007	43.0 ± 22.5	Dec	55.7 ± 26.5	12	55.7 ± 26.0	2007	34.0 ± 22.7	Dec	48.0 ± 23.1	12	42.2 ± 25.4
2008	44.0 ± 22.4			13	57.6 ± 27.1	2008	38.9 ± 21.4			13	43.9 ± 27.3
2009	44.3 ± 23.1			14	58.0 ± 27.6	2009	38.2 ± 22.4			14	44.2 ± 27.8
				15	57.8 ± 27.3					15	44.2 ± 27.7
				16	56.8 ± 27.1					16	43.7 ± 27.2
				17	54.1 ± 26.5					17	42.3 ± 25.8
				18	50.1 ± 25.6					18	39.9 ± 23.8
				19	46.0 ± 24.3					19	37.8 ± 21.9
				20	42.8 ± 23.4					20	36.1 ± 20.9
				21	40.7 ± 22.7					21	34.6 ± 20.2
				22	38.7 ± 21.6					22	32.7 ± 19.4
				23	36.0 ± 20.0					23	30.6 ± 18.2
				24	33.2 ± 18.5					24	28.4 ± 16.9

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