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Characterization of black carbon at roadside sites and along vehicle roadways in the Bangkok Metropolitan Region

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HIGHLIGHTS

- Roadside and on-road black carbon pollution in Bangkok was characterized.
- Black carbon level in the wet season was lowered not by rain but by wind direction.
- Roadside black carbon level was ~7-fold higher than the urban background value.
- Roadside pollution was similar to on-road level inside cars on the congested roads.
- NO_x could be a black carbon indicator at the roadside because of good correlation.

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ABSTRACT

To understand the seasonality of concentrations of traffic-related black carbon (BC) in a megacity, BC concentrations in fine particles were monitored at the roadside and on roads during both the wet and dry seasons of 2010 in the city center of Bangkok, Thailand. The BC concentration measured every 2 min by an aethalometer at the Dingdaeng roadside in the dry season was 17.9 ± 6.6 μg m^{-3}, which was 1.6-fold higher than the value (11.5 ± 2.7 μg m^{-3}) during the wet season. This seasonal difference could not be explained by washout by rain but was instead due to more frequent upwind conditions caused by a prevailing wind direction from the monitoring site toward the road in the wet season. When the prevailing wind direction was from the road, the average BC concentration at the roadside increased up to 30 μg m^{-3} during both seasons. In contrast, when the wind direction was from the site to the road, the BC concentration was reduced to the level of urban background concentrations measured inside Lumphini Park and the Dusit Zoo of Bangkok. Roadside BC concentrations were strongly correlated with NO_x concentrations and elemental carbon (EC) concentrations measured in 24-h $PM_{2.5}$ filter samples. Both relationships exhibited linear determination coefficients of more than 0.80, implying that NO_x can be used as an indicator and an alternative for traffic-related BC at this roadside site when real-time BC monitors are not available.

The average on-road BC concentration (25.5 μg m^{-3}) was similar to the average at the roadside under downwind conditions (25.5 μg m^{-3}) from morning to evening only. In contrast, the latter value was 1.7-fold higher than the daily average at the roadside (14.7 μg m^{-3}) and 7.3-fold higher than the urban background level during the daytime (3.5 μg m^{-3}). The results of this study suggest that residents who live next to major roads, pedestrians at the roadside, and drivers on the roads experience a high risk of exposure to severe levels of traffic-related air pollutants.

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1. Introduction

Incomplete combustion of fossil fuels for heating, transportation, industrial activities, as well as and biomass burning from forest fires and the clearing of agricultural residuals can function as sources of carbonaceous particles in the form of elemental carbon (EC) or black carbon (BC) and numerous organic carbon (OC) species, all of which are major contributors to urban air pollution of particulate matters (PM). In particular, BC pollution has become a crucial issue due to its multiple effects on urban air quality, global climate change, and public health. Furthermore, BC has been reported as the second highest contributor as a single compound to global warming, after CO_2 (Ramanathan and Carmichael, 2008; Bond et al., 2013). BC has been implicated as a cause of lowered heart rate variability (Schwartz et al., 2005), increased cardiovascular and respiratory mortality (Maynard et al., 2007), blood pressure changes (Wilker et al., 2010), and cancer (Silverman et al., 2012). Recently, the International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), classified diesel engine exhaust, for which BC is used as an indicator, as carcinogenic to humans (Group 1) based on sufficient evidence that exposure is associated with an increased risk of lung cancer (WHO, 2012).

Criteria pollutants, such as PM, CO, NO_2, SO_2, and O_3, are monitored in urban areas in almost all countries worldwide (Bachmann, 2007). Based on their economic status and scientific background, each country has its own regulations and laws to reduce air pollutants. The WHO (2008) has set the air pollution guidelines for both developed and developing countries since 2005, with the most recent update in 2008 for selected air pollutants (i.e., PM, O_3, NO_2 and SO_2) that could be applied across all WHO regions. BC, however, is currently absent from all of these guidelines and in ambient air quality standards. The emission inventory in Asia based on fuel consumption in 2006 reported that BC from the transportation sector accounted for 14% of total BC emissions (Zhang et al., 2009). Therefore, air pollution levels and the phenomena of traffic-related BC should be better understood to manage urban air quality, to mitigate climate change, and to protect public health. In particular, impairment of urban air quality and health effects caused by vehicle exhaust can be more serious in megacities because of the high density of vehicles in traffic congestion inside of urban street canyons surrounded by tall buildings.

In 2010, Bangkok was ranked sixteenth among 30 megacities (i.e., cities with populations over 10 million) in Asia (World Gazetteer, 2010). Bangkok is known for its air pollution problems due to the rapid growth of the population, industry, and services, which have all accelerated with concomitant enormous increases in transportation activities and related pollutant emissions. Mobile sources are the major emitters of NO_x (80%), CO (75%), and particulate matter (54%) (UNEP, 2001). The World Bank (2002) published a special issue concerning air pollution in Thailand, citing that the health costs of exposure to pollutants in Bangkok accounted for up to 10% of total citizen income, while air pollution cost up to 1.6% of the GDP of Thailand. The Asian Development Bank (ADB) (2006) reported that diesel vehicles account for only 28% of the in-use vehicle fleet registered in Bangkok in 2001, yet these vehicles are estimated to emit 89% of inhalable (PM_{10} or finer) emissions put out by the fleet. Unfortunately, BC values were not measured in these studies.

The Asian Institute of Technology (AIT), located in a suburban area of Bangkok, has measured seasonal and diurnal variation of BC aerosols; the AIT has reported that higher levels occur during the dry season compared to the wet season and that diurnal variation in BC reaches a minimum around noon, falling well below values in the early morning around 2:00–4:00. These results were mainly due to a dilution effect in diurnal variation regardless of season (Kondo et al., 2009; Sahu et al., 2011) as well as potential contributions from trucks that are permitted to operate in the city only at night. To minimize the dilution effect due to air mixing, the background concentration effect from long-range transport, and the effects of pollution sources other than traffic, roadside and on-road monitoring offer a valuable approach to characterizing real-world air pollution by traffic. Roadside measurements in the urban street canyons of Bangkok have also been conducted to assess the fleet hourly emissions of gaseous pollutants such as NO_x, CO, and volatile organic compounds (Kim Oanh et al., 2008). However, the air pollution of traffic-related BC near roads in the city center of Bangkok has not yet been examined.

To characterize the traffic-related air pollution near roads in urban areas of the Bangkok Metropolitan Region (BMR), our monitoring activities were conducted in Bangkok in 2010. Results for concentrations of $PM_{2.5}$ and BTEX (benzene, toluene, ethylbenzene, and xylenes) at fixed roadside sites and along roadways in 2010 have been reported elsewhere (Kim Oanh et al., 2013). These previous results have documented a strong association between roadside pollutants levels and traffic flow. The present study reports BC concentrations monitored at the same fixed roadside sites and along the same urban roadways in urban Bangkok that were studied in Kim Oanh et al. (2013). The effects of meteorology (rainfall and wind) on seasonal BC pollution levels were also investigated to better understand the air pollution caused by traffic-related BC in Asian megacities.

2. Measurements

2.1. Roadside and on-road measurements

Bangkok is the capital, largest urban area, and sole megacity in Thailand. Bangkok and its surrounding six provinces are collectively known as the Bangkok Metropolitan Region (BMR), with a population of 10,376,753 in 2011 (Bangkok Metropolitan Administration, 2011). The region experiences a monsoon climate with a dry (mid-October to mid-May) and wet season each year. The average rainfall of 1400 mm per year mainly falls during the wet season, when the area is under the influence of the southwest monsoon, which transports oceanic air masses into the city.

BC concentrations were measured on the rooftop of a roadside air quality monitoring station managed by the Pollution Control Department (PCD) of Thailand. The monitoring station was located at the southern side of the Dingdaeng Road (PCD site in Fig. S1, SI). BC concentrations were also measured from a van travelling along an urban route (Fig. 1). Simultaneously, $PM_{2.5}$ and BTEX sampling were conducted as reported in detail by Kim Oanh et al. (2013). For comparison, daily concentrations of elemental carbon (EC) and organic carbon (OC) were measured using the thermal optical transmittance (TOT) method for $PM_{2.5}$ quartz filter samples collected at both sides of the Dingdaeng Road (the PCD side and the opposite side; i.e., the so-called school side). The sampling locations were 8 and 5 m away from the curbside of the road on the PCD and school sides, respectively; the sampling height was ~3 m above the ground for both roadsides. All inlets of monitoring instruments for air pollutants were placed at the top of the PCD monitoring station (3.5 m above the ground). Meteorological data from the Dingdaeng roadside monitoring station was obtained from a mast situated ~10 m above the ground; these data may not be representative of the area neighboring the PCD side because of its semi-street canyon configuration surrounded by 4–5-story buildings (20 m). However, wind data were considered to be valuable in terms of the air pollution data measured at the same location.