Vertical Variation of Carbonaceous Aerosols within the PM_{2.5} Fraction in Bangkok, Thailand

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ABSTRACT

Asian megacities are undergoing rapid population and infrastructure growth, which is resulting in significant air quality problems linked to atmospheric fine particles (PM_{2.5}). This study focuses on characterizing carbonaceous aerosols in an urban area of Bangkok, Thailand. The Microclimate and Air Pollutants Monitoring tower is located on the edge of Kasetsart University campus and was used to perform vertical measurements. Mass concentration data were collected using area dust monitors (ADR1500) at different levels above the ground (30 m, 75 m, and 110 m) during two time periods, daytime (08:00–19:00) and nighttime (20:00–07:00), throughout the monsoon season in 2015. All relevant micrometeorological parameters were simultaneously monitored. Backward air mass trajectories were calculated using HYSPLIT to assess the possible external pollution contributions. The thermal optical transmittance (TOT) method following the NIOSH 870 protocol was used to determine amounts of elemental carbon (EC) and organic carbon (OC) in samples. A data analysis showed average PM_{2.5} values at observation heights of 30 m, 75 m, and 110 m of 6.21 ± 2.45 , 8.12 ± 3.65 , and $9.03 \pm 3.93 \mu\text{g m}^{-3}$, respectively; corresponding OC concentrations of 4.13 ± 2.65 , 4.01 ± 4.07 , and $4.11 \pm 3.58 \mu\text{g m}^{-3}$, respectively, and EC concentrations of 1.02 ± 0.84 , 1.07 ± 0.95 , and $0.50 \pm 0.70 \mu\text{g m}^{-3}$, respectively. The results show distinct gradients of increasing concentrations of PM_{2.5} with increasing elevation in contrast with the OC and EC concentrations which decrease with height.

Keywords: Urban aerosols; Carbonaceous species; Fine particles; Vertical distribution

INTRODUCTION

The Bangkok Metropolitan area is a prime example of an Asian megacity. It has a rapidly growing population, and this has resulted in a significant degradation of air quality due to the increased traffic burden and changing urbanization profile – a situation often enhanced by adverse meteorological conditions. Atmospheric fine particulate matter (PM_{2.5}) has received an increasing attention due to its negative health and environmental impacts. Carbonaceous aerosols have a major role in light-particle interactions within the atmosphere and are one of the key components of PM_{2.5}; they are thus related to the negative environmental and climatic impacts and the deterioration in air quality and public health (Dan *et al.*, 2004; Han *et al.*, 2009a; Cheng *et al.*, 2011; Kim *et al.*,

2011; Chow *et al.*, 2011; Srivastava *et al.*, 2014; Zhao *et al.*, 2015; Han *et al.*, 2016).

The carbonaceous fraction of ambient PM_{2.5} contains both organic carbon (OC) and elemental carbon (EC). OC may be emitted directly from a source as a primary aerosol (as plant spores, pollen, or soil organic matter), but secondary organic aerosols are formed in the atmosphere from low vapor pressure products in atmospheric chemical reactions, such as oxidation and the gas-to-particle conversion of volatile organic compounds (VOCs) (Cao *et al.*, 2006). OC may also originate from exchanges between the ocean with the atmosphere caused by diffusive exchange and dry and wet deposition. EC is frequently used as a surrogate for black carbon (BC) and is emitted into the atmosphere predominantly through combustion processes (U.S. EPA, 1996; Ji *et al.*, 2016). EC is mainly responsible for light absorption in the atmosphere, which strongly influence the Earth's radiative balance (Cao *et al.*, 2006; Li *et al.*, 2016). Six primary sources of EC have been identified using organic tracers: vehicle exhaust, cooking, biomass burning, cigarette smoke, vegetative detritus, and coal combustion (Li *et al.*, 2013).

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Biomass-sourced aerosols (with high OC/EC) and VOCs can precipitate from the atmosphere with rain during the monsoon period (Li *et al.*, 2016). It has also been found that the dominance of carbonaceous aerosols (which are obtained from wood-fuel and agricultural waste burning) in PM_{2.5} has a strong impact on the deterioration in air-quality and visibility and also influences radiative forcing on a regional scale (Ram and Sarin, 2011; Bisht *et al.*, 2016).

The atmospheric boundary layer (ABL) is an important meteorological factor that affects air pollution (Tang *et al.*, 2016). The vertical distribution of meteorological parameters within ABL strongly determines pollutant concentrations in the near-surface layer (around 100 m) as well as their diffusion, reaction, settlement and other processes (Sun *et al.*, 2013; Srivastava *et al.*, 2014; Li *et al.*, 2015; Azimi *et al.*, 2018; Kanawade *et al.*, 2019) which are influenced by thermal turbulence and surface roughness.

Within the ABL, the vertical distributions of temperature, humidity, wind speed and wind direction are usually inhomogeneous and having impact on the distribution and variation of PM_{2.5} concentrations (Sun *et al.*, 2013). Therefore, the structure of the near-surface layer is very important for understanding the PM_{2.5} concentration levels and their content of carbonaceous particles for assessing air quality in all regions. Consequently, it is important to analyze the vertical distribution of PM_{2.5} and to consider the origin of PM_{2.5} contributed from local source or long-range transport. However, direct observational studies of the PM_{2.5} vertical distribution in the near-surface layer together with their chemical characterization are very limited so far (Satsangi *et al.*, 2012; Sun *et al.*, 2013; Bisht *et al.*, 2016; Chilinski *et al.*, 2016; Azimi *et al.*, 2018; Li *et al.*, 2018; Singh *et al.*, 2018; Thien *et al.*, 2019; Zhao *et al.*, 2019).

Backward-trajectory analysis is one of the standard procedures used to determine the spatial location of possible emission sources. It uses interpolated meteorological fields to estimate the most likely central path that air was transported to a receptor in a given time within a geographical area. The method essentially follows a parcel of air backwards in given time steps for a specified length of time. It is known that back trajectories provide certain oversimplifications of the atmospheric transport processes because dispersion is not accounted for. For example, they generally tend to underestimate near-receptor sources because of the lack of stochastic dispersion for the backward trajectory and to overestimate distant sources because of the lack of dispersion treatment (Koracin *et al.*, 2011). Nevertheless, backward trajectories still provide undeniable insights into the history of sampled air masses.

Seasonal and microclimate pattern in Thailand results in 3 seasons: summer, rainy and winter season. The summer season begins from February and lasts until July, in which period a change from northeast (NE) monsoon to southwest (SW) monsoon direction occurs. The winter season begins in October lasting until February, in which period the prevailing wind direction is from NE. The rainy season goes from July until October, typically with SW monsoon direction and heavy precipitation. It is in this period of time when this study was conducted – starting with July 15 until September

15, 2015. For that reason, we refer from now on to this period of time as a “monsoon season”.

The meteorological situation, topography and source potential, e.g., road or waterways transport strongly determines PM_{2.5} concentrations and hence also the amount and kind of carbonaceous aerosols in the near-surface layer. However, the PM-vertical distribution and carbon-related processes in connection with the underlying land surface have not been adequately quantitatively explored yet. Moreover, laboratory experiments regarding formation of secondary organic particles show that they are typically rather different in their chemical composition from ambient aerosols (Nozière *et al.*, 2015) and consequently having potentially different environmental effects. This discrepancy has yet to be well understood.

This study focuses on determining the vertical distribution of PM_{2.5} concentrations and the carbonaceous aerosol content of PM_{2.5} at various mixing heights in relation to meteorological parameters and applies the backward trajectory analysis to assess a possible contribution of remote sources.

METHODS

Measurement Site, Monitoring and Sampling Techniques Employed

PM_{2.5} particles were continuously and simultaneously monitored and sampled at three heights of 30 m, 75 m, and 110 m above the ground. Considering that Bangkok as well as the base of the sampling site (Fig. 1) are on average about 1.5m above the sea level the term “above the sea level” and “above the ground” are very comparable in this case. Consequently, we will use here the term above the ground. Measurements were undertaken during daytime (08:00–19:00 local time) and night time (20:00–07:00) using an area dust monitor (ADR1500, Thermo Fisher scientific Inc.) during the monsoon season specified before. Sampling site (Fig. 1) was the Microclimate and Air Pollutants Monitoring Tower at Kasetsart University (KU) (Latitude: 13.854529N, Longitude: 100.570012E). All relevant aspects regarding the performed measurements are summarized in Table 1. There is a following usage of land within the radius of 5 km around the measuring site: buildings and community land use amounts to about 94%, roads cover 4%, with remaining 2% being water and other usage. The nearby road is busy with the traffic volume of about 77,734 vehicles per day.

The ADR1500 is a photometric system equipped with omni-directional sampling heads that have a cut-off diameter of 2.5 µm. The measured signal is based on particle ensemble light scattering, where the intensity of scattered light is proportional to particle mass concentrations. Continuous concentration data are provided together with temperature and relative humidity (RH). The volumetric flow through the instrument was controlled based on ambient pressure and temperature. After the sample had passed through the sensing volume of the instrument, PM_{2.5} particles were collected on quartz microfiber filters (Tisch Environmental Inc., 37 mm diameter). Filters were preheated before sampling at 550°C for 1h to remove carbonaceous contaminants, then cooled to ambient temperature before placement in the ADR1500.

Fig. 1. Location of study area and photograph of the Microclimate and Air Pollutants Monitoring Tower at Kasetsart University (KU) (GPS- Latitude: 13.854529N, Longitude: 100.570012E).

Table 1. The Description of sampling PM_{2.5}.

Sampling	Detail
1. Site	Kasetsart University
Latitude	13.854529N
Longitude	100.570012E
2. Period of time	2 time per day
Daytime	08:00–19:00 local time
Nighttime	20:00–07:00 local time
3. Level	30, 75 and 110 m
4. Season	Monsoon season
5. Date	15 July to 15 September 2015

After collection, loaded filters were stored in a refrigerator at about 4°C before chemical analysis to prevent the evaporation of volatile components. The carbon analyzer (Sunset Laboratory Inc.) was calibrated prior to use by a series of sucrose solutions ($N = 5$, $R^2 = 0.99$). The lower detection limit of this method is on the order of 0.2 micrograms per cm² for both OC and EC. The difference between the initial and replicate analyses was smaller than 5% for total carbon (TC), and 10% for OC and EC.

The three ADR1500 monitors used in this study were prior the measurement inter-compared and showed agreement within 9.63%.

Analysis of Carbonaceous Compounds

Addressing the question of the quantitative amounts of OC and EC in PM_{2.5} samples collected material was evaluated based on the thermal-optical transmittance (TOT) method (Han *et al.*, 2007) using the NIOSH 870 protocol for analyzing carbonaceous aerosols with the Sunset Laboratory Analyzer. Following the usual measuring an area cutout of the sample quartz filter measuring 1.5 cm² was exposed

stepwise to temperatures. In the first phase of the analysis sampled material was thermally desorbed using varying temperatures in pure helium (He) atmosphere and detected delivering series of carbon peaks (OC1–OC4). The selected temperatures were: 310°C (OC1), 475°C (OC2), 615°C (OC3), and 870°C (OC4). The second phase of analysis occurs in 2% O₂ and 98% He atmosphere at temperatures of: 550°C (EC1), 625°C (EC2), 700°C (EC3), 775°C (EC4), 850°C (EC5), and 870°C (EC6). The split point between those phases is automatically set when the measured optical signal returns to the baseline (Bautista *et al.*, 2015) to minimize the uncertainty due to the formation of pyrolytic carbon (PC) from the OC into the thermally stable form having similarity with EC (Karanasiou *et al.*, 2015). The NIOSH870 protocol applied in this evaluation protocol defines total OC as OC1 + OC2 + OC3 + OC4 + PC, and total EC as (EC1 + EC2 + EC3 + EC4 + EC5 + EC6) – PC. The results are summarized in Tables 2 and 3 and discussed below.

Modelling of Air Mass Movements Using HYSPLIT Model

Modelling of air mass movements based on actual meteorological conditions enables an assessment of the spatial location of possible emission sources and an understanding of their selective contribution to the local air pollution burden. This study employed the Hybrid-Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, which was developed by the National Oceanic and Atmospheric Administration (NOAA). HYSPLIT employs archived 3-dimensional meteorological fields generated from observations and short-term forecasts and can be run to generate forward or backward trajectories using several available meteorological data archives (Draxler *et al.*, 1998; Makra *et al.*, 2011; Stein *et al.*, 2015; Rungratanaubon *et al.*, 2017).

Table 2. Concentrations (averaged over 3 month) of PM_{2.5}, OC, and EC and micrometeorology data obtained at 30 m, 75 m, and 110 m above ground level during the monsoon season in Bangkok, Thailand, 2015.

Time	Level (m)	PM _{2.5} (μg m ⁻³)	OC (μg m ⁻³)	EC (μg m ⁻³)	OC/EC	Wind direction (Deg.)	Wind speed (m s ⁻¹)	Temp. (°C)	RH (%)	Precipitation (mm)
Daytime	30	7.07 ± 2.55	4.09 ± 2.73	1.02 ± 0.75	4.00	226.79 ± 51.74	3.16 ± 0.96	30.34 ± 2.22	61.86 ± 11.82	0.20 ± 1.70
	75	9.04 ± 4.04	4.44 ± 4.60	1.05 ± 1.04	4.23	225.45 ± 49.39	4.17 ± 1.42	30.18 ± 2.15	63.74 ± 11.73	-
	110	10.07 ± 4.22	3.95 ± 3.89	0.46 ± 0.72	8.59	228.66 ± 46.57	4.29 ± 1.86	29.62 ± 2.08	64.68 ± 11.08	-
Nighttime	30	5.46 ± 2.11	4.17 ± 2.61	1.02 ± 0.93	4.09	206.30 ± 62.87	2.79 ± 0.59	27.51 ± 1.82	75.90 ± 11.33	0.27 ± 2.10
	75	7.19 ± 2.99	3.57 ± 3.46	1.09 ± 0.87	3.28	207.72 ± 55.94	3.69 ± 1.04	27.54 ± 1.75	76.92 ± 10.90	-
	110	2.90 ± 3.29	4.28 ± 3.25	0.54 ± 0.69	7.93	213.66 ± 51.83	3.73 ± 1.75	27.16 ± 1.64	76.81 ± 9.89	-

Backward air mass trajectories were modelled (Air Resource Laboratory (ARL) Advancing Atmospheric Science and Technology Through Research (<http://www.ready.noaa.gov/HYSPLIT.php>) by applying data from the meteorological database of the Global Data Assimilation System (GDAS) (0.5 degree, global, 09/2007–present) to simulate backward air mass trajectories for three days (72 h) preceding sample acquisition. Air mass movements were modelled for the monsoon season in Thailand (July 15, 2015 to September 15, 2015) at a height of 110 m above the ground level.

RESULTS AND DISCUSSION

Vertical Variations in PM_{2.5} Mass Concentrations

Average PM_{2.5} concentrations at 30 m, 75 m, and 110 m above ground level were measured to assess key factors influencing variations in PM_{2.5} concentrations. Concentrations of PM_{2.5} averaged over 22 h (sampling time) at 30 m, 75 m, and 110 m were 6.21 ± 2.45, 8.12 ± 3.65, and 9.03 ± 3.93 μg m⁻³, respectively. Fig. 2 shows the PM_{2.5} concentrations at each height during both daytime and nighttime. Daytime concentrations were 7.07 ± 2.55, 9.04 ± 4.04, and 10.07 ± 4.22 μg m⁻³, respectively, and nighttime concentrations were 5.46 ± 2.11, 7.19 ± 2.99, and 7.90 ± 3.29 μg m⁻³, respectively. The observed PM_{2.5} concentrations showed an increased trend with altitude, with daytime concentrations generally higher than those recorded during nighttime. Urban areas comparable to Bangkok are mainly influenced by pollution from traffic, where car engines are considered to be the major source of PM_{2.5}. That can also be related to the daytime photochemical formation of NO₃⁻, which also facilitates oxidation of VOCs to form secondary organic aerosols (SOAs), which in turn increases the hygroscopicity of aerosols (Brown *et al.*, 2006) resulting in haze. However, in cities similarly located to Bangkok the PM_{2.5} levels due to ground and water traffic could also increase owned to long-range transmission of smoke plume into the residual layer (Sun *et al.*, 2013).

Carbonaceous Concentrations in PM_{2.5}

Concentrations of carbonaceous species in PM_{2.5} and correlations between OC and EC provide a hindsight regarding the emission sources and possible combustion processes (e.g., Dan *et al.*, 2004; Srivastava *et al.*, 2014). Here a compilation of averaged PM_{2.5} concentrations at 30 m, 75 m, and 110 m above ground together with OC, and EC values obtained in this study is shown in Table 2. Daytime OC concentrations were 4.09 ± 2.73, 4.44 ± 4.60, and 3.95 ± 3.89 μg m⁻³, and EC values were 1.02 ± 0.75, 1.05 ± 1.04, and 0.46 ± 0.72 μg m⁻³, respectively; whereas nighttime OC concentrations were 4.17 ± 2.61, 3.57 ± 3.46, and 4.28 ± 3.25 μg m⁻³, and EC concentrations were 1.02 ± 0.93, 1.09 ± 0.87, and 0.54 ± 0.69 μg m⁻³, respectively.

Carbonaceous aerosols have been found to comprise 20–50% of the PM_{2.5} mass in most urban areas whereby differences are influenced by seasonal variations in emission intensities and meteorological factors (Cao *et al.*, 2006; Srivastava *et al.*, 2014; Han *et al.*, 2016; Ji *et al.*, 2016). The high OC concentrations in this study are likely the result of

Table 3. Representative percentages of backward air mass trajectory directions, and PM_{2.5}, OC, EC, and TC concentrations during monsoon season.

Group	Cluster	%	PM _{2.5} ($\mu\text{g m}^{-3}$)	OC ($\mu\text{g m}^{-3}$)	EC ($\mu\text{g m}^{-3}$)	TC ($\mu\text{g m}^{-3}$)
1	SW	13	4.92–10.88	0.69–7.05	0.00–0.95	0.75–7.86
2	SSW	19	4.83–24.41	0.18–8.75	0.00–3.54	1.65–9.35
3	WbS	30	3.93–17.18	0.33–5.62	0.00–3.46	0.29–7.57
4	WSW	22	4.28–11.92	1.24–5.29	0.00–0.87	0.94–5.54
5	W	17	4.17–18.74	0.23–5.11	0.00–2.02	0.94–7.17

Fig. 2. Increasing concentrations of PM_{2.5} with elevation above ground, showing different trends observed in daytime (08:00–19:00) and nighttime (20:00–07:00) sampling throughout monsoon season (July–September 2015).

emissions from combusted fossil fuel and the formation of secondary aerosols (e.g., Ji *et al.*, 2016). Concentrations of OC and EC significantly increase with an increase in the number of diesel vehicles (Cao *et al.*, 2006). Moreover, higher values of OC1 and pyrolytic carbon (PC) are found in urban areas and rural sites, respectively (Vodicka *et al.*, 2015). In addition, high variabilities in OC concentrations likely result from contributions coming from different emission sources (Cao *et al.*, 2005). With respect to EC concentrations, higher values are related to the increased use of fossil fuel during the daytime (Han *et al.*, 2009b; Srivastava *et al.*, 2014) and they indicate the important role of combustion sources with an anthropogenic origin (Li *et al.*, 2015). In the period of this study the average OC/EC ratios at 30 m, 75 m, and 110 m during the daytime were 4.00, 4.23 and 8.59 and at nighttime 4.09, 3.28 and 7.93, respectively, which are higher than levels recorded previously in the outskirts of the Bangkok urban area (Sahu *et al.*, 2011). The OC/EC ratios are used to interpret the emission and transformation characteristics of carbonaceous aerosol. Consequently, it can be expected that at levels of 30 and 75 m, the carbonaceous aerosol was emitted source from diesel- and gasoline-powered vehicular

exhaust indicated by the OC/EC ratios of 1.0 to 4.2 (Schauer *et al.*, 2001; Srivastava *et al.*, 2014). At the level of 110 m the likely source would be biomass burning with OC/EC ratios of 3.8–13.2 (Satsangi *et al.*, 2012; Ji *et al.*, 2016). Analysis of the average nighttime vs. daytime OC/EC ratios from Table 2 indicates relatively high contribution of secondary organic aerosols (to total OC) during daytime (e.g. Ram and Sasin, 2011). Concentrations of EC appear to be better correlated with the wind speed than OC; therefore, the lesser dependence of OC on wind speed, particularly in the monsoon season, could be due to the significant presence of secondary OC in Bangkok and surrounding regions (Sahu *et al.*, 2011). The concentrations of OC and EC in this study can be explained by washout caused by rainfall and the high relative humidity typical for the monsoon season. As some part of OC is water soluble, it will be consequently scavenged, which leads to lower concentrations in the monsoon compared to other seasons: concentrations of OC follow the trend: winter > summer > monsoon (Duangkaew *et al.*, 2011; Satsangi *et al.*, 2012). A decrease in the mixing depth with a decrease in temperature has also been observed during the monsoon season (Han *et al.*, 2016), when cleaner

air, wet deposition, and negligible biomass burning results in the lowest concentrations of OC and EC (Cao *et al.*, 2005; Sahu *et al.*, 2011). Fig. 3 shows that in this study, the major fractions determined near the ground were OC2, OC3, OC4, and PC; their enrichment is largely related to gasoline motor vehicle exhaust. In addition, the EC2 and EC3 fractions mainly originate from diesel exhaust, but the OC1 fraction is the result of biomass burning (Cao *et al.*, 2005; Cao *et al.*, 2006). Variations in carbon fractions can be related to the contribution of different emission sources, and it is very conceivable that motor-vehicular emissions were the dominant source of carbonaceous particle pollution during the time that sampling was conducted. Fig. 4 shows that the correlation (determination coefficient R^2) of OC with $PM_{2.5}$ decreases with height. Determination coefficients between OC and $PM_{2.5}$ at 30 m, 75 m, and 110 m (R^2) were 0.27, 0.20, and 0.19, respectively in August, showing the highest correlations for the monsoon season. The associated meteorological factors were low wind velocity (average 2.76 m s^{-1}) and insignificant rain fall (average 0.12 mm) compared with the other monsoon season months. In addition, the correlations shown are rather low, which is likely due to the complexity

of sources for emitted and secondary $PM_{2.5}$ and the environmental topography. Under steady weather conditions, the impact of relative humidity becomes more significant, while the low temperatures at higher altitudes facilitate the formation of organic aerosols (Sun *et al.*, 2013).

Air Mass Backward Trajectory with HYSPLIT

The meteorological database: Global Data Assimilation System (GDAS) was applied to the software HYSPLIT Model Version 4.0 (<http://www.ready.noaa.gov/HYSPLIT.php>), and modelled backward air mass trajectories (0.5 degree, global, 09/2007–present) for the monsoon season (July–September 2015) at 110 m (63 sets of data). Simulations were performed for 72 h prior to sampling to analyze and categorize the direction of air mass movements reaching the study area. The clustering pathways and a summary of essential cluster characteristics in different seasons are shown in Fig. 5 and Table 3. Table 3 shows the concentrations of $PM_{2.5}$, OC, EC, and TC for each cluster. Trajectory analyses for our study reveal that the air masses flowing through the study area at 110 m above the ground can be assigned to five major directional categories 1: South-West $\sim 225^\circ$ (SW),

Fig. 3. Average vertical variations in eight carbon fractions in $PM_{2.5}$ throughout monsoon season in 2015 during daytime (08:00–19:00) and nighttime (20:00–07:00).

Fig. 4. Relationship between OC and $PM_{2.5}$ sampled at heights of 30 m, 75 m, and 110 m averaged over monsoon season in 2015.

2: South-South-West $\sim 202.5^\circ$ (SSW), 3: West-by-South $\sim 258.75^\circ$ (WbS), 4: West-South-West $\sim 247.5^\circ$ (WSW) and 5: West $\sim 270^\circ$ (W).

The major movement direction of air masses passing through the Bangkok Metropolitan area was from south-west Thailand: category 3 (30%), category 4 (22%), and category 2 (19%). In addition, these air masses originated from urban areas (category 1 and 4) and industrial areas (category 2). The concentrations of $PM_{2.5}$, OC, EC, and TC from these directions (category 1 and 4) ranged from 3.91–17.18, 0.33–5.62, 0.00–3.46, and 0.29–7.57 $\mu g m^{-3}$, respectively. The concentrations of $PM_{2.5}$, OC, EC, and TC from these directions (category 2) ranged from 4.83–24.41, 0.18–8.75, 0.00–3.54, and 1.65–9.35 $\mu g m^{-3}$, respectively. In the monsoon season, the concentrations of aerosols emitted from local sources were diluted due to the flow of cleaner air from the Indian Ocean and wet removal (Sahu *et al.*, 2011). It is also possible that the observation site was influenced by the flow of oceanic air that contained ship exhaust, due to the prevailing southwest monsoon during the wet season; however, quantification of this contribution was difficult. Nevertheless, vehicle emissions appear to be the major anthropogenic source of aerosols also found previously for the period 2007–2008 (Sahu *et al.*, 2011).

CONCLUSIONS

This study aims to contribute to the rather limited amount of experimental data regarding the vertical pollution profiles and combining $PM_{2.5}$ concentrations with those of carbonaceous aerosols. To better understand the worsening of near-surface air pollution in megacities caused by the so-called dome-effect (e.g., Wang *et al.*, 2018) the vertical pollutants' concentrations in relationship with the underlying land surface and environmental situation has to be taken into account.

The analysis of data obtained in this study shows that average values of $PM_{2.5}$ at observation heights of 30 m, 75 m, and 110 m increased slightly with height and were 6.21 ± 2.45 , 8.12 ± 3.65 , and 9.03 ± 3.93 $\mu g m^{-3}$, respectively. OC concentrations at these observation heights were 4.13 ± 2.65 , 4.01 ± 4.07 , and 4.11 ± 3.58 $\mu g m^{-3}$, respectively, and corresponding EC concentrations were 1.02 ± 0.84 , 1.07 ± 0.95 , and 0.50 ± 0.70 $\mu g m^{-3}$. Although results show increasing $PM_{2.5}$ concentrations with elevation above the ground, trends for OC and EC were found to decrease. Dominant fractions in the monsoon season near the ground were OC2, OC3, and EC4, which are associated with motor vehicle exhaust emissions. At higher elevations, particles likely originate from atmospheric chemical reactions forming SOA, however surface inversions and circulations can result

Fig. 5. Backward trajectories of air masses passing through Bangkok during monsoon season (July–September 2015).

at lower elevations even of the order of 100 m in multi-layer structures (Chilinski *et al.*, 2016), a fact which needs to be explored further in the future. Results presented here indicate that measurements obtained at various elevations can provide next to the evidence of primary and secondary particulate pollution, also the impact of the near surface effects. Moreover, they could contribute to better understanding of atmospheric interactions leading to haze formation processes. Consequently, the results could be applied in guidelines for monitoring fine particle concentrations in large urban environments, such as Bangkok, being also useful in the pollution-related modelling and helpful in air quality management of cities.

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