Characteristics of Ambient Particle-bound Polycyclic Aromatic Hydrocarbons in the Angkor Monument Area of Cambodia

Masami Furuuchi[1*], Takahiro Murase[1], Shinji Tsukawaki[2], Peou Hang[3], Sotham Sieng[4], Mitsuhiko Hata[1]

[1] *Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, Japan.*
[2] *Institute of Nature and Environmental Technology, Kanazawa University, Kanazawa, Japan.*
[3] *Department of Water and Forestry, Authority for the Protection of the Site and the Management of Angkor and the Region of Siem Reap (APSARA), Cambodia.*
[4] *Department of Geology, Ministry of Industry, Mines and Energy (MIME), Cambodia.*

Abstract

The characteristics of ambient particle-bound polycyclic aromatic hydrocarbons (PAHs) in the Angkor monument area of Cambodia were studied to evaluate the status of air pollution and the influence of possible emission sources. Ambient particulates were sampled at four sites during the same seasons: Angkor monument area, including Angkor Wat, in Siem Reap city, along a main road, and on a small hill beside Lake Tonle Sap. Monitoring of ambient particles in the city and Angkor Wat were conducted on a continuous basis. Meteorological data were continuously monitored at two sites to evaluate the role of wind in the transport of pollutants. The concentrations of total suspended particulates (TSP), PAHs and heavy metals were analyzed to examine the influence of anthropogenic emissions, as well as contributions from soil and miscellaneous particles. Profiles of 15 PAH compounds were compared to determine the influence of wind direction on the seasonal characteristics of PAHs.

TSP concentration proved to be proportional to the sum of the concentrations of Al, Ca and Fe, which were the major metals present in particles, regardless of location and season. The mass fraction of PAHs with 4-6 rings in Angkor Wat was almost equal to, or larger than, that found in the city. During the rainy season's southwest monsoon, the PAH profile in Angkor Wat was similar to that found in the city, while it was similar to that found in the rural areas during the dry season's north, or northeast, monsoon. This indicates that in the rainy season air pollutant transport from the city to the monument is an important factor. PAH concentration in Angkor Wat was similar to that measured in Bangkok, indicating a serious air pollution situation.

* Corresponding author. Tel.: +81762344646, Fax: +81762344644

E-*mail address*: mfuru@t.kanazawa-u.ac.jp

***Keywords*:** Tourism; Air pollution; PAHs; Biomass burning; Wind transportation.

INTRODUCITON

During the past 10 years, tourism in the Angkor monument areas of Cambodia has grown dramatically, while the populations in Siem Reap and the monument areas also have increased significantly (JICA, 2001). Tourist numbers have increased by a factor of about 100, to the point of almost one million a year (Statistics & Tourism Information Dept., Ministry of Tourism, Cambodia, 2005). According to the Authority for the Protection of the Site and the Management of Angkor and the Region of Siem Reap (APSARA), the population in the preserved monument areas (called Zones I and II) has increased from 20,000 (1992) to 100,000 (2002) and continues to grow (APSARA, 2006a).

Increases in the consumption of energy and water, traffic and the demand for waste material treatment associated with rapid tourism growth have also increased, and insufficient pollution control devices and facilities have compounded serious environmental impacts on the monument area. Air pollution is an unexpected factor that has not been recognized by the local population. Because of increased energy consumption, such as power generation for electricity, burning fuels for cooking and lighting, traffic and waste incineration, the amount of air pollutants from these emission sources presumably have increased significantly.

Air pollution in this area may now be a serious issue that could have a severe influence, not only for human health, but also on biodiversity and the sustainability of the Angkor monuments. In order to apply effective methodologies for reducing such environmental loads, it is essential to understand the status of air pollution and contributions from emission sources. However, little information is available, although the *Department of Water and Forestry* of APSARA has continued to monitor gaseous pollutants twice annually since 2004. This paper's authors have begun preliminary investigations, as well (Furuuchi *et al*., 2005a; Furuuchi *et al.*, 2006a).

For this study, air pollution in the Angkor monument area was evaluated to examine the present status of air pollution and possible emission sources, focusing on particle-bound polycyclic aromatic hydrocarbons (PAHs), which are typical hazardous and carcinogenic pollutants emitted from various anthropogenic sources. Ambient particulates were continuously sampled using high-volume air samplers at different sites in Siem Reap and in the Angkor monument area. Meteorological data were monitored at two different sites to determine the influence of weather conditions, particularly focusing on the transport of pollutants by wind.

Sampling and analysis

Locations

Fig. 1. is a map of the Siem Reap and Angkor monument areas showing sampling site locations.

Siem Reap is located where Route 6 crosses the Siem Reap River. The city spreads out in approximately a 3-km radius. According to the APSARA authority, the monument areas around the city are classified into five different categories: Zone I (monument sites), Zone II (protected archaeological reserves), Zone III (protected cultural landscapes), Zone IV (sites of archaeological, anthropological or historic interest), and Zone V (socio-economic and cultural development zones of the Siem Reap region, comprising the whole of Siem Reap province—the largest zone to which protective policies apply) (APSARA, 2006a). Zones I and II, which are important as areas needing preservation, make up more than 350 km^2. Lake Tonle Sap, south of Siem Reap, is the largest lake in Southeast Asia and is famous for its unique characteristic of changing remarkably with the seasons (Tsukawaki *et al.*, 2006).

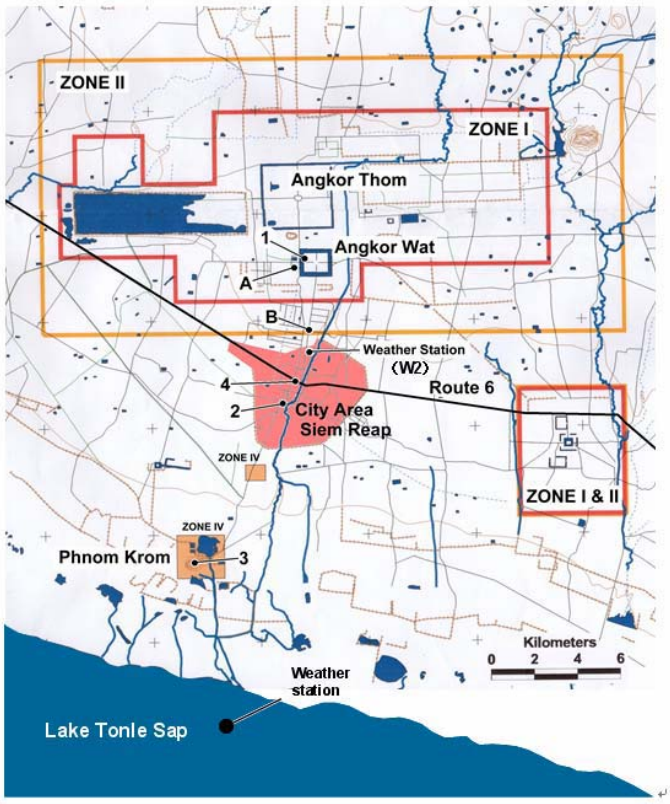

Fig. 1. Map of Siem Reap and the Angkor monument areas showing the locations of sampling and weather monitoring sites.

Four sampling sites were established: Angkor Wat (Site 1); Siem Reap (Site 2); Phnom Krom, a small hill (elevation ~140 m) beside Lake Tonle Sap (Site 3); and Route 6 (Site 4). Site 1 was located in an open space between the western corridor of Angkor Wat and the moat surrounding it, which features terrain typical for the area, such as forest, open space and small roads for tourism. Site 2 was located on the balcony of a room on the second floor of a two-story building

("Tap Rohm Hotel"), facing a partly paved city road. The distance to the road was about 2.5 m, and the wall height and width of the balcony were 0.6 and 1 m, respectively. Daytime traffic on the road was rather busy. This site was in a typical busy area of the central city near the "Old Market," prone to possible emission sources, such as traffic, cooking, heating and electricity generation.

Site 3 was located first on a hilltop (May, 2005), then moved to the east side of the hill (June and November, 2006). Site 3 characteristics were suitably representative of areas with fewer residents. These areas were covered by bush and low trees and were partly submerged under the lake from August through December. Depending on the availability of electricity, the different locations were used for Site 3 in 2005 and 2006, but both locations were very similar with few emission sources in the surrounding vicinity. Site 4 was located at the northern side of a temple "Preah Ang Chaik Preah Ang Chorm," at a distance of 5 m from Route 6, the busiest road in Siem Reap. Each sampling site was chosen as representative of the surrounding environment. Sites A and B were APSARA gas-sampling sites.

Sampling equipment and procedures

Total suspended particulates (TSP) were collected using high-volume air samplers (SHIBATA KAGAKU, HV-500F) on binder-less quartz-fiber filters (110 mm, ADVANTEC, QR-100) prepared in a desiccator at a constant temperature and humidity (room temperature and ~50% RH) for 72 hours. The present work is not only for the evaluation of the status of air pollution, but also as a first step in building a monitoring network for air pollution while transferring the monitoring methodology to APSARA coworkers. Therefore, the high-volume air samplers were used because of their simplicity of handling, which is practical and very important for the transfer of technology in developing countries (Kato, 2006). They were used also for their large flow rate, which is important for limited sampling durations due to problems with security and an available supply of electricity. Sized particles could provide more detailed information on air pollution (e.g., PM_{10} and $PM_{2.5}$ samples), as well as nano-aerosol particles smaller than 0.1 μm (now being tested with results to be reported soon). At each sampling site, the sampler was installed on a chair at about a 50 cm sitting height, along with a temperature-hygro sensor and a data logger (SATO KEIRYOKI, SK-L200TH II), which recorded during the entire sampling period.

Simultaneous samplings of TSP were conducted in Sites 1, 2 and 3 (monument area) in May 2005, and in June and November 2006. Continuous monitoring for TSP samples occurred from March through November 2006 at Site 1, and at Site 4 every two weeks. Security considerations and the availability of electricity at Site 1 and 3 dictated that samplings be conducted there only during the daytime. Conditions for samples used for PAHs analysis are summarized in Table 1, which includes both conditions during preliminary surveys in 2005 by the authors, and continuous sampling started in March 2006 by APSARA personnel after their training on

sampling methodologies. The sampling at Site 3 (2005) was accidentally stopped after a short period due to problems with electrical supply, thus only TSP values are discussed. Limited numbers of samples are due mostly to logistical difficulties, such as equipment shortages and security concerns. These problems cannot be easily solved in a developing country like Cambodia, but should improve with time. Nevertheless, even a broad discussion of the present status of air pollution is an important first step.

In order to minimize the degradation and evaporation of chemical compounds in particles due to the UV irradiation and temperature fluctuation, the samples were covered with aluminum foil immediately after sampling and kept in a freezer in the hotel during sampling activities. All filters were kept in a freezer (-20^{o}C) until they were analyzed after transport to Japan (about one day of travel time). Travel blank filters were handled in the same manner.

Table 1. Sampling conditions.

No.	Location	Sample date				Sampling duration(min)	weather
1	Angkor Wat	27/05/2005	6:20	~	27/05/2005 17:10	710	cloudy/fine
2	Angkor Wat	30/09/2005	6:11	~	30/09/2005 10:26	255	fine/cloudy/rain
3	Angkor Wat	20/12/2005	6:45	~	20/12/2005 15:19	514	cloudy/fine
4	Angkor Wat	28/03/2006	7:20	~	28/03/2006 19:20	720	fine
5	Angkor Wat	21/04/2006	7:05	~	21/04/2006 18:05	660	fine
6	Angkor Wat	23/05/2006	7:00	~	23/05/2006 18:00	660	fine
7	Angkor Wat	07/06/2006	7:30	~	07/06/2006 18:00	630	fine
8	Angkor Wat	17/11/2006	7:00	~	17/11/2006 18:00	660	Fine
9	City Area	05/26/05	10:30	~	26/05/2005 17:40	395	fine
10	City Area	05/27/05	5:09	~	27/05/2005 16:00	657	cloudy/fine
11	City Area	12/19/05	11:40	~	19/12/2005 16:45	305	fine
12	City Area	06/08/06	7:45	~	08/06/2006 16:20	515	fine
13	City Area	17/11/2006	7:00	~	17/11/2006 18:00	660	fine
14	Phnom Krom	27/05/2005	8:28	~	27/05/2005 9:05	21	fine
15	Phnom Krom	07/06/2006	7:45	~	07/06/2006 16:48	543	fine/partly cloudy-wind
16	Phnom Krom	17/11/2006	8:24	~	17/11/2006 17:55	571	Fine
17	Route 6	01/10/2005	7:03	~	01/10/2005 18:57	714	cloudy
18	Route 6	21/12/2005	6:40	~	21/12/2005 18:40	720	fine/cloudy
19	Route 6	27/03/2006	7:15	~	27/03/2006 19:15	720	fine
20	Route 6	20/04/2006	7:00	~	20/04/2006 19:00	720	fine
21	Route 6	22/05/2006	7:00	~	22/05/2006 19:00	720	cloudy/fine
22	Route 6	6/6/2006	7:00	~	06/06/2006 19:00	720	fine/cloudy
23	Route 6	15/11/2006	7:00	~	15/11/2006 18:00	660	fine

Analysis of chemicals

Filters were weighed after 72 hours of conditioning (room temperature ~25^{o}C, RH approximately 50%); then they were analyzed to obtain concentrations of PAHs and heavy metals. Heavy metals were analyzed by ICP-AES (HITACHI, P-4010) after decomposing the samples

with nitric, hydrofluoric and perchloric acids in a microwave digester (CEM, Mars X) following a previous procedure (Vandecasteele and Block, 1993). The recovery efficiency was confirmed as 0.97 ± 0.18 (n = 7), which is the average for all analyzed heavy metals, using standard materials (NIST SRM1648). Following the same procedure used in a previous paper (Toriba *et al*., 2003), 15 different PAH compounds – Naphthalene (Nap), Acenaphthene (Ace), Phenanthrene (Phe), Anthracene (Ant), Fluorene (Fle), Fluoranthene (Flu), Pyrene (Pyr), Benz[a]anthracene (BaA), Chrysene (Chr), Benzo[a]pyrene (BaP), Benzo[b] fluoranthene (BbF), Benzo[k]fluoranthene (BkF), Dibenz[a,h]anthracene (DbA), Indeno[1,2,3-cd]pyrene (IDP), and Benzo[ghi] perylene (BghiPe) – were analyzed by HPLC (HITACHI, L-2130, 2200, 2300, 2485) with a fluorescence detector and an Inertsil ODS-P column (5 μm, 4.6 mm diameter, 250 mm length) + acetonitril/ultra-pure water mobile phase after ultrasonically dissolving the samples on the filter in an ethanol/benzene (1:3) solution and evaporated on a rotary vacuum evaporator. The recovery efficiency was confirmed to be 0.82 ± 0.12 (n = 3) by adding a standard reagent [Accustandard 0.2 mg/mL in CH_2Cl_2:MeOH (1:1)] to dissolved samples (Tang *et al.*, 2005). Travel blank values of heavy metals and PAHs were subtracted from analyzed values: Al (2.06 ± 0.2 μg/cm^2), Ca (1.36 ± 1.6 μg/cm^2), Fe (0.34 ± 0.2 μg/cm^2) (n = 3), 2-3 ring PAHs (8.5 ± 5 pg/cm^2), and 4-6 ring PAHs (5.5 ± 5 pg/cm^2) (n = 3). These blank values are less than the concentrations of each element and compound in all samples used in the following discussion. For example, in the Angkor Wat samples, the average travel blank concentration of PAHs (2-15 rings) was estimated as 0.10 ± 0.1% of the average particle-bound PAH concentration, which indicates that PAH blank values were reasonably small. Blank values of Al, Ca and Fe correspond to fractions of 11.1 ± 6, 0.18 ± 0.05 and 3.2 ± 1.4%, respectively, of the average value of Angkor Wat and Phnom Krom samples. Blank values may slightly reduce the data reliability, although they were constant.

Meteorological data

Data for meteorological conditions, such as wind direction and velocity, solar radiation, temperature, and humidity were measured at two monitoring sites in the Siem Reap and monument areas (shown in Fig. 1). Site W1, the monitoring site managed by the Agricultural Village Engineering Institute, Japan, was located near the northern cost of Lake Tonle Sap ("Chong Khneas"). The sampling equipment was installed on a tower in the lake (13^{o}13'N, 103^{o}50'E) at two elevations (10 and 15 m) from the lake bottom (Tsujimoto, 2006). Site W2, installed by the authors and managed by the APSARA authority, was located in a botanical garden about 1 km southeast of Angkor Wat (13^{o}22'N, 103^{o}51'E). Beginning in June 2006, Site W2 weather conditions were monitored at a height of 1.5 m by a mobile weather station (Agri-Weather, Weather Bucket). The equipment was calibrated by the manufacturer using a widely used wind monitor (Campbell, CGY-5103). The reported standard deviations of measuring errors were 0.27 m/s, 0.98 m/s, 7.79^o and 14.61^o for average velocity, maximum

velocity, average wind direction, and direction of maximum wind velocity (Agri-Weather, 2006), respectively.

RESULTS AND DISCUSSION

Meteorological characteristics

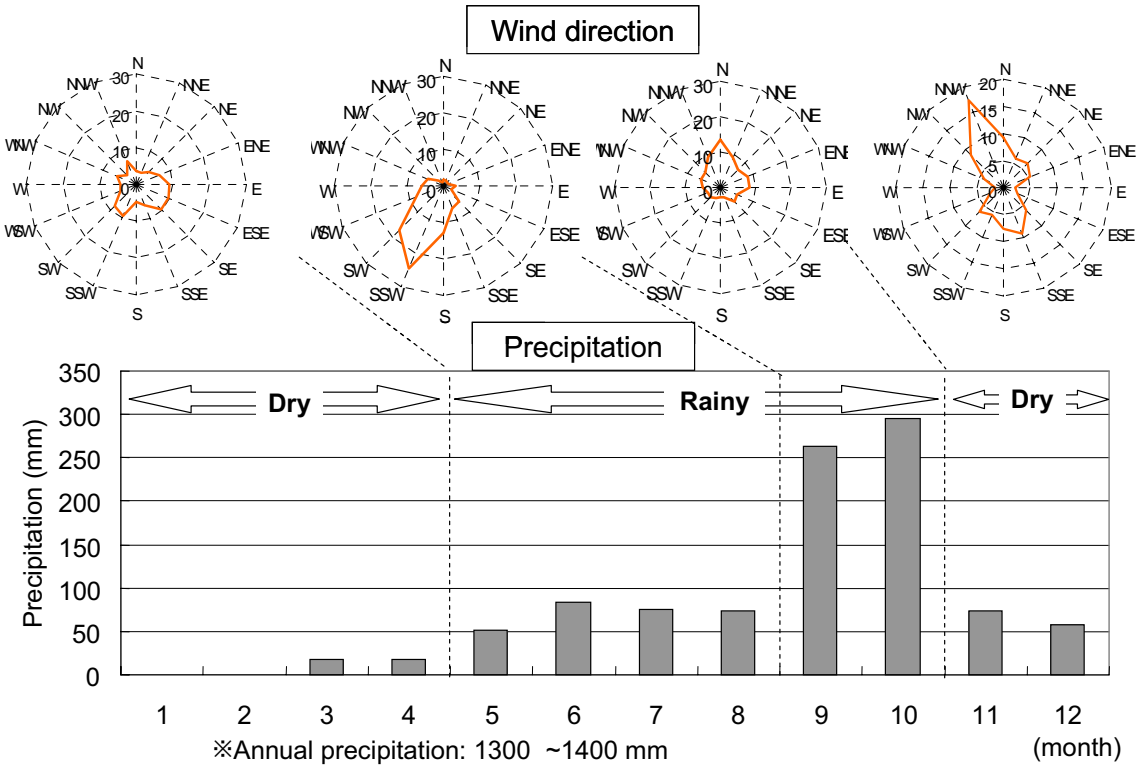

Fig. 2. Meteorological characteristics in the Siem Reap region measured at a site in Lake Tonle Sap (Site W1) (2005).

Fig. 2 shows the seasonal changes in wind direction and monthly precipitation for the lake area (Site W1, 2005). Precipitation reached its peak during September and October in 2005. This pattern was similar to 2004 (Tsujimoto, 2006). The seasons in this area are classified customarily as either rainy (May-Oct.) or dry (Nov.-April) (Hori, 1996; Garami and Kertai, 1993). The authors use this terminology in the following discussion despite a recent (last 3-4 years) pattern of precipitation decreasing in May and increasing in November (Tsujimoto, 2006; Mekong River Commission (MRC), 2002; MRC, 2003). Generally speaking, the northeast winter monsoon from central Asia dominates in the dry season while the southwest summer monsoon dominates in the rainy season (Hori, 1996). However, Fig. 2 shows more-detailed characteristics: south-southwest-southeast and south-southwest winds are prominent January-April and

May-August, respectively, while the frequency of a north wind increases from September, then becomes prominent October-December, as previously reported (Tsujimoto, 2006). Fig. 3 shows wind velocity in the monument area (Site W2) compared with that in the lake area (Site W1). Data are available only for June through September 2006 at Site W2 and from June 2003 through November 2006 at Site W1. The average wind velocity in the monument area was higher (1/4-1/5) than that in the lake area, while the direction was similar. The wind velocity difference at elevation may be explained roughly by the logarithmic velocity profile law (Pal Arya, 1999), taking into account the average water level during these months (~5 m) (Tsujimoto, 2006).

Taking into account the meteorological characteristics, there are two points of view concerning the locations of emission sources and wind transport of air pollutants. The city area (Sites 2 and 4), which is the prominent emission source, is located upwind from Zones I and II and from Angkor Wat (Site 1), where emissions come from sources such as tourism traffic, biomass burning for household use, and a number of small restaurants from May through August. However, during some periods of the year, particularly October through December, the city is downwind of the monument area. In addition, Phnom Krom (Site 3), where very few emission sources exist, is located upwind of the city from May through August, but downwind October to December.

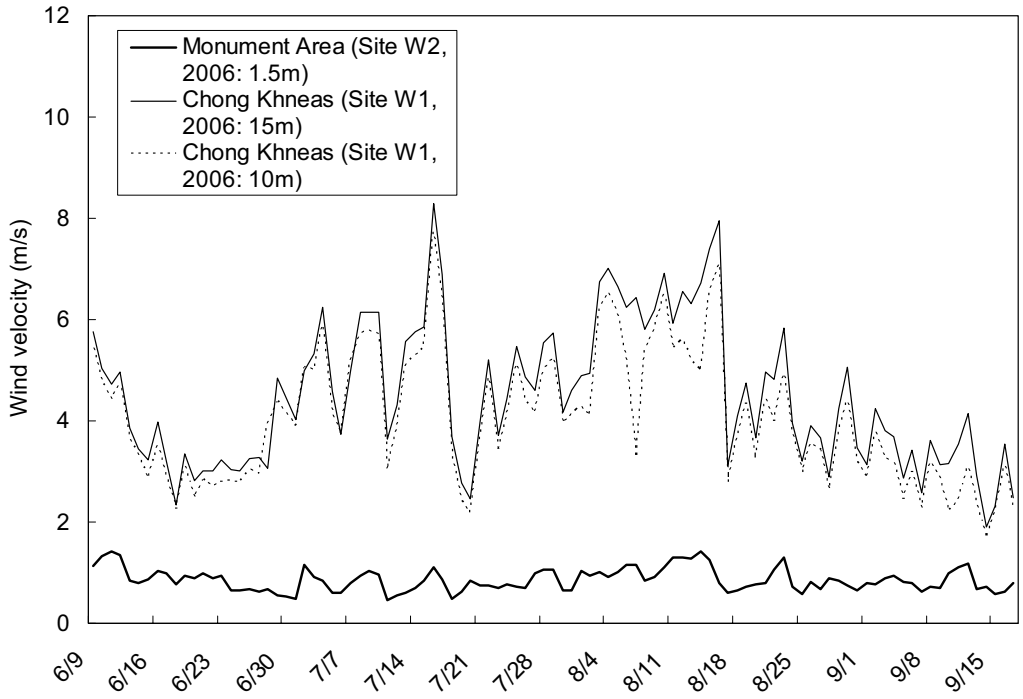

Fig. 3. Wind velocity measured in the monument area (Site W2, 2006) compared with Lake Tonle Sap (Site W1, 2006).

TSP and heavy metal concentrations

The monthly average for total suspended particulate (TSP) concentration at the four monitoring sites is shown in Fig. 4 where the number of samples for each month is different for each site. No value means no sample (see Table 1). There seems to be a weak correlation between TSP concentration and precipitation at Angkor Wat. However, this correlation is not so clear at other sites. For a more reliable discussion, more data needs to be gathered from all sampling sites, although logistical difficulties abound.

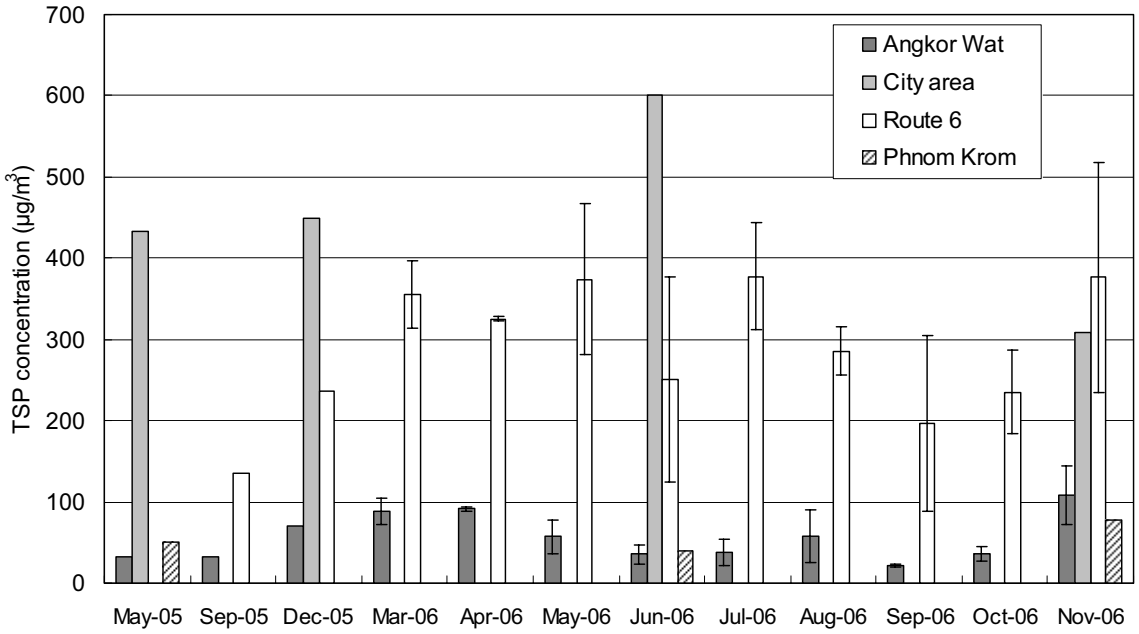

Fig. 4. Seasonal change in TSP concentration at each sampling location.

The TSP concentrations in the city area and along Route 6 are much larger than those in Angkor Wat and Phom Krom. Inside the city, there are many unpaved or low-quality paved roads where a lot of soil particles are produced by busy traffic. Although the pavement of the roads around Angkor Wat is of poor quality, and the roads in nearby Phnom Krom are not paved at all, the traffic is light and both sites are separated from roads, particularly Phnom Krom. The TSP concentrations at the Route 6 site were lower in spite of the much heavier traffic. This may be due to a better quality of pavement. Fig. 5(a) shows the relationship between the summed concentration of the major metals, Al, Ca and Fe, and TSP concentrations. The concentrations of these elements, of soil and cement origin, are almost proportional to the TSP concentration regardless of location and season. However, as shown in Fig. 5(b) the mass fraction of the major elements is slightly lower in Angkor Wat and 1/3-1/4 in Phnom Krom than it is in the city.

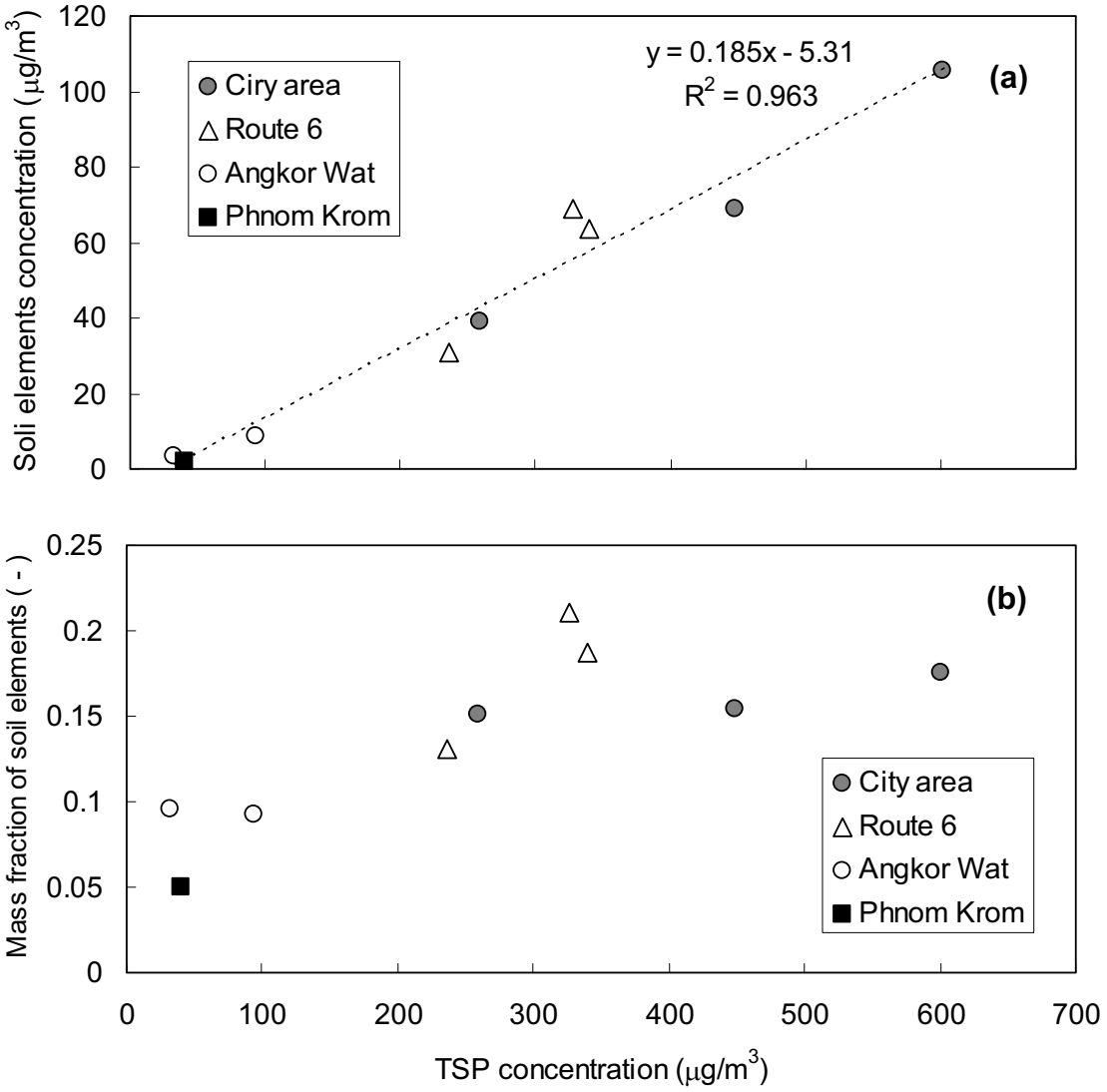

Fig. 5. TSP concentration in relation to: (a) the summed concentration of major metal elements in particles (Al, Ca and Fe), and (b) the mass fraction of these elements.

Concentration of particle-bound PAHs

Figs. 6 and 7 show the summed mass concentration and mass fraction of particle-bound PAHs, respectively, with 4-6 aromatic rings in different seasons at the four sampling sites. The concentrations of these compounds may be an index of anthropogenic emissions from fuel burning (Environmental Health Criteria 202, 1998; Seinfeld and Pandis, 1998; Finlayson-Pitts and Pitts, 1999; Spurny, 1999). PAH concentration was always greater in the city than in other sites, but the mass fraction of PAHs was lower, or similar, to the other sites. This is because of the larger contribution of soil or cement particles to the particle concentration, as shown in Fig. 5. The seasonal variation in PAH concentration and mass fraction at Angkor Wat were not so clear, but values were larger than Phnom Krom in the rainy season (June 2006), where these values can

be regarded as background, since the southwest monsoon wind is prominent and few emission sources are located nearby. In the dry season north/northeast monsoon (December 2005 and November 2006), they are still larger than the background in spite of the fact that Angkor Wat is located upstream from the city area. This suggests the presence of emission sources from nearby Angkor Wat, such as restaurants and illegal food stands, nearby parking, electric power generators, tourist road traffic, and fuel burning in small villages spreading over Zone I (APSARA, 2006b). Most inhabitants there use wood fuels for cooking and heating. No electricity or gas has been supplied to this area in order to reduce the number of people living there illegally. The emission from these sources may increase during the tourism high season (Nov.-Feb.). There might be an influence of emissions from the city area on PAH concentration in Phnom Krom in November.

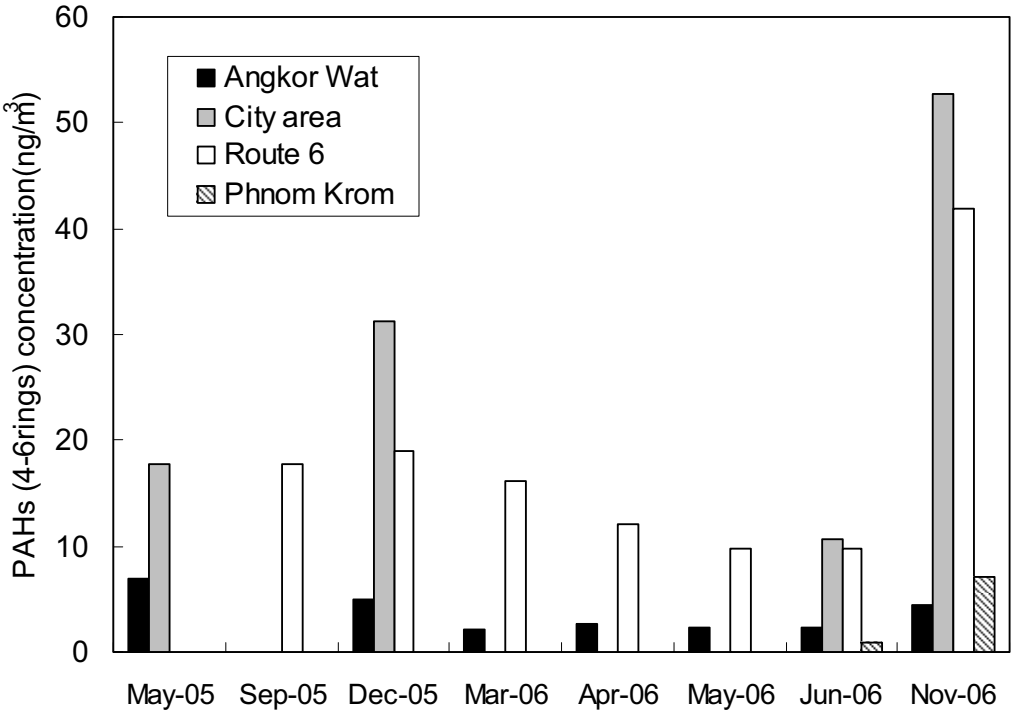

Fig. 6. Seasonal change in the summed mass concentration of PAHs with 4-6 aromatic rings at each sampling location.

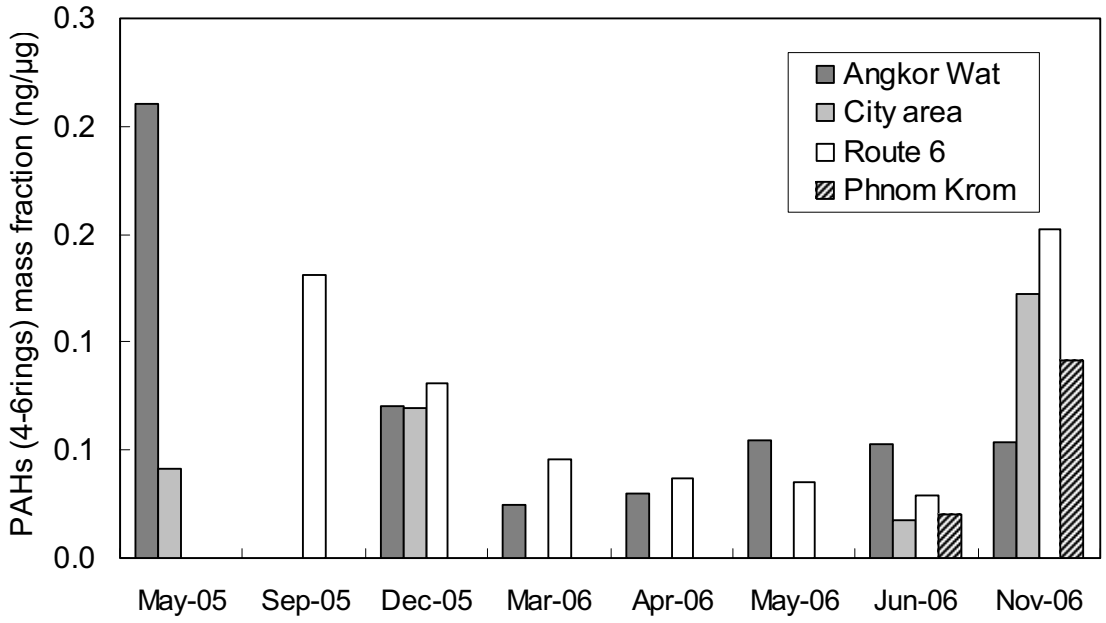

Fig. 7. Seasonal change in the mass fraction of summed mass concentration of PAHs with 4-6 aromatic rings measured at each sampling location.

Seasonal change in profiles of mass fraction of PAHs

Figs. 8(a) and 8(b) show profiles of the mass fraction of each PAH compound respectively for the rainy season southwest monsoon (May-June) and for dry season north/northeast monsoon (Nov.-Dec.) season for Siem Reap, Angkor Wat and Phnom Krom. During the former season, PAH profiles in the city and Angkor Wat are very similar, while the Flu and Pyr fractions, typical compounds produced by biomass burning (Environmental Health Criteria 202, 1998; Furuuchi *et al*., 2006b; Tekasakul *et al*., 2006a), are definitely large in Phnom Krom, where bush burning may be a unique source of smoke; although the numbers are very limited and the amount is small. In contrast, the fractions of BaP, BghiPe and IDP, typical compounds emitted from anthropogenic sources, such as diesel engines used in the traffic and power generation (Finlayson-Pitts and Pitts, 1999; Bernaudat *et al*., 2006), are of importance in the city and Angkor Wat. However, the compounds thought to be caused by biomass burning (Flu and Pyr) increased in the dry season (Nov.-Dec), both in the city and Angkor Wat.

During the rainy season southwest monsoon, particle-bound PAHs, the concentration of which was an increase in fine particles (Furuuchi *et al*., 2005b; Furuuchi *et al*., 2006a; Tekasakul *et al*., 2006a), may be transported from the city areas to Zones I and II in the north, increasing PAH concentration in Angkor Wat to a similar profile found in the city area. Emission sources near Angkor Wat contribute, but pollutants transported from the city northward may significantly influence air pollution in Zones I and II during this period. During the dry season north/northeast

monsoon, however, the wind direction should not increase air pollutants in Zones I and II north of the city, since very few emission sources exist in the northern forest area. The PAH profiles obtained for Angkor Wat during the dry season are very similar to Phnom Krom during the wet season monsoon, indicating a contribution from wood burning. In the city, compounds both from fossil (BaP, BghiPe and IDP) and biomass (Flu, Pyr) fuels contain large fractions while the amount of biomass pollutants transported from Zones I and II to the city area may not be so important. This may be due to the fact that wood burning is extensive for heating during the dry season (Nov.-Dec.) where wood burning is the main energy source in Cambodia – 96.1% of cooking fuel used in Siem Reap is wood (National Institute of Statistics, Ministry of Planning, Cambodia, 2006).

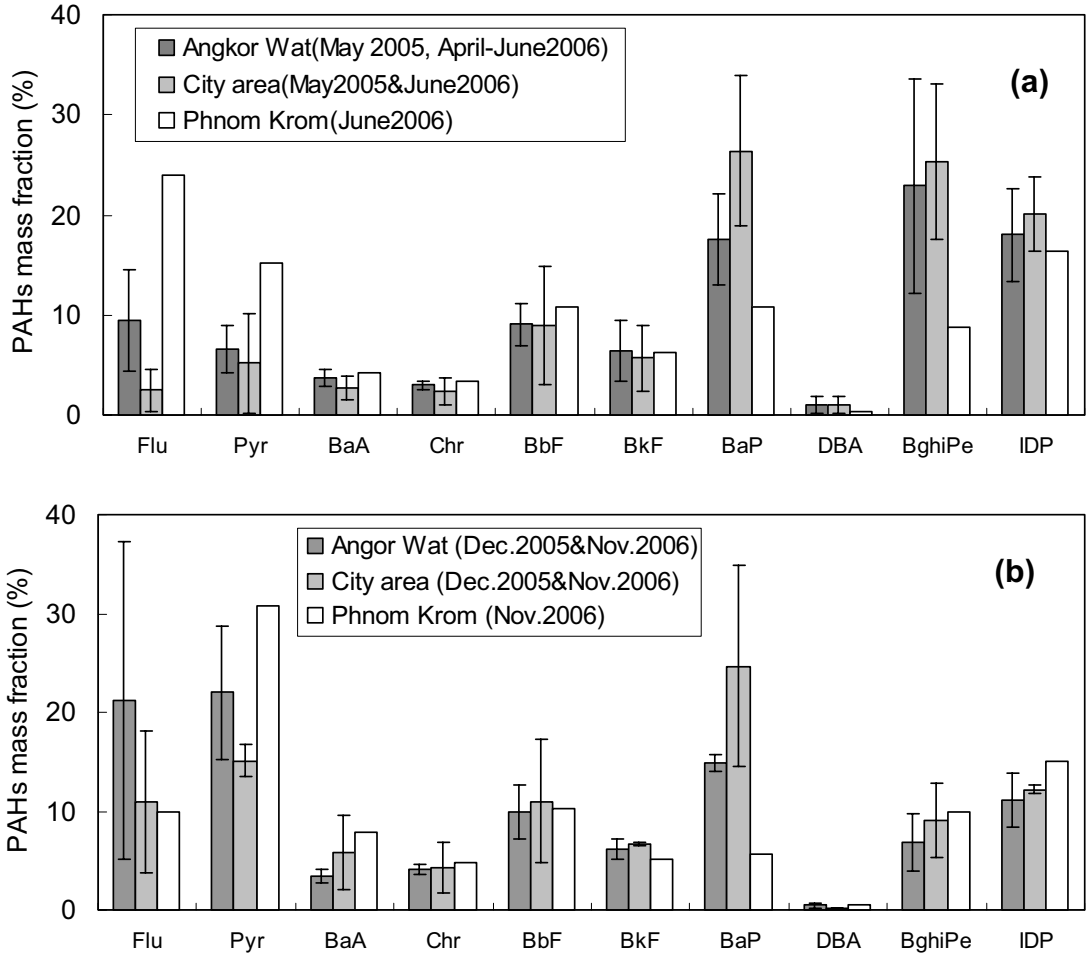

Fig. 8. Profiles for 15 PAH compounds on a mass fraction basis, respectively, for: (a) rainy season southwest monsoon, and (b) dry season north/northeast monsoon comparing Siem Reap, Angkor Wat and Phnom Krom.

Comparison with other Asian cities

Figs. 9(a) and 9(b) show the summed concentrations of 4-6 ring PAHs and the mass fractions of PAHs in particles, respectively, compared with those in other Asian cities in Cambodia (Furuuchi *et al*., 2005c; Murase *et al*., 2006), Thailand (Furuuchi *et al*., 2002; Kato *et al*., 2003; Tekasakul *et al*., 2006a; Furuuchi *et al*., 2006b, 2006c) and Japan (Furuuchi *et al*., 2002). The total concentration of PAHs with 4-6 rings was about five times higher in Angkor Wat than in Kanazawa, Japan in May, and 2-3 times than in Tokyo. It was almost the same as in Bangkok, yet 1/8 of that found in Phnom Penh. The mass fraction of total PAHs in Angkor Wat (0.074 ng/μg) was similar to that found in Bangkok (0.070 ng/μg).

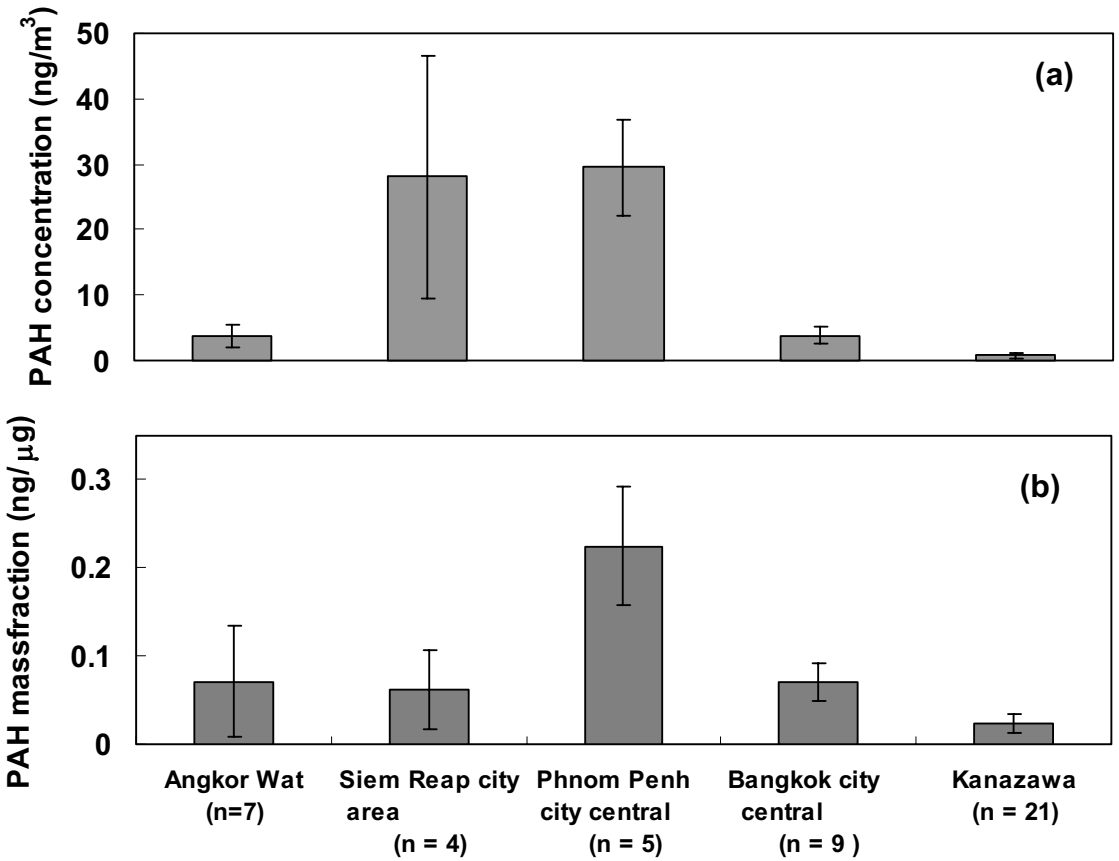

Fig. 9. Concentrations (a) and mass fraction (b) of PAHs with 4-6 rings in the city area (Site 2 and 4) and Angkor Wat (Site 1) compared with other Asian cities.

CONCLUSION

The TSP concentration was shown to be proportional to the summed concentrations of Al, Ca and Fe, which were the major metals in particles, regardless of location and season. The mass

fraction of total concentration of PAHs with 4-6 rings in Angkor Wat was almost equal to or larger than that found in the Siem Reap city area. During the rainy season's southwest monsoon, the profile of PAHs in Angkor Wat was similar to that found in the city area, but during the dry season north/northeast monsoon, it had rural area characteristics. This indicates that during the southwest monsoon, the transport of air pollutants from the city is an important contributor to air pollution in the monument areas.

As shown by the fact that PAH concentration in Angkor Wat, a remote area, is similar to that in Bangkok city central, emissions from possible anthropogenic sources, such as traffic, generators and biomass burning, are contributing to a very serious situation. Similar threats from other air pollutants are suspected, although they are not discussed in the present study. Since this situation may be related to the explosion of tourism in a region devoid of any environmental protection policies, a much more serious situation will develop soon if nothing is done to control pollution.

The effective application of methodology for the reduction of such environmental loads, and to obtain data for each possible emission source, such as the number of emissions sources, and emission amounts, profiles and distributions in this area, it is important to continue monitoring and to increase statistical reliability. As shown for Phnom Penh, Cambodia (Murase *et al*., 2006), PAH concentrations during the nighttime are larger than during the day, probably owing to related differences in sources and emitted amounts. Such hourly observations should provide more detailed information on emission sources in Siem Reap, also. Particle size dependency of the pollutants is also important information since anthropogenic pollutants are enriched by smaller fractions (Spurny, 1999), and since particle size affects wind transportation. These studies will be the next step and must soon begin.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the kind cooperation of the Ta Prohm Hotel and also to the staffs in APSARA and the Department of Geology, MIME, for the kind assistance in sampling. The authors also acknowledge the staffs at the Sofia University office in Siem Reap for their generous support. The authors deeply acknowledge Dr. Masumoto, *the Agricultural Village Engineering Institute, Japan*, for the permission to use the meteorological data.

REFERENCES

Agri-Weather (2006). http://www.agw.jp/bucket/accuracy.html.

APSARA (2006a). http://www.autoriteapsara.org/en/apsara/demography.html.

APSARA (2006b). http://www.autoriteapsara.org/en/apsara/about_apsara/legal_texts/decree3.html (Zoning map).

Bernaudat, L. and Nelson, P. (2006). Study of Polycyclic Aromatic Hydrocarbon Levels to Identify Particulate Matter Sources in Hanoi, Vietnam. *Proc.7th Int. Aerosol Conf.* St. Paul, USA: 1303-1304.

JICA Country Report on Cambodia. (2001). JR 01-16.

Environmental Health Criteria 202, International Programme on Chemical Safety, United Nations Environmental Programme, International Labor Organization, World Health Organization, 1998.

Finlayson-Pitts, B.I. and Pitts, Jr., J.N. (1999). *Chemistry of the Upper and Lower Atmosphere*, Academic Press, San Diego, p. 436-466.

Furuuchi, M., Kanaoka, C., Kato, S., Kizu, R., Hayakwa, K., Komura, K., Limpaseni, M. and Amourunkitbamrung, M. (2002). New Approach to Estimate PM Emission Sources in Bangkok. *Proc. 6th Int. Aerosol Conf.* Taipei, Taiwan: 1153-1154.

Furuuchi, M., Murase, T., Tsukawaki, S., Sieng, S., Hang, P. and Sakai, K. (2005a). Air Pollution in Angkor Monuments Area in Cambodia. First International Symposium on Evaluation of Mechanisms Sustaining the Biodiversity in Lake Tonle Sap, Cambodia, Dec.1-2, Phom Penh: 73-78.

Furuuchi, M., Sakano, T., Kizu, R., Shimizu, Y., Okubo, and Kanaoka, C. (2005b). PAHs in Ultra-fine Ambient Aerosol Sampled by a Supersonic Impactor (in Japanese). *J. Aerosol Res*. 20: 135-142.

Furuuchi, M., Murase, T., Tsukawaki, S., Sieng, S. and Yamashita, M. (2005c). Air Pollution in Phnom Penh: Concentration and Chemical Compositions of Ambient Particles, Proc. First International Symposium on Evaluation of Mechanisms Sustaining the Biodiversity in Lake Tonle Sap, Cambodia, Dec.1-2, Phom Penh: 82-90.

Furuuchi, M., Murase, T., Tsukawaki, S., Hang, P., Sieng, S. and Hata, M. (2006a). Characteristics of Air Pollutants in Angkor Monuments Area, Cambodia. *Proc.7th Int. Aerosol Conf.* St. Paul, USA: 1723-1724.

Furuuchi, M., Tekasakul, P., Otani, Y., Tekasakul, S., Sakano, T., Bai, Y., Murase, T. (2006b). Characteristics of Particulates Emitted from Rubber Wood Burning. *J. Ecotechnology Res*. 12: 135-139.

Furuuchi, M., Murase, T., Yamashita, M., Oyagi, H., Sakai, K., Tsukawaki, S., Sieng, S. and Hata, M. (2006c). Temperature Distribution and Air Pollution in Phnom Penh, Cambodia - Influence of Land Use and the Mekong and Tonle Sap Rivers. *Aerosol Air Qual. Res.* 6: 134-149.

Garami, F. and Kertai, I. (1993). *Water Management in the Angkor Area.* Angkor Foundation, Budapest, 109-114.

Hori, H. (1996). *Development and Environment of River Mekong* (in Japanese), Kokon Shoin,

Tokyo, p. 25-26.

Kato, S., Iwasaki, S., Kokubu, H., Furuuchi, M., Amorunkitbamrung, M., Lumpaseni, W., Kizu, R., Hayakawa, K. and Kanaoka, C. (2003). Current Status of Air Pollution in Bangkok (in Japanese). *Kankyo Gijutsu*. 32: 153-162.

Kato, S. (2006). Methodologies and Problems of Environmental Technology Transfer Intended for Developing Countries. *J. Aerosol Res*. 21:130-135.

Mekong River Commission, WUP–FIN. (2002). Water Utilization Program–Modeling of the Flow Regime and Water Quality of the Tonle Sap. Data Collection Report. Finish Environment Institute (http:/www/eja.fi/wup-fin/).

Mekong River Commission, WUP–FIN. (2003). Water Utilization Program–Modeling of the Flow Regime and Water Quality of the Tonle Sap. Tonle Sap Development Scenario Impacts and Guidelines. Finish Environment Institute (http:/www/eja.fi/wup-fin/).

Murase, T., Furuuchi, M., Tsukawaki, S., Sieng, S., Hata, M. and Yamashita, M. (2006). Present Status and Characteristics of Ambient Air Pollution in Phnom Penh, Cambodia (in Japanese). *J. Aerosol Res.* 21: 101-107.

National Institute of Statistics, Ministry of Planning, Cambodia. (2006). Main Source of Cooking Fuel, Main Source of Light, 1998 Population Censes of Cambodia.

Pal Arya, S. (1999). *Air Pollution Meteorology and Dispersion*, Oxford University Press, New York, p. 91.

Seinfeld, J.H. and Pandis, S.N. (1998). *Atmospheric Chemistry and Physics*, Wiley Interscience, New York, p. 111, 700-702.

Spurny, K.R. (1999). *Analytical Chemistry of Aerosols*, Lewis Pub., New York, p. 61- 66.

Statistics & Tourism Information Dept., Ministry of Tourism, Cambodia. (2005). Tourist Statistical Report , November (2005).

Tang, N. Hattori, T., Taga, R., Igarashi, K., Yang, X., Tamura K., Kakimoto, H., Mishukov, V. F., Tproba, A., Kizu, R. and Hayakawa, K. (2005). Polycyclic Aromatic Hydrocarbons and Nitropolycyclic Aromatic Hydrocarbons in Urban Air Particulates and Their Relationship to Emission Sources in the Pan-Japan Sea Countries. *Atmos. Environ.* 39: 5817-5826.

Tekasakul, P., Furuuchi, M., Tekasakul, S., Otani, Y., Tsukawaki, S., Jinno, T. and Murase, T. (2006a). Environmental Impacts of Particulates Emitted from Rubber-wood Burning in Rubber Smoked Sheet Production in Thailand: *Proc.7th Int. Aerosol Conf.* St. Paul., USA: 1526-1528.

Tsukawaki, S. and Members of EMSB Team and EMSB-u32 Team (2006). Preliminary Results from the Research Missions of EMSB and EMSB-U32 Programmes: Evaluation of Mechanisms Sustaining the Biodiversity of Lake Tone Sap, Cambodia. Proc. International Conference on Mekong Research for the People of Mekong, Oct.18-21, Chiang Rai, Thailand: 36-43.

Toriba, A., Kuramae, Y., Chetiyanukornkul, T., Kizu, R., Makino, T., Nakazawa, H. and

Hayakawa, K. (2003). Quantification of Polycyclic Aromatic Hydrocarbons (PAHs) in Human Hair by HPLC with Fluorescence Detection: A Biological Monitoring Method to Evaluate the Exposure to PAHs. *Biomed. Chromatogr*. 17: 126-132.

Tsujimoto, K. (2006). Hydro-Meteorological Environment at Tonle Sap Lake and its Environs: As a Case Study of Lake Basins in the Tropical Humid Region (in Japanese). Master thesis, Graduate School of Global Environmental Studies, Kyoto University, p. 10-12.

Vandecasteele, C. and Block, C. (1993). *Modern Methods for Trace Element Determination*, John Wiley & Sons, New York, p. 10-23.

Received for review, January 6, 2007
Accepted, March 7, 2007