APPROACHES TO MONITORING OF AIR POLLUTANTS AND EVALUATION OF HEALTH IMPACTS PRODUCED BY BIOMASS BURNING

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INTRODUCTION

Biomass burning is a persistent activity occurring throughout the world. Biomass burning refers to the burning of live or recently living vegetation to clear land for agriculture, plantations, and resettlement; for the disposal of agricultural and domestic refuse; and as fuel for cooking and heating. Intense forest fires can also ignite subsurface organic soil components (e.g., peat), which can continue to smoulder long after the original surface fires are out. In many instances, biomass fires can result in human exposure to high levels of various air pollutants. Among the air pollutants (or their precursors) emitted from biomass fires that are often of most concern for general population exposures are certain widespread pollutants, e.g., particulate matter (PM), sulfur oxides (SO_x), carbon monoxide (CO), etc., typically found in urban air mixes, as well as a variety of other toxic metals and volatile and semi-volatile organic compounds (VOCs).

In general, comprehensive approaches intended to be standardized for use in dealing with potential risks to public health of emissions from biomass fires should include: (a) characterization of the magnitude and composition of the emissions and their transformations during transport; (b) quantification of resulting concentrations of toxic air pollutants in ambient air in populated areas; (c) evaluation of likely exposure scenarios

for affected populations (both indoors and outdoors); and (d) assessment of consequent health risks posed by such human exposures.

This paper first highlights, briefly, certain key types of health-related information that can be useful in evaluating the potential health impacts of air pollution resulting from biomass fires. It also provides an overview of general air monitoring approaches and preferred methods for monitoring ambient concentrations of selected key air pollutants useful in evaluating the effects of biomass fire emissions. Lastly, the methods employed and results from a specific monitoring study designed to support assessments of health risks caused by exposure to high air pollutant levels in areas affected by biomass burning emissions (specifically in SE Asia) are also discussed as a case study. This study, carried out in Indonesia and Malaysia during the haze event of 1997 (1), focused mainly on measuring PM_{10} and $PM_{2.5}$ concentrations, and on characterizing the chemical composition of the aerosol. The emphasis on measuring PM components arose because PM levels were by far the most elevated compared to US values and the highest air pollutant alert system values were obtained for PM_{10}, compared to the other pollutants that were measured simultaneously with PM_{10}. Levels of air pollutants in US cities are also presented as part of the case study to give an idea of what typical levels of these pollutants in urban areas are with pollution control measures in place. These data can also be used as background values in estimates of health risks posed by exposure to aerosol components.

This paper does not address issues related to the atmospheric chemistry or transformations of biomass burning emissions, nor on the use of remote methods (e.g., satellite imagery) for monitoring the spread of biomass burning plumes (i.e., as given in item (a) above). These issues will be covered in other reviews. Methods for characterizing total human exposure to biomass burning products and to other pollutants (i.e., as given in item (c) above) in indoor and outdoor environments will also not be covered. However, it should be noted that significant exposures to biomass burning products occur in indoor environments in developing countries where wood and other biomass fuels are burned for cooking and heating in an inefficient manner (2). Thus, fully comprehensive evaluations of total human exposures would also need to consider exposure to indoor sources.

APPROACHES FOR EVALUATION OF POTENTIAL HEALTH IMPACTS

Probably of most use, currently, in evaluating potential health impacts of air pollution derived from biomass fires is the comparison of monitored ambient air concentrations of toxic pollutants against already established pertinent air standards or guidelines and associated air pollution alert system levels, e.g., the US National Ambient Air Quality Standards (NAAQS) and the associated Pollutant Standard Index (PSI) alert system, and/or World Health Organization (WHO) Air Quality Guidelines.

Concern about health and welfare effects of exposure to ambient air pollution levels led to the passing in 1970 of the US Clean Air Act to control the levels of ambient air pollutants in the United States. The Clean Air Act, which was last amended in 1990, requires the US Environmental Protection Agency to set NAAQS for widespread ambient air pollutants considered harmful to public health and the environment. The Clean Air Act established two types of NAAQS. Primary standards set limits to protect public health, including the health of sensitive subgroups of the general population such as the asthmatics, children, and the elderly. Secondary standards set limits to protect public welfare, including protection against visibility degradation, and damage to aquatic and terrestrial ecosystems, agricultural crops, vegetation, and buildings. The current NAAQS for the various "criteria" pollutants are shown in Table 1. The US Pollutant Standard Index (PSI) alert system has been developed as a way to provide accurate, timely, and easily understandable information to the public about the general health effects associated with different pollution levels, and to describe the precautionary steps that need to be taken if air pollutant levels rise into the unhealthful range. The correspondence between pollutant concentrations, the NAAQS and PSI values is shown in Table 2. It should be noted that the PSI value that is reported does not include the combined effects of different pollutants; instead the highest individual PSI value and the responsible pollutant involved are reported.

Markedly elevated particulate matter (PM) levels are one common feature of air pollution resulting from biomass fires and, hence, the typical need arises to emphasize evaluation of potential PM-related health

impacts as a key part of any assessment of public health risks associated with any given biomass fire situation. By far, the bulk of information concerning health effects resulting from exposure to PM air pollution has been collected in urban areas in Europe and North America. Severe air pollution episodes involving high PM concentrations, e.g., those that occurred in the Meuse Valley, Belgium; Donora, Pennsylvania; and London, England (among others), have been found to contribute to notable increases in mortality and morbidity. The most notable episode in this regard occurred in London from December 5 to 8, 1952 in which some 4000 excess deaths were recorded. During this episode, peak citywide 24-h particle concentration (measured as "British smoke") was 1.6 mg/m^3, and the mean citywide daily smoke level was approximately 1.0 mg/m^3. The mean citywide sulfur dioxide concentration was also over 1 mg/m^3 but the peak 24 h average SO_2 concentration was about 2 mg/m^3. The correspondence between smoke measurements and the mass of suspended particulate matter (PM) is not straightforward (3).

The high PM and SO_2 values that occurred during the above noted air pollution episodes are generally no longer found in industrialized areas in North America and Western Europe, but can still be found in Eastern and Central Europe and in China. Also, high concentrations of PM_{10} of about 1.6 mg/m^3 have been reported in the city of Jambi on Sumatra, Indonesia (4) in the haze produced by biomass burning in 1997, and similar concentrations were obtained in some Florida areas affected by forest fires in June 1998 (5). By comparison, annual average PM_{10} concentrations in the United States range from about 10 g/m^3 in very clean wilderness areas to about 50 g/m^3 in western US cities which are subject to dust storms and dust suspension by traffic on paved or unpaved roads, agriculture and construction; and maximum 24-h average concentrations are typically factors of two to five times the annual average values.

Although existing guidelines for evaluating the health effects of exposure to PM have been based on data collected in industrialized areas, it should be noted that there are distinct differences in the composition and toxicity of PM produced by biomass burning and fossil fuel burning (6). In addition, the physical conditions which characterized the above-mentioned urban episodes (i.e., acidic fogs and low temperatures) do not necessarily apply to biomass burning episodes. Insufficient data exist to characterize differences in mortality caused by exposures to these two

types of PM mixtures but, in general, emissions from fossil fuel burning and industrial operations appear to be more toxic than those from biomass burning (7).

Available data indicate that most of the particulate matter produced by the combustion of either fossil or biomass fuels is found in particles less than 2.5 micrometres in aerodynamic diameter (6). Recent research summarized in the USEPA report (6) has found evidence for small, but significant, increases in mortality at much lower PM_{10} levels than in the episodes mentioned above.

PM_{10} particles having aerodynamic diameters less than 10 micrometres (also known as thoracic particles) can be inhaled past the nose and throat into lower respiratory tract areas, including the lungs. PM_{10} particles consist of two main groups:

(i) $PM_{2.5}$ particles having aerodynamic diameters less than 2.5 micrometres, and
(ii) $PM_{10\text{-}2.5}$ particles having aerodynamic diameters between 2.5 and 10 micrometres.

$PM_{2.5}$ particles are often referred to as "fine" particles, whereas $PM_{10\text{-}2.5}$ particles are often referred to as "coarse" particles. They can reach lower regions of the lung, and are of much concern with regard to a variety of potential adverse health outcomes. $PM_{2.5}$ in populated areas is composed mainly of substances derived from high temperature processes (e.g., combustion of fossil or biomass fuels). $PM_{2.5}$ in remote areas may be produced by the oxidation of SO_2 or NO emitted by natural processes. There may also be some addition of crustal materials from the coarse mode mixed into the $PM_{2.5}$ size fraction. Coarse ($PM_{10\text{-}2.5}$) particles include substances such as suspended crustal material, plant and insect debris, mould spores, etc., some of which may also be of health concern (e.g., they may exacerbate asthma symptoms). The efficiency of penetration of particles of different sizes deep into the lungs depends on the health status of the individual and his (or her) ventilation rate. Increasing the level of physical activity and switching from nasal to oral breathing results in increased ventilation rates and enhanced delivery of inhaled particles to lower respiratory tract areas.

In addition to evaluating possible acute health risks in relation to the total mass of PM_{10} and/or $PM_{2.5}$ particles, efforts should be made to assess possible chronic health risks associated with specific chemical subcomponents of the aerosols resulting from biomass burning. This may include the assessment of health risks associated with exposures to ambient levels of trace metals and/or benzo[*a*]pyrene (B*a*P) or other polycyclic aromatic hydrocarbons (PAHs) found often in fossil fuel or biomass combustion emissions. Consideration should also be given to the assessment of potential risks associated with other gaseous compounds often directly emitted or formed as transformation products from precursors emitted from biomass fires, e.g., carbon monoxide, nitrogen oxides, ozone, and/or various volatile organic compounds (VOCs) such as xylenes, benzene or toluene (so-called "XBT").

AIR MONITORING APPROACHES AND METHODS

Under ideal circumstances, a monitoring network, which can provide the necessary information about exposures to pollutants emitted by local sources as well as from biomass burning emissions would already be in place in affected areas. There are several general considerations which should be considered in the design of monitoring networks, e.g., the objectives of the monitoring programme, the spatial and temporal resolution of the monitors needed to meet these objectives, the specifications of performance of the monitoring devices, the siting of the individual monitors, the management of data, and the development of a quality assurance/quality control programme. Meteorological parameters should also be monitored along with air pollutants. The criteria used for the placement of monitoring sites vary according to the intended uses of the monitoring data. In many specialized studies designed to evaluate the health effects of exposure to ambient air pollutants, the general approach has been to site monitors within a variety of environments in an urbanized, metropolitan area to obtain a clear picture of the variability in ambient concentrations likely to be encountered by the general population. Large urban areas also have a sufficiently large population to be able to discern differences in health outcomes that are related to variations in air pollutant levels.

Data collected by air monitors are meant to represent variations in ambient concentrations over a range of separate spatial scales. The highest concentrations of pollutants in an urban area are typically found close to highways and major point sources (e.g., power plants, smelters, etc.), and monitors located near these sources collect data meant to be representative over spatial scales ranging from tens to hundreds of metres. Sites designed to characterize exposures of the general population to ambient concentrations in environments ranging from residential-suburban to city centre obtain data meant to be representative over spatial scales ranging from kilometres to a few tens of kilometres.

Finally, sites designed to characterize background concentrations are intended to obtain data meant to be representative over spatial scales ranging from tens of kilometres to hundreds of kilometres. The microenvironmental characteristics of any monitoring site must be evaluated to minimize the effects of potential artifacts caused by nearby sources or by physical features (e.g., overhanging tree limbs, close-by buildings, etc.), which may interfere with the interpretation of the data. Methods are available for determining the optimum placement of monitoring sites to meet the objectives given above while minimizing the artifacts caused by nearby objects (8).

The spatial and time representativeness of the monitoring sites also depends on the pollutant being measured. A number of studies (see e.g. (9)) have indicated that the spatial distribution of $PM_{2.5}$ particles is relatively uniform and the day-to-day variability in their concentrations tends to be similar across a given urban area. This coherence in the $PM_{2.5}$ data results in part from long range transport from distant sources on spatial scales which are much larger than the city under study and from widespread area sources which exhibit similar temporal behaviour (e.g., motor vehicle traffic). $PM_{2.5}$ particles also have an atmospheric lifetime (with respect to removal by wet and dry deposition), which is long compared to the transport time across a given urban area, leading to more complete mixing in urban airsheds. However, coarse mode particles (aerodynamic diameters $>2.5\mu m$) have much shorter atmospheric lifetimes than $PM_{2.5}$ particles and, as a result, are less likely to be as evenly distributed across an urban area. These considerations likely form the basis for the health effects associated with exposure to ambient PM,

demonstrated by epidemiological analyses using central site monitors in urban areas (6).

For the purposes of examining the effects of distant sources (e.g., biomass burning) on a local population, at least one additional monitor should be placed at a site which is expected to be affected by the emissions before they reach the urban study area. This monitoring site should be sited to capture the effects of the pollution plume before additions from local sources have occurred. Thus, the contributions from local sources can, in principle, be separated from those of distant sources. Data from such a site can also be used for health studies relating to the non-urban population. The location of this site could be determined on the basis of calculations of the most likely transport routes (i.e., climatological trajectories) from fire prone areas. However, the extent to which data collected by such a site can be used to generate early warnings for the urban area can only be evaluated after the most likely transport routes have been calculated. In addition, monitoring should also be performed at a control site which is unaffected by either the long range transport of the pollutants under study or high levels of local pollution.

A quality assurance plan is essential for ensuring maximum credible use of results of a monitoring effort. Elements which are included in the development of USEPA quality assurance plans (10) relate to understanding the objectives to be met by the monitoring programme, personnel training requirements, sampling methods, sample handling, calibration standards, the frequency of calibration of monitoring devices, external performance and system audits, data acceptance criteria, data management and archiving, data review and evaluation, and reconciliation of data reporting with user requirements.

Monitoring of the pollutants shown in Table 1 is routinely performed throughout the United States: to characterize trends in and the current status of air quality; to determine compliance with the relevant NAAQS; to evaluate the effectiveness of control strategies; to provide data for atmospheric modelling and health studies; and to provide timely warning to the public before potentially hazardous levels of pollutants are reached. Monitoring requirements are met in the United States by using Federal Reference Methods (FRMs) or designated equivalent methods. Methods accepted for measuring PM_{10} are summarized in Table 3. These

methods are also used in many monitoring networks elsewhere in the world. Since the announcement of NAAQS for $PM_{2.5}$ on 18 July 1997, four manual FRMs for monitoring $PM_{2.5}$ concentrations have been developed. These are: BGI $PM_{2.5}$ Ambient Fine Particle Sampler (RFPS-0498-116); Graseby Anderson $PM_{2.5}$ Ambient Air Sampler (RFPS-0598-119); Graseby Anderson $PM_{2.5}$ Sequential Air Sampler (RFPS-0598-120); Ruprecht and Patashnik Partisol® FRM Model 2000 Air Sampler (RFPS-0498-117); and Ruprecht and Patashnik Partisol® Plus Model 2025 Sequential Air Sampler. A list of Federal Reference Methods and designated equivalent methods for the pollutants shown in Table 1 can be found on the USEPA website: *www.epa.gov/ttn/amtic/criteria.html*.

The principal FRMs for monitoring $PM_{2.5}$ and PM_{10} involve the collection of aerosol deposits on filter substrates. PM filter samples are collected based on 24-hour sampling periods. The filters are weighed prior to, and after sampling following equilibration under conditions of fixed relative humidity and temperature for 24 hours. Timely information about ambient levels for reporting to the public or for taking measures to protect the public health cannot therefore be obtained by filter measurements because of the constraints imposed by the long sampling and equilibration times. For purposes of determining compliance with the NAAQS, particle sampling is conducted using a schedule ranging from once per day to once every six days in the United States. However, two automated methods are capable of providing near real time, hourly measurements of PM concentrations and have been designated as equivalent methods, based on their performance in comparisons with FRMs (Table 3). These are the beta gauge sampler (11) and the Tapered Element Oscillating Microbalance (TEOM) method (12). Data collected using these methods are used to calculate PSI values in the United States in metropolitan statistical areas whose populations are over 200,000. Such automated methods represent feasible sampling techniques for operating an effective alert system.

It should be noted that both of these automated methods are subject to artifacts which result from the heating of the inlets to temperatures ranging from 30°C to 50°C (to avoid interference from the condensation of moisture). The heating tends to drive off semi-volatile components such as ammonium nitrate and some organic compounds. The magnitude of error in the mass measurement, therefore, depends on the composition

of the particles that are being sampled, which in turn, depends on the nature of contributing PM sources. Under same circumstances, then, the actual ambient PM mass concentration may be underestimated by such methods (unless site-specific calibrations against gravimetric measurements are performed)—thus arguing for caution in ascribing precise quantitative accuracy to the values obtained and associated PSI values.

In addition to determining the mass of particles in the PM_{10} and $PM_{2.5}$ size ranges, the composition of the ambient particles can also be determined for estimating the potential consequences of long-term exposures to toxic trace components. Thus, airborne concentrations of trace elements (e.g., potassium, lead, etc.) and concentrations of total organic and elemental ("black" or "soot") carbon in the particles can be measured. Images of particles on selected samples can be obtained by scanning electron microscopy to provide additional insights about the sources of the particles. The concentrations of PAHs in the gas phase and in the particulate phase can also be measured. Methods of sampling and analysis for trace components summarized in Table 4 (as employed in the SE Asia case study presented later) have been used extensively by the USEPA (13-15) and are considered to be EPA recommended methods. However, other sampling and analysis techniques are in use by other governmental and non-governmental organizations in the United States and elsewhere.

Although the foregoing discussion focuses on techniques for sampling and analyzing aerosol components, gaseous components also need to be considered. As part of initial assessments, canister samples of gaseous hydrocarbons of potential health concern (e.g., xylenes, benzene, and toluene) should be obtained.

SOUTHEAST ASIA CASE STUDY

During the summer and autumn of 1997, uncontrolled biomass burning in the SE Asia region (especially in Indonesia) created a widespread, dense smoke haze, which spread as far as the Philippine Islands to the northeast and the SE Asian mainland (including areas of Vietnam, Thailand, and Malaysia) to the north and northwest. As

described in earlier reports (16, 17, 18), haze episodes resulting from biomass burning have previously affected Malaysia, Singapore and Indonesia. The 1994 haze event described by Nichol (18) was associated with an El Niño atmospheric pattern, as was the haze event of 1997.

The biomass burning in SE Asia resulted in the exposure of millions of people to potentially dangerous levels of pollutants during the 1997 episode. At the height of the episode in late September 1997, the Malaysian Air Pollution Index (API) reached values of over 800 in Kuching, Sarawak and a peak API of 300 was reached in Kuala Lumpur, Malaysia. The high values of the API were caused in both places by elevated levels of suspended particles in the air (as depicted in Figure 1 for Kuala Lumpur). Malaysian API values are analogous to USEPA Pollutant Standard Index (PSI) values, in that both the API and PSI value of 100 is assigned to the concentration of the 24-h standards in the respective countries. In this case, the Malaysian 24-h PM_{10} standard is equivalent to the comparable 24-h PM_{10} US National Ambient Air Quality Standard (NAAQS).

Most of the data shown in Figure 1 for Malaysia were collected during the period of the southwest monsoon, which transported pollutants from biomass burning areas in Kalimantan and in Sumatra. The peak PM_{10} level measured by the Malaysian Department of the Environment (MDOE) during late September, probably represents short-term incremental PM contribution from the biomass fires of about 350 $\mu g/m^3$ above background PM levels from sources in Kuala Lumpur, assuming that the urban background level could be represented by the average PM_{10} level observed during November. However, because of enhanced stability in the boundary layer during the haze, the background PM levels resulting from the local, urban sources may have been larger. The transition to the northeast monsoonal regime occurred in November and was associated with lower PM concentrations. The levels of other criteria pollutants during the period of the southwest monsoon were all significantly lower with respect to either exceedences of the relative NAAQS or to their API values. Corresponding values could not be shown for affected areas on Sumatra or Kalimantan because of a lack of reported measurements.

Air pollution monitoring was conducted by USEPA from 2 to 11 November, 1997 in Petaling Jaya, several km to the southwest of central Kuala Lumpur. Particle mass in the $PM_{2.5}$ and PM_{10} size ranges was measured in Malaysia to provide an initial comparison with data obtained by the MDOE. However, measurements of $PM_{2.5}$ only were obtained at Shah Alam. The period of measurement in Malaysia is indicated by the bar labelled "EPA" in Figure 1. Samples were also collected from 4 to 8 November, 1997 in Palembang, and on the campus of Sriwijaya University (30 km to the south of Palembang) in Sumatra, Indonesia, to obtain data in areas affected by the haze in Indonesia and situated closer to the biomass fire sources. Aerosol composition data in both countries were obtained using the methods summarized in Table 4. The mix of sampling sites chosen in Malaysia and Indonesia were similar (i.e., measurements were made in both countries at urban sites and at more rural upwind sites). The upwind measurements were meant to capture the composition of the particles transported from the biomass burning before substantial additions of particles from local, urban sources, while the urban measurements were meant to capture the composition of the particles produced by local sources in addition to those produced by biomass burning. The two sets of monitoring sites were deployed along the prevailing wind direction in both countries (i.e., along the Klang Valley in Malaysia, and south to north in Sumatra from Inderalaya to Palembang in Indonesia). The general locations of the sampling sites and the general meteorological and haze conditions during the period of sampling are shown in Figure 2.

The daily 24-h PM_{10} concentrations obtained at Petaling Jaya with the modified dichotomous sampler, along with data from collocated MDOE -gauge monitoring equipment are shown in Figure 3. The average PM_{10} levels recorded by the MDOE -gauge sampler (82.4 $\mu g/m^3$) were about 11 $\mu g/m^3$ (15 per cent) higher than those obtained using the modified dichotomous sampler (71.1 $\mu g/m^3$). This difference is within the range of more extensive comparisons, although the direction of the discrepancy is opposite to what is expected. A longer record is needed to draw more definitive conclusions (19).

It rained on several days during the sampling period, resulting, in part, in the day-to-day variability seen in the PM_{10} levels shown in Figure 3. Winds were mainly from the northeast during this period (Figure 2),

except for a brief time when they had originated in the southwest and may have brought in contributions of the biomass burning particles from Sumatra. Therefore, the results presented here may be viewed mainly as representing contributions from local sources to the measured ambient particles with some contribution from the Indonesian biomass fires. The mean $PM_{2.5}$ concentration measured at Petaling Jaya was 59.1 $\mu g/m^3$. The US Army, Centre for Health Promotion and Preventative Medicine, measured $PM_{2.5}$ concentrations at Shah Alam and at Petaling Jaya. They obtained mean $PM_{2.5}$ concentrations of 59.7 $\mu g/m^3$ at Petaling Jaya and 50.1 $\mu g/m^3$ at Shah Alam. Data obtained at Shah Alam were highly correlated with those obtained by either method at Petaling Jaya ($r > 0.98$). All of the above considerations suggest that the samplers at Petaling Jaya and Shah Alam were monitoring primarily the urban plume from Kuala Lumpur during the early November sampling period. These findings are also consistent with remarks in the preceding sections about the uniformity of $PM_{2.5}$ levels across urban areas. The measurements made on Sumatra, discussed below, are considered to be more representative of the composition of the biomass burning emissions.

The mean concentrations and composition of suspended $PM_{2.5}$ and $PM_{10-2.5}$ particles measured in Petaling Jaya, Palembang, and Inderalaya (Sriwijaya University) are shown in Table 5. As can be seen from Table 5, $PM_{2.5}$ constituted over 80 per cent of PM_{10} at Petaling Jaya and Palembang. There are many possible sources (e.g., motor vehicles, vegetation burning, plant and animal debris, pollen, fungal spores, organic compounds which condensed onto existing particles) for the carbonaceous constituents that were sampled in Petaling Jaya. The value shown for organic carbon also reflects a rough estimate of the amounts of organic compounds containing hydrogen, nitrogen and oxygen. Selected filter samples were analyzed by scanning electron microscopy to obtain information about the nature of the carbonaceous particles collected on them. Most of the larger particles were mould spores, with a few particles present that are typical of diesel exhaust. The smaller particles were probably generated by combustion by motor vehicles, power plants, and perhaps by vegetation burning. These types of particles are to be expected, given the proximity of the monitoring site to vegetation and to a nearby road. The mean concentration of lead (Pb) in Petaling Jaya was 39 ng/m^3, compared to the US National Ambient Air Quality Standard for lead of 1500 ng/m^3 (1.5 g/m^3 90-day ave.). The concentrations of other

heavy metals such as nickel (Ni), copper (Cu), and zinc (Zn) were all substantially lower, and cobalt (Co) and cadmium (Cd) were not detected. An example of a typical profile of trace elemental composition of emissions from wood burning is shown in Figure 4. It is again worth noting that organic compounds constitute the major component of biomass burning emissions, thus underscoring the need for detailed evaluations of artifacts which may be produced by heating the inlets in continuous monitors. The ratio of potassium (K) to $PM_{2.5}$ in the data collected at Petaling Jaya is consistent with biomass burning emissions; however, it is difficult to say how much of the fine particle mass measured in Petaling Jaya was due to local vegetation burning or transport from Indonesian biomass fires. Background levels of K could have been contributed by other sources (e.g., soils, coal burning, etc.) in the Kuala Lumpur area.

Sulfate in aerosol samples collected in the United States is associated typically with the oxidation of sulfur dioxide (SO_2) emitted by power plants and to a lesser extent by motor vehicles. Similar sources may also have contributed to the sulfate seen at Petaling Jaya. Wind blown dust suspended from roads, construction sites, and natural surfaces probably represents the major source of the crustal elements (e.g., Al, Si, Ca, Ti, Fe). Heavy metals originate from a variety of industrial processes such as incineration, manufacturing, smelting, etc. Motor vehicles are also a likely source of Pb seen in the samples collected in Malaysia. As is the case for biomass burning emissions, automotive emissions consist mainly of organic carbon species and they likely contributed to the observed organic carbon levels in Petaling Jaya.

The mean daily (24-hr) PM_{10} concentration at Palembang was 402 $\mu g/m^3$. The mean daily fine particle ($PM_{2.5}$) concentration was 341 $\mu g/m^3$ at Palembang and 264 $\mu g/m^3$ at Sriwijaya University. The concentrations of PM_{10} and $PM_{2.5}$ exceeded the 24-h US NAAQS for both PM_{10} (150 $\mu g/m^3$) and $PM_{2.5}$ (65 $\mu g/m^3$) by large margins on all five days. The PM_{10} average corresponded to a USEPA PSI value of about 300 for PM_{10} levels, with values for several individual days reaching higher levels categorized as "Hazardous". Approximately 85% of the mass of the particles was concentrated in the $PM_{2.5}$ (fine size) fraction at Palembang. Since the Indonesian government does not routinely monitor airborne particulate matter levels at the Sumatran sites sampled by USEPA, no

intercomparisons with their equipment or evaluation of their techniques could be performed.

Scanning electron microscopy (SEM) images of filter deposits collected in Palembang indicate that the particles were composed mainly of hygroscopic carbon compounds. Small amounts of the organic compounds could have also been produced by motor vehicle emissions and the condensation of organic vapours. Mould spores and plant and animal debris were also present in the images.

As can be seen from Table 5, the values for most trace metals in Palembang and Inderalaya (Sriwijaya University) are similar to those obtained in Petaling Jaya, but concentrations of chlorine (Cl) and potassium (K) are much higher at the Indonesian sites. Ratios of K to total mass ranged from 0.5 to 1.0% in the $PM_{2.5}$ samples collected. These values are characteristic of wood burning emissions (Figure 4). As mentioned above, most of the mass of the emissions from biomass burning is typically in the form of organic compounds, and these were elevated at both the Palembang and Sriwijaya University sites. Thus, the organic matter and the overall $PM_{2.5}$ particle composition at both Indonesian sites appear to be dominated by biomass burning emissions. Sources of sulfate, crustal elements and heavy metals are probably similar to those in Malaysia.

The composition of the coarse particles, i.e., particles with aerodynamic diameters between 2.5 and 10 micrometres ($PM_{10-2.5}$), is dominated by soil particles and some biological material, such as mould spores at Petaling Jaya. The composition of the coarse particles at Palembang reflects mainly soil, perhaps suspended by motor vehicle traffic, with additions of biomass burning products.

The composition of particle samples obtained in selected US cities (Los Angeles, CA, Philadelphia, PA, and Roanoke, VA) and in a city in the Czech Republic (Teplice) are shown for comparison in Table 6. The same sampling and analysis methods that were used in SE Asia were also used to collect and analyze samples in Philadelphia and Teplice. These comparisons are shown to help place the air pollution values obtained in SE Asia in perspective in relation to those encountered elsewhere. Los Angeles and Philadelphia were chosen because they are both large urban

areas with a somewhat different mix of aerosol characteristics, and Roanoke because it is frequently impacted by wood smoke during the winter. Teplice was chosen because it is a heavily industrialized Central European city, which is subject to frequent air pollution episodes during the winter when lignite (a soft brown coal formed from peat) is widely used for residential heating and results in exposures to elevated levels of many of the same air pollutants derived from biomass fires. During the period from January through March 1993, as shown in Table 6, the overwhelming bulk of suspended aerosol mass in Teplice was found to be due to coal combustion (13).

During a severe episode that occurred in February 1993, a peak 24-h average PM_{10} level of about 1 mg/m^3 was reached. As can be seen from a comparison of Tables 5 and 6, concentrations of the trace metals observed at the three sites in SE Asia are well within the range of values routinely observed in US cities. However, the concentration of K and the ratio of K to total fine particle mass is elevated in the SE Asian samples compared to the samples collected in Los Angeles and Philadelphia. The ratio of K to total fine particle mass is similar among the samples collected in Roanoke and in SE Asia. In Philadelphia, K is mainly found in the coarse size mode, consistent with wind-blown soil as a major source of K. In contrast, K is mainly found in the fine particle mode in the SE Asian and in the Teplice samples, which is consistent with a combustion source of K.

Levels of sulfate, reported as S, are highly elevated in the samples collected in Sumatra compared to those collected in US cities. They are more reminiscent of the values found in Teplice, a heavily industrialized city, during a winter season marked by several air stagnation-pollution episodes. The ratio of S to total mass in particulate emissions from wood burning is about 0.005 (Figure 4), while the ratio of S to total fine particle mass was about 0.032 in Palembang and 0.026 at Sriwijaya University.

Thus, over 80 per cent of the observed sulfate at the two sites is due to other sources (e.g., the oxidation of SO_2 emitted by power plants and biomass burning and sea spray). Unfortunately, pH measurements were not performed on extracts of the samples collected in Sumatra.

PAHs are produced by the incomplete combustion of biomass, motor vehicle fuels (e.g., diesel fuels are rich sources of PAHs), and other fossil fuels such as coal and oil. They may be present in either the gas phase or attached to particles, depending mainly on temperature. Benzo[*a*]pyrene (BaP) is a PAH found mainly in the particulate phase and is of potential health concern because it is a strongly carcinogenic compound. BaP concentrations found in a number of studies are shown in Table 7. Airborne levels of BaP and other PAHs measured in approximately 60 urban areas around the world since the mid-1970's are reviewed by Menichini (25), to which the reader is referred for further characterization of PAH levels.

POTENTIAL HEALTH IMPLICATIONS

Malaysia

The potential health implications of the air monitoring data collected in Petaling Jaya are difficult to assess because of the very limited data set. Based on data collected by MDOE, the short-term excursions of ambient PM_{10} concentrations to levels notably above the USEPA and Malaysia's daily PM_{10} standards nearly every day during the last two weeks of September, 1997 must certainly be viewed as having posed some increased acute health risks for the general population in the Kuala Lumpur area. This is especially likely, given indications from the USEPA air monitoring efforts that a substantial proportion ($\sim$80 per cent) of the PM_{10} mass in the Kuala Lumpur area appeared to be small sized, fine ($PM_{2.5}$) particles. Available epidemiological studies, reviewed in the recent USEPA air quality criteria document for particulate (6) and by WHO (26), indicate that short-term (24-hr) exposures to ambient particles measured as PM_{10} or $PM_{2.5}$ are associated with some increased risk of mortality and morbidity (measured as increased respiratory symptoms, hospital admissions, etc.), especially among the elderly ($>$65 yrs old) and persons with preexisting cardio-respiratory disease. Some increased risk for exacerbation of asthma symptoms in asthmatic individuals or, possibly, worsening of acute respiratory disease (e.g., in the case of acute respiratory infections or pneumonia), could also occur based on available PM epidemiological studies.

As for the health implications of specific PM constituents (e.g., elemental or organic carbon, crustal materials, heavy metals, sulfate, or PAHs), the EPA monitoring results obtained in Kuala Lumpur were not indicative of much, if any, increase in acute exposure health risks. This outcome is not necessarily very meaningful, however, given that the USEPA monitoring data were obtained during a distinctly lower air pollution period after the peak period of haze from the biomass fires had passed. Also, increased risks of possible cancer and non-cancer health risks associated with the specific compounds measured are typically of most concern in relation to prolonged chronic exposures to ambient air concentrations encountered by the general public (versus usually much higher acute exposure levels often experienced in occupational settings). Such chronic environmental exposure health risks are generally assessed and quantified based on the assumptions of daily (24-hr) exposures over an entire lifetime (70 yrs average) for susceptible individuals—a scenario clearly not met by the relatively brief increased exposures in Malaysia to biomass fire emissions components in 1997. Repeated, more prolonged exposures to biomass fire smoke constituents every few years, however, might result in cumulative doses projected to be associated with increased health risks. Much more extensive data and assessment efforts would be necessary to attempt any more specific estimation of potential health impacts of increased air pollution concentrations in Malaysia due to haze from biomass fires. On the other hand, people with undiagnosed asthma or those progressing toward more severe asthma from mild forms readily amenable to effective medication control, or persons with acute respiratory infections (e.g., pneumonia), could be placed at increased risk for rapid onset of worsening of respiratory systems and lung function declines due to short-term acute exposure to the haze produced by the biomass fires.

Indonesia

The situation in Indonesian areas impacted by haze from the biomass fires, especially those relatively close to "hot spots" where concentrations of PM and certain other air pollutants are likely at their highest, almost certainly posed substantially greater risk for the local general population. Daily PM_{10} levels in Palembang approached or exceeded levels that would be deemed to be "Hazardous" in terms of the USEPA Pollutant Standard Index (PSI) or analogous Malaysian API

values shown in Figure 1. Furthermore, given that the USEPA monitoring effort occurred after the extent and intensity of the fires had already been substantially reduced from earlier peak levels, the local population in Palembang and its vicinity were likely exposed on a daily basis to even higher PM levels during the preceding months of September and October.

Of particular concern is the very high percentages (i.e., 85 per cent) of the PM_{10} mass attributable to $PM_{2.5}$, the "fine particle" size fraction thought to be most clearly implicated in increasing risks of mortality and morbidity due to exposures to PM of ambient origin, as evaluated by both USEPA (6) and WHO (26). Assuming that the average $PM_{2.5}$ mass concentration of 264 g/m^3 detected by USEPA monitoring at Sriwijaya University largely reflects the impact of smoke from nearby biomass burning and that similar biomass smoke input levels contributed to the average 341 g/m^3 $PM_{2.5}$ mass found by USEPA monitoring in Palembang, it can be estimated that an average increment of about 250 g/m^3 $PM_{2.5}$ from the biomass burning haze was added to the daily average of about 75 g/m^3 of $PM_{2.5}$ generated from other local sources in Palembang. That increment of haze-related particle exposure in excess of background particle levels due to local sources can be projected based, for example, on quantitative risk estimates published by WHO (26), to have contributed to detectable increases in respiratory symptoms and hospital admissions for respiratory problems among the local general population and, even possibly, some mortality among the elderly and those with preexisting chronic lung diseases or cardiac conditions. Again, much more extensive information and assessment efforts would be needed to attempt even a rough estimate of potential increases in mortality or morbidity among members of the general population in Palembang or other Indonesian areas impacted by the haze from the biomass burning. The public health impacts could be fairly substantial given the PM concentrations involved and the size of the likely affected Indonesian populations in Sumatra, Kalimantan, etc. Even larger, very substantial public health impacts would be projected if Jakarta and other parts of densely populated Java (which was much less impacted by the 1997 biomass burning haze than were Sumatra and Kalimantan) experienced any prolonged periods of haze from biomass burning.

The lack of any well-established, routinely operating air monitoring network in Indonesia precludes having data available by which to attempt analyses analogous to the one presented here based on MDOE PM data for KL during August-November, 1997. Nevertheless, even the brief period of USEPA monitoring in early November at two sites near biomass fire hot spots in Sumatra indicates that ambient levels of both PM_{10} and $PM_{2.5}$ markedly exceeded US PM standards and approached or exceeded 24-h PM_{10} levels designated as "Hazardous" in terms of US PSI values. Most of the particles were in the $PM_{2.5}$ fraction, and the specific composition of the particles and presence of particular PAH compounds are characteristic of wood smoke. The daily (24-h) PM_{10} and $PM_{2.5}$ concentrations measured by USEPA at the Sumatra sites (Palembang and Sriwijaya University) probably posed increased public health risks for the local general population. The USEPA monitoring was conducted after reductions in the number of hot spots seen in satellite images had occurred. Thus, exposures of the general population to even higher PM levels for prolonged periods of time (weeks, months) likely occurred, pointing toward even more substantial public health impacts in Indonesia being associated with exposures to haze from the biomass burning.

Annual average data for heavy metals and B[*a*]P can be compared to cancer and noncancer dose-response assessments available in the integrated risk information system (IRIS) (27) or the health effects assessment summary tables (HEAST) (28) to obtain estimates of the long-term risks posed by exposure to these substances. Needless to say, the data reported here cannot be used for defining long-term average concentrations. However, the data can be used to place potential attendant health risks in perspective, if frequently repeated extended exposures to the levels measured in SE Asia were to occur annually over an individual's lifetime.

SUMMARY AND RECOMMENDATIONS

Summary of findings in SE Asia

Based on MDOE air monitoring results during the last half of September, 1997, daily PM_{10} concentrations in Kuala Lumpur (KL) dramatically increased to levels well in excess of US and Malaysian PM_{10}

air standards, on some days approaching levels judged to be "Hazardous" in terms of US PSI or Malaysian API values, largely as the result of haze transported from Indonesian biomass fires. Although data are not readily available from affected areas in Kalimantan and Sumatra, it may be surmised that similar or worse conditions were found in these areas.

USEPA air monitoring results, obtained during the first two weeks of November, 1997 (after the peak period of biomass fire haze over Malaysia had passed), indicated good agreement with MDOE results (within 15 per cent) obtained from collocated PM_{10} monitoring at Petaling Jaya (a KL suburb). Approximately 80 per cent of the PM_{10} mass at Petaling Jaya was attributable to $PM_{2.5}$ concentrations monitored there. Based on current knowledge of the sizes of particles produced by biomass burning and the results in Sumatra (which indicate that over 80 per cent was present as $PM_{2.5}$), most of PM_{10} monitored at Kuala Lumpur during the haze episodes was probably made up of $PM_{2.5}$.

Recent USEPA and WHO evaluations of available PM epidemiological studies indicate that such incremental acute exposures to daily (24-h) PM concentrations as found during the haze episode in Malaysia and Indonesia were likely associated with increased risk of adverse health effects (e.g., increased mortality or respiratory symptoms and hospital admissions of the elderly, those with preexisting chronic cardiorespiratory disease, and asthmatic persons) among the general local population, especially in Indonesian areas affected by the biomass fire haze.

The concentrations of specific chemical components monitored by EPA in the KL area or in Sumatra (e.g. trace metals, PAH compounds, etc.) were not found to be particularly remarkable, individually, in being likely to pose much, if any, health threat, unless repeated prolonged exposures over several weeks or months occurred virtually every year. Such repeated exposures could result in cumulative doses associated with some increased risk of adverse cancer or non-cancer health effects. However, even though the concentrations reported here were observed after peak exposures to haze components had passed, cancer risks projected to be possibly associated with much higher air pollution levels experienced earlier during the 1997 haze episode would still be much

smaller than mortality or morbidity rates estimated to be associated with exposures to measured PM_{10} or $PM_{2.5}$ levels.

Recommendations

1. In addition to strong measures to control the setting and spread of biomass fires, public education programmes should be conducted to better inform the populations in affected regions about the detrimental health and environmental impacts of uncontrolled biomass burning.

2. Air quality monitoring should be conducted on a regular basis in major urban areas and in areas likely to be impacted by biomass burning emissions. Monitoring the so-called criteria air pollutants (PM_{10}, $PM_{2.5}$, O_3, CO, SO_2, NO_x, and Pb) should be given priority, with measurements of PM_{10} and $PM_{2.5}$ given highest priority.

3. Prior to the establishment of a ground-based monitoring network, the location of sampling sites should be determined in accordance with existing guidelines (8, 29) to minimize artifacts in sample collection and measurement. An ongoing quality assurance programme should also be established according to international guidelines.

4. Efforts should be made to separate contributions to total aerosol mass and toxic components (e.g., sulfate, B[*a*]P, metals, etc.) from biomass burning and other sources.

5. An effective air quality index system analogous to the USEPA PSI system should be implemented to better inform local civil authorities and citizens about unhealthy air quality conditions and to assist in taking appropriate actions to avert or lessen public health impacts.

6. Possibilities for conducting health effects measurement studies to evaluate health impacts of recurring biomass fires should be explored. As an example, retrospective epidemiological analyses

relating health statistics (e.g. hospital admissions, mortality rates, etc.) in Kuala Lumpur to PM_{10} levels measured by the MDOE from August to November, 1997 could be done to evaluate quantitatively the potential health impacts of the biomass burning haze on the general population.

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REFERENCES

1. Pinto JP, Grant LD, Hartlage TA. Report on USEPA air monitoring of haze from SE Asia biomass fires. Research Triangle Park, NC (National Centre for Environmental Assessment - RTP Office), Report No. EPA/600/R-98/071, USA, 1998.

2. World Health Organisation. Biomass fuel combustion and health. WHO Report No. EFP/84.64, Geneva, 1984.

3. Mage DT. The relationship between total suspended particulate matter (TSP) and British smoke measurements in London: development of a simple model. J. Air Waste Manage. Assoc 1995;45: 737-9.

4. Yajima I. Personal communication, 1997.

5. Steven, RK. Personal communication, 1998.

6. US Environmental Protection Agency. Air quality criteria for particulate matter. Research Triangle Park, NC, Report Nos. EPA/600/P-95/001aF-cF. 3v, USA, 1996.

7. Beck BD, Brain JD. Prediction of the pulmonary toxicity of respirable combustion products from residential wood and coal stoves. In: Proceedings: Residential Wood & Coal Combustion Specialty Conference; March; Louisville, KY. Pittsburgh, PA: Air Pollution Control Association 1982; 264-80.

8. US Environmental Protection Agency. Network design and optimum site exposure criteria for particulate matter. Research Triangle Park, NC: Office of Air Quality Planning and Standards; Report No. EPA-450/4-87-009, May, 1987.

9. Suh HH, Allen GA, Koutrakis P, Burton RM. Spatial variation in acidic sulfate and ammonia concentrations within metropolitan Philadelphia. J. Air Waste Manage Assoc 1995;45: 442-52.

10. US Environmental Protection Agency. Quality assurance guidance document 2.12: monitoring $PM_{2.5}$ in ambient air using designated reference or class I equivalent methods. Research Triangle Park, NC: National Exposure Research Laboratory, April 1998.

11. Wedding JB, Weigand MA. An automatic particle sampler with beta gauging. J. Air Waste Manage Assoc 1993;43: 475-9.

12. Patashnick H, Rupprecht EG. Continuous PM-10 measurements using the tapered element oscillating microbalance. J. Air Waste Manage Assoc 1991;41: 1079-83.

13. Pinto JP, Stevens RK, Willis RD, *et al.* Czech air quality monitoring and receptor modeling study. Environ. Sci. Technol 1998;32: 843-54.

14. Winberry WT, Murphy NT Riggan RM. Methods for determination of toxic organic compounds in air: EPA methods, Noyes Data Corporation, Park Ridge, New Jersey, 1990.

15. US Environmental Protection Agency. Compendium of methods for the determination of inorganic compounds in ambient air (in review) 1999.

16. Chia LS, Wong ML. Atmospheric pollution and its control in Singapore. Proc. Symp. on Our Environment, Singapore, 1977; 100-23.

17. Samah AA, Tick LJ. Investigation of transport of air pollution in the Klang Valley, Kuala Lumpur, Malaysia. J. Fiz. Mal. 1992;13: 18-28.

18. Nichol J. Bioclimatic impacts of the 1994 smoke haze event in Southeast Asia. Atmos Environ 1997;31: 1209-19.

19. Arnold S, Hague W, Pierce G, Sheetz R. The use of beta gauge monitors for PSI and every day SIP monitoring: an overview of the Denver experience. In: Chow JC, Ono DM (eds). PM_{10} Standards and Nontraditional Particulate Source Controls, an A&WMA/EPA International Specialty Conference, January, Scottsdale, AZ Pittsburgh, PA. Air & Waste Management Association 1992; 13-23.

20. Chow JC, Watson JG, Fujita EM, Lu Z, Lawson DR, Ashbaugh LL. Temporal and spatial variations of $PM_{2.5}$ and PM_{10} aerosol in the southern air quality study. Atmos Environ 1994;28: 2061-80.