Smoke-haze pollution: a review of the 1997 episode in Southeast Asia

A. Heil · J.G. Goldammer

Abstract In the second half of 1997, large areas in Southeast Asia were severely affected by a smoke-haze pollution episode caused by the emissions of an estimated 45,600 km^2 of vegetation that burnt on the Indonesian islands Kalimantan and Sumatra. To document the impacts of these fires on air quality, data for total suspended particulate matter (TSP) and for particulate matter below or equal to 10 microns in diameter (PM_{10}) from selected sites in Indonesia, Malaysia and Singapore are analysed in this paper. These data are supplemented by meteorological data, satellite images and a summary of related research. TSP was above 2,000 μg m^{-3} for several days in Indonesian locations close to the most extensive fire activity. In Malaysia and Singapore, ambient particle concentrations increased to several times their average September levels. Characteristically for emissions from vegetation burning, the additional atmospheric particle loading during the smoke-haze episode was predominantly due to an increase of the fraction below or equal to 2.5 microns in diameter ($PM_{2.5}$). Due to the dominance of respirable particles ($PM_{2.5}$) in the smoke-haze, air quality reporting based on TSP or PM_{10} may be inadequate to assess the health risk. Upgrading of $PM_{2.5}$ monitoring facilities is therefore needed. Reducing the probability of similar smoke-haze events in future would require appropriate fire use and smoke management strategies.

Keywords Southeast Asia · Vegetation fire 1997 · Air pollution · Particulate matter · Impacts

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Introduction

In Southeast Asia, there is a regular (periodic) incidence of fire-related regional air pollution episodes. Since the 1970s, nine such incidents have been reported (Singapore Meteorological Service 1995; World Meteorological Organisation 1998; Goldammer 1999), the most recent of which (i.e. in 1994 and 1997–1998) are frequently considered to be unprecedented in extent and intensity (Singapore Meteorological Service 1995; Nichol 1997; World Health Organization 1998; Levine et al. 1999). Meanwhile, the term 'haze' or 'smoke-haze' in Southeast Asia has become associated with fire-related, large-scale air pollution. For instance, the regional and national Haze Action Plans for the Association of Southeast Asian Nations (ASEAN) aim to prevent and mitigate regional air pollution from large-scale forest and land fires (Consultative Group on Indonesian Forestry 1998). However, the World Meteorological Organisation (WMO) (1992) defines haze as a suspension of extremely small, dry particles in the atmosphere and hence does not specify a specific source. Most of the extensive smoke-haze events in Southeast Asia resulted from fires that occurred mainly in Sumatra and the Kalimantan region of Borneo island (Dennis 1998; Radojevic and Hassan 1999). They generally occurred when the Southeast Asian weather was strongly influenced by the El-Niño Southern Oscillation (ENSO) event (World Meteorological Organisation 1998). During ENSO years, the above-normal atmospheric surface level pressure building up over the western Pacific region is coupled with a diminished upward motion. The ensuing reduction of convective activity results in abnormal drought throughout Southeast Asia, generally reaching its peak between July and September in Indonesia (Philander 1990). Throughout the tropical southern hemisphere, fires are set to clear vegetation during the relatively dry southern monsoon season from June to October (Olson et al. 1999). The burning activities usually cease by October/November when the gradually interspersing northern monsoon brings abundant rainfall. The prolonged drought during ENSO years increases the susceptibility of vegetation to

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fire, enabling the clearing and conversion of more land (Goldammer et al. 1996; Goldammer and Price 1998). Under these conditions, fires are also more likely to become uncontrolled. For these reasons, the area burnt in Indonesia and the amount of emissions produced may greatly exceed the normal annual total.

The low-level, southern monsoon wind circulation prevailing during the main burning season produces a northward, cross-equatorial transport of fire emissions from Indonesia, particularly towards Singapore, Malaysia and Brunei. Subsidence generally characteristic of the southerly monsoon (Depperman 1941) increases atmospheric stability and favours the accumulation of fire products in the lower atmosphere. The ENSO-related anomalies tend to reinforce the meteorological conditions contributing to the development of persistent regional haze. Diminished ascending motion coupled with increased atmospheric stability and inversions cause fire emissions to be more efficiently trapped in the lower troposphere than during non-ENSO years (Chandra et al. 1998; Ziemke and Chandra 1999). Reduced rainfall prolongs atmospheric residence time of fire products as they are less abundantly scavenged by precipitation. Anomalous easterly surface winds during August to October in a canonical ENSO year over the Malay–Indonesia region (Rasmusson and Carpenter 1982) may enhance the westward transport of pyrogenic emissions from Kalimantan towards Peninsular Malaysia and Singapore. In summary, because of increased fire and reduced dispersion, the regional smoke-haze events in Southeast Asia generally occur during the southern monsoon period in ENSO years (Singapore Meteorological Service 1995).

Despite the existing in-depth knowledge on fire and its underlying causes in Southeast Asian ecosystems (Goldammer and Peñafiel 1990; Goldammer and Seibert 1990; Stott et al. 1990; Goldammer 1993; Goldammer et al. 1996), little literature and research exist on the implications of vegetation burning in this region on atmospheric chemistry and public health (Goldammer 1997; Goldammer et al. 1997; Nichol 1997, 1998; World Health Organization 1998; Balasubramanian et al. 1999; Fujiwara et al. 1999; Geophys Res Lett 1999). This is mainly because the international fire-atmosphere science community has largely concentrated its research efforts on Africa and South America where regular wildland fire occurrence and land-use fire application created sufficient attention to set up focused research campaigns in the 1980s–1990s (J Geophys Res Special Issue 1996; Lindesay et al. 1996; International Global Atmospheric Chemistry 1998; cf. also Hao and Liu 1994; Board et al. 1999), but also due to the scarcity of air quality and meteorological data as well as of health statistics, notably in Indonesia.

In this paper we document the impacts of the vegetation fires in Indonesia in 1997 on air quality in Southeast Asia. Emphasis is given to the particulate emissions because they are by far the most important emission from a public health standpoint (Sharkey 1997). Data for particulate matter from selected sites in Indonesia, Malaysia and Singapore were obtained from the national routine air monitoring networks and are analysed in this work.

Biomass burning and atmospheric implications

Vegetation fires emit a wide spectrum of trace gases and aerosols (Andreae 1991; Yokelson et al. 1999). Gaseous compounds released include carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x), ammonia (NH_3), hydrogen (H_2) and a variety of hydrocarbons, e.g. methane (CH_4), formaldehyde and methyl chloride. Secondarily, ozone (O_3) can be formed downwind from fires through photochemical reactions involving NO_x and other biomass burning products (Crutzen and Carmichael 1993). Particulate fire emissions are largely (approx. two thirds) composed of carbonaceous material – organic carbon (OC) and elemental ('black') carbon (EC) – (Crutzen and Andreae 1990). Characteristically for combustion-derived particles, the bulk of the particle mass emitted (40 to 95%) is in the fine size range [particulate matter=2.5 μm in diameter ($PM_{2.5}$)] (Ward 1990; Novakov et al. 1997).

The emission production and characteristics from vegetation fires strongly depend on the combustion stage (basically flaming and smouldering combustion), the combustion efficiency and the physico-chemical properties of vegetation burnt (Lobert and Warnatz 1993). Large-diameter or densely packed necromass (such as logs, stumps or peat) and large-diameter live vegetation (trunks) are usually only partially consumed and mainly by smouldering combustion (Stocks and Kaufman 1997; Yokelson et al. 1997), in contrast to the small-diameter, dry, dead fuels (necromass) and low-density vegetation (such as grass and leaves). Characteristically for low-efficiency combustion processes, smouldering combustion emits larger amounts of incompletely oxidised compounds than flaming combustion per unit amount of biomass consumed by a fire. These incompletely oxidised compounds include CO, methane (CH_4) and other hydrocarbons, NH_3 as well as fine particles (with high OC and low EC content) (Lobert and Warnatz 1993 ; Ward et al. 1996). Fine particulate emission factors range from $\sim$3 g kg^{-1} fuel consumed in the flaming phase to $\sim$12 g kg^{-1} for smouldering combustion (Einfield et al. 1991). The fuel loads of different vegetation types, in turn, range from 2 t ha^{-1} for low-productivity grasslands in Africa (Hoffa et al. 1999) to as much as 97.5 t ha^{-1} (dry matter) for dry peat of 1.5-m thickness (Supardi et al. 1993); depending on site conditions and degree of pre-fire forest utilisation (logging) the total above-ground fuel loads in forest ecosystems may reach several hundreds of tons of dry organic matter per hectare.

The fate of the initial fire emissions depends strongly on both their composition and the regional state of the atmosphere. Once airborne, the particles begin to grow slightly in size as they age through condensation and coagulation. In addition, new fine particles are created by nucleation of gaseous fire emissions; such as the conver-

sion of NO_x to nitrates (Jänicke 1993). Particles are removed from the atmosphere by gravitational settling, precipitation and cloud scavenging. Because gravitational settling velocity increases with particle diameter, larger particles (particularly those with a diameter larger than 10 μm) are lost from the plume faster than smaller ones. Wet removal thus dominates the atmospheric lifetime of pyrogenic particles, which is therefore largely controlled by meteorology (Garstang et al. 1997). Ultimately, removal of trace gases from the atmosphere is mainly by oxidation processes (Crutzen and Carmichael 1993).

It was first recognised in the late 1970s that tropical vegetation burning is a major global source of trace gases and aerosols with significant impacts on regional and global climate, atmospheric chemistry and hydrological cycles (Crutzen et al. 1979); this has been confirmed by numerous studies during the 1980 and 1990s (Andreae 1998), which were synthesised in several review articles and monographs, e.g. by Crutzen and Andreae (1990), Goldammer and Crutzen (1993) and Levine (1996). Greenhouse gases released by the fires, such as CO_2, CH_4 and ozone, exert a permanent additional warming effect which conversely leads to changed climate–fire relationships in the tropics (Goldammer and Price 1998) and in other vegetation zones (Fosberg et al. 1996). Particulate emissions scatter and absorb incoming solar radiation both directly and indirectly through their role as cloud condensation nuclei, resulting in a global net cooling effect (Dickinson 1993; Charlson and Lelieveld 1994). Chemically active emissions may appreciably affect the oxidising efficiency of the troposphere (Crutzen and Carmichael 1993) and stratospheric ozone chemistry (Andreae 1991; Manö and Andreae 1994). It is estimated that the gross CO_2 emission from biomass burning (i.e. 13,500 Tg CO_2 year^{-1} (1 teragram=10^{12} g) contributes around 40% to the global anthropogenic annual gross release of carbon dioxide, while it accounts for roughly 43 and 23%, respectively, of CO and total particulate matter produced globally (Andreae et al. 1996).

Fire development in Indonesia in 1997 and emission production

Vegetation fires in Kalimantan and Sumatra started with the onset of the relatively dry season in May/June 1997 (Fang and Huang 1998; United Nations Disaster Assessment and Coordination Team 1998) and reached a maximum during September and October (Makarim et al. 1998). Many fires got out of control and affected the surrounding vegetation (logged forests, peat swamps and grassland) (Dennis 1998). Figure 1 shows the monthly distribution of fires on these islands in September and October as depicted as High-Temperature Events (HTEs or 'fire pixels') by the Along-Track Scanning Radiometer (ATSR) satellite instrument. It illustrates that the fire activity was mainly concentrated on the southeastern parts of Sumatra and southern Kalimantan during these months. According to Stolle et al. (1999), a remarkably dense time spacing in the number of HTEs was recorded in the week from 12 to 18 October 1997 in Sumatra. In Kalimantan, a peak in fire activity was noticed in late September (D. Fuller, personal communication 1999). By mid-November, fire activity gradually subsided along with the onset of the monsoonal rain.

Using SPOT 'quicklook' satellite images, Liew et al. (1998) estimated that an area of approximately 45,600 km^2 burnt from August to December 1997 in Kalimantan and Sumatra. The estimate of Liew et al. (1998) represents only a lower limit estimate since fires in other parts of Southeast Asia were not included. However, estimates of the area burnt vary significantly between different institutions (c.f. Levine et al. 1999).

Levine (1999a, 1999b) estimated the emission production resulting from the 1997 fires in Sumatra and Kalimantan. For his calculations, he used both the estimate of the area burnt and the estimate of the ecosystem burnt of Liew et al. (1998), which suggests that 20% of the area burnt consisted of peat swamp forests and the remainder of agricultural and plantation areas, forest and bushes. Levine assumed that the peat ignited everywhere and burned to a depth of 1 m. As a result of this and other assumptions, fires in peat swamp forests accounted for the largest part of the total emission production, with 89% for CO_2 and more than 93% for all other species. Levine proposes total emissions of 701.6 Tg CO_2, 76.5 Tg CO, 7.1 Tg O_3, 2.5 Tg CH_4, 3.1 Tg NH_3, 0.97 Tg N(NO_x) and 16.2 Tg particulate matter, and claims an uncertainty for these estimates of 50%. On the other hand, Nakajima et al. (1999) roughly estimated a total smoke aerosol production of 5.6 Tg for the entire burn, only, based on Advanced Very High Resolution Radiometer (AVHRR)-derived optical thickness distributions.

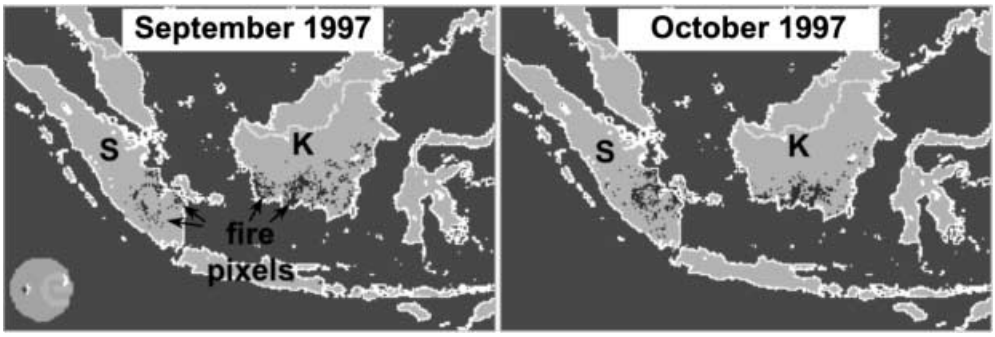

Fig. 1
Monthly night-time fire activity map of Kalimantan (*K*) and Sumatra (*S*) for September and October 1997 as depicted by the ATSR satellite instrument. (Adapted from Arino and Rosaz 1999)

Development of the smoke-haze layer and its physicochemical characteristics

Satellite images from September 1997 onwards reveal that the fire emissions formed a dense, widespread smoke-haze layer, merging together the plumes from many fires. Figure 2 shows examples of UV-absorbing aerosol index maps of the Southeast Asian region derived from the Total Ozone Mapping Spectrometer (TOMS) for early and late September 1997. Since the TOMS instrument measures the presence of aerosols in the whole atmospheric column with a height-dependent sensitivity, the ground concentrations cannot be inferred without assumptions on the vertical profile of the aerosol layer (J.R. Herman, personal communication 1999).

In early September (Fig. 2, left), the smoke-haze layer principally concentrated over the fire centres in southern Kalimantan and central Sumatra. On several days in late September (Fig. 2, right), the smoke-haze layer covered large parts of Kalimantan and Sumatra, Singapore and parts of Malaysia. Its northernmost extension reached as far as Thailand and the Philippines. After an intermediate decrease in early October, the smoke-haze layer increased again in the second half of October, but exhibited a stronger westward than northward component compared to September. The smoke-haze layer gradually disappeared in the first half of November along with the onset of the rainy season. Based on AVHRR-optical thickness distribution, Nakajima et al. (1999) estimated that the smoke-haze layer covered an area of up to 10 million km^2, with a peak enhancement in October. Increased TOMS tropospheric column ozone spread between 75–110°E and 10°S–8°N during that period (Chandra et al. 1998).

Several aircraft and ground-based measurements confirmed increases of biomass burning products in the troposphere. Within the smoke-haze layer in the southeast of Kalimantan, whose top was restrained below 4,000 m, CO mixing ratios around two orders of magnitude higher than the background level and enhanced concentrations of NO_x, hydrogen (H_2), O_3 and aerosols were measured in late October (Sawa et al. 1999; Tsutsumi et al. 1999). Enhanced trace gas concentrations such as CO, CO_2, CH_4 and O_3 were observed throughout the troposphere from eastern Java to the South China Sea south of 10°N between September and November (Fujiwara et al. 1999; Matsueda and Inoue 1999). The appearance of anomalous increases of CO in the upper troposphere (8–13 km) over the entire western Pacific region up to 20°S during September to November 1997 indicates that air masses influenced by the Indonesian fires reached well into the upper troposphere and were possibly transported through the upper levels towards the southern subtropics (Fujiwara et al. 1999; Matsueda et al. 1999).

The optical properties of the aerosols found during the smoke-haze episode point to predominantly smouldering rather than flaming combustion sources (Gras et al. 1999; von Hoyningen-Huene et al. 1999; Nakajima et al. 1999). The small visible light absorption found indicates a very small elemental carbon content in the aerosols, which is characteristic for aerosols derived from smouldering combustion (Yokelson et al. 1997). In addition, the aerosols exhibited a strong hygroscopic growth in scattering comparable to that of peat smoke. These findings, with other observations (e.g. Narukawa et al. 1999), indicate that much of the emissions were produced by smouldering combustion, which points to a significant contribution of emissions from peat fires. The latter is also supported by the high concentration of sulphate aerosols observed during the smoke-haze episode which are attributed to the strong sulphur emission from peat fires (c.f. Balasubramanian et al. 1999; Gras et al. 1999). Furthermore, Legg and Laumonier (1999) stated that the source of probably 90% of the smoke-haze were seven clusters of fires along the edges of degraded peat-swamp forests in southern Sumatra and Kalimantan.

Impacts on ambient air quality in Indonesia and neighbouring countries

The influence of the vegetation fires on ambient air quality in Southeast Asia was discernible by July 1997, peaked in September and decreased towards the beginning of the

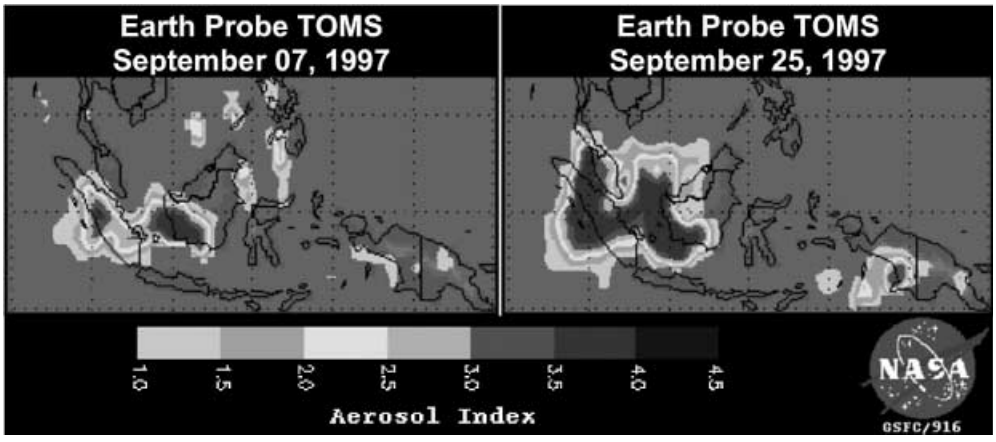

Fig. 2
Total Ozone Mapping Spectrometer (TOMS) aerosol index maps of Southeast Asia for 7 September 1997 (*left*) and 25 September 1997 (*right*). (Courtesy of Laboratory for Atmospheres, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA)

rainy season in November (Department of Environment 1998; Fang et al. 1999). Similar to other smoke-haze episodes, the pollutant that consistently increased above national ambient air quality thresholds during the 1997 smoke-haze episode was particulate matter (Department of Environment 1998; Emmanuel and Lim 1998; Phonboon 1998; World Health Organization 1998; Radojevic and Hassan 1999). In Singapore, Malaysia and Thailand, gaseous compounds remained generally below the respective national air quality guidelines, although a partial increase of compounds such as CO, O_3 and SO_2 was observed (Brauer 1997; Department of Environment 1998; Emmanuel and Lim 1998; Phonboon 1998; Davies and Unam 1999).

Air quality monitoring and data source

Indonesia does not yet have an integrated monitoring network which could provide real-time, region-covering air quality information (Ferrari 1997; Kandun 1998). Only in some provinces is air pollution monitored on behalf of the Meteorological and Geophysical Agency (BMG) and the Ministry of Health (MoH), and generally only discontinuously and solely for total suspended particles (including particles up to diameters of ~40 μm). As a surrogate, impairment of visibility was widely used as an indicator for ambient air quality during the smoke-haze episode. However, visibility is not only dependent on particle concentration, but also on the subjective perception of the observer, relative humidity and light conditions.

A more advanced air quality monitoring network is in place in Malaysia and Singapore. For reporting, Singapore adopted the pollutant standard index (PSI) used by the US Environmental Protection Agency (USEPA) until recently (c.f. US Environmental Protection Agency 1994, 1999), while Malaysia employs an air pollutant index (API) based on similar principles (Radojevic 1998). The pollutant index includes sub-indices for particulate matter, O_3, CO, SO_2 and NO_2, which relate ambient pollutant concentrations to index values on a scale from 0 through 500. The upper bound index value of 500 is set at a level that represents an imminent and substantial endangerment to public health (significant harm level). During smoke-haze episodes, the PSI or API is invariably based on particulate matter concentrations, monitored as PM_{10} (particulate matter with an aerodynamic diameter ≤ 10 μm, 24-h average), as these greatly exceed those of other pollutants (Radojevic and Hassan 1999). A pollutant index from 0 to 100 is described as 'good' to 'moderate' (corresponding to $PM_{10} \leq 150$ μg m^{-3}), an index value up to 200 as 'unhealthy' ($PM_{10} \leq 350$ μg m^{-3}), to 300 as 'very unhealthy' ($PM_{10} \leq 420$ μg m^{-3}) and an index from 301 to 500 as 'hazardous' ($PM_{10} \leq 600$ μg m^{-3}) (US Environmental Protection Agency 1994). In Singapore and Malaysia, the national ambient air quality guidelines for PM_{10} (24-h average) coincide with a PSI/API value of 100. In Indonesia, the national ambient air quality standard for particulate matter is 260 μg m^{-3} TSP (24-h average) (Department of Environment 1995; Ferrari 1997).

To document the impacts of the 1997 vegetation fires on ambient particle concentration in Southeast Asia, 24-h average particle measurement data from selected stations in Indonesia, Malaysia and Singapore were compiled (Fig. 3). TSP and PM_{10} records for Indonesia originate from the Ministry of Health (MoH) and from a special air-quality monitoring campaign on behalf of the Environmental Impact Management Agency (BAPEDAL), respectively. TSP and PM_{10} records for Malaysia were obtained from the Malaysian Meteorological Services (MMS) collected at meteorological sites as a part of their routine air monitoring program. The recording is daily at Kuching and Petaling Jaya and every second day at the other locations. PM_{10} data for Singapore are converted from the daily PSI readings provided by the Ministry of the Environment (MoE), Singapore, which are derived from 12 ambient air monitoring stations throughout the island (Emmanuel and Lim 1998). Information on the range of uncertainty of the measurement results was not provided. However, according to Ferrari (1997), both Singapore and Malaysia use effective internationally accepted quality

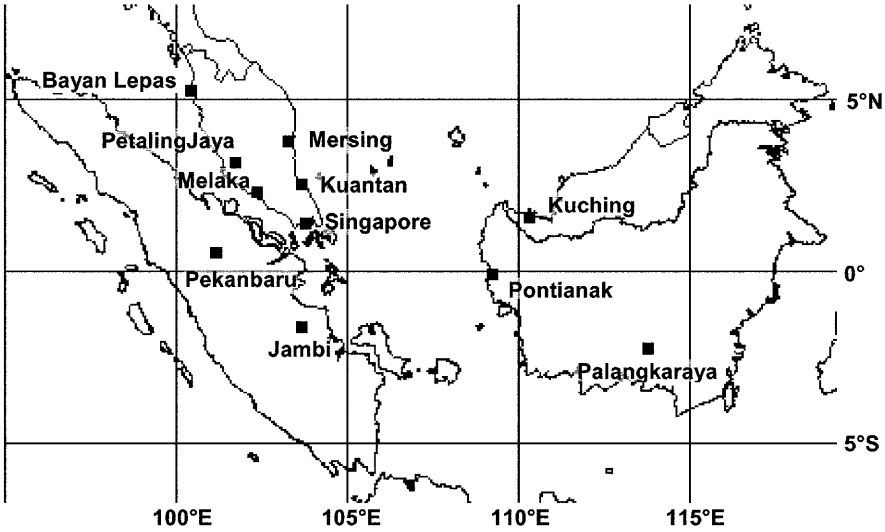

Fig. 3
Map showing the locations mentioned in this paper

assurance procedures on data before reporting. Visibility records from the meteorological stations at the selected sites were provided by the respective meteorological services [BMG, MMS and Meteorological Services Singapore (MSS)]. In Indonesia, visibility records were based on observations taking place at 3-h intervals; in Malaysia and Singapore (Changi Airport Station), there were hourly records.

Development of ambient particle concentration

The development of ambient particle concentration as well as of daily mean horizontal visibility at selected sites in Indonesia, Malaysia and at Singapore during the second half of 1997 is displayed in Figs. 4 and 5. Scanty particle measurement data at hand for the four locations in Kalimantan and Sumatra (Fig. 4) indicate that ambient particle concentration was above 2,000 μg m^{-3} TSP on several days in late September and October, with the highest concentrations (up to around 4,000 μg m^{-3} TSP) recorded at locations in the vicinity of the main fire activity (Palangkaraya and Jambi). Monthly mean horizontal visibility declined from above 5 km to around 1 km in Pontianak and Pekanbaru in July and to around 0.5 km in Palangkaraya and Jambi in September. Whereas at the first two locations, monthly mean visibility increased to 2.2–2.7 km in October, it remained below 1 km at Palangkaraya and Jambi until it sharply increased to above 6 km in mid-November. While particle measurement data are generally missing for the period before late September, impaired visibility suggests that ambient particle concentration had already exceeded background levels by late July/August. In Kuching (Fig. 4), north-western Borneo-Malaysia, ambient particle concentration rose gradually from background levels [around 60 μg m^{-3} TSP (Department of Environment 1996)] in the first half of July to 290 μg m^{-3} TSP in the second half of August, reaching a peak value of

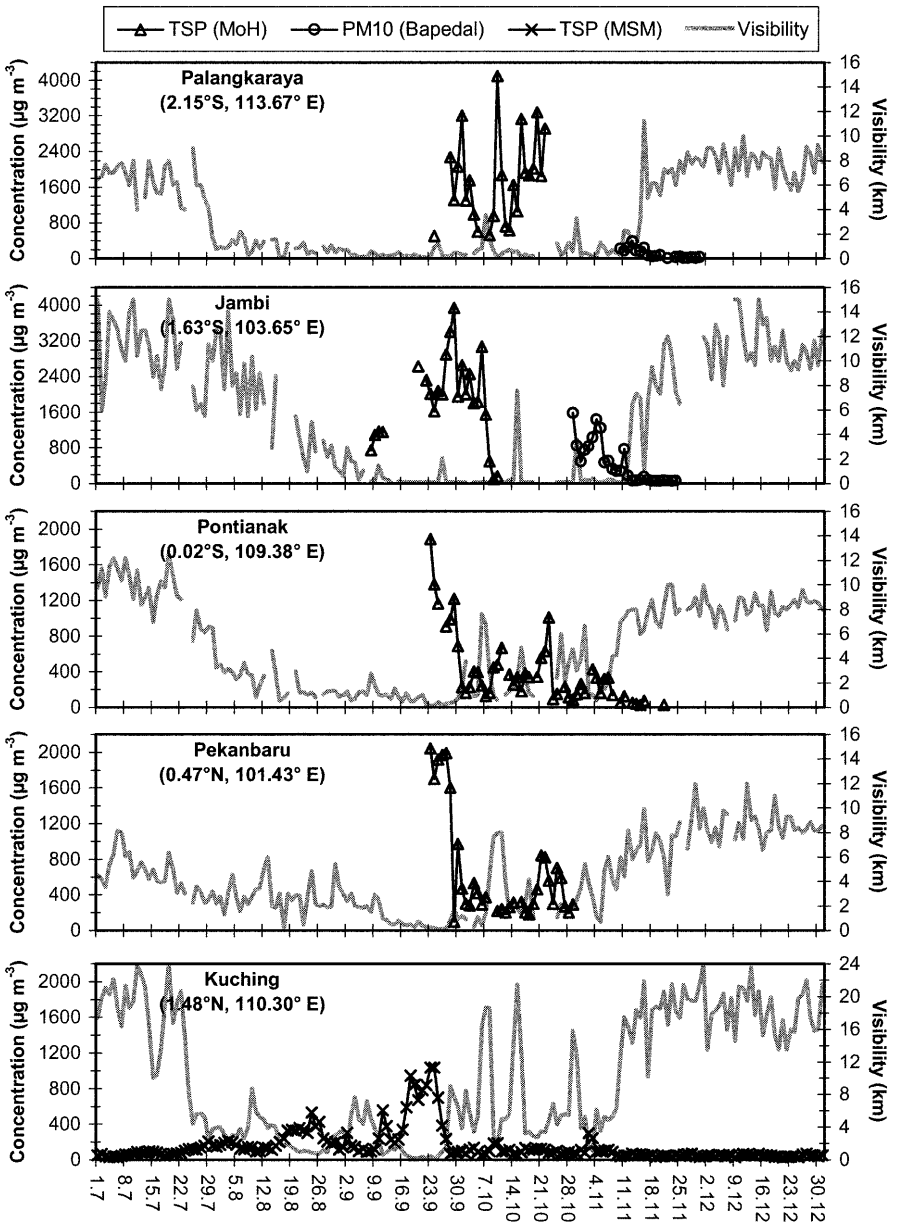

Fig. 4
Development of ambient particle concentration (TSP and PM_{10}) and daily mean horizontal visibility at selected locations in Kalimantan and Sumatra as well as at Kuching, Borneo-Malaysia, during the second half of 1997. (Data source: MoH, Bapedal, BMG, MMS)

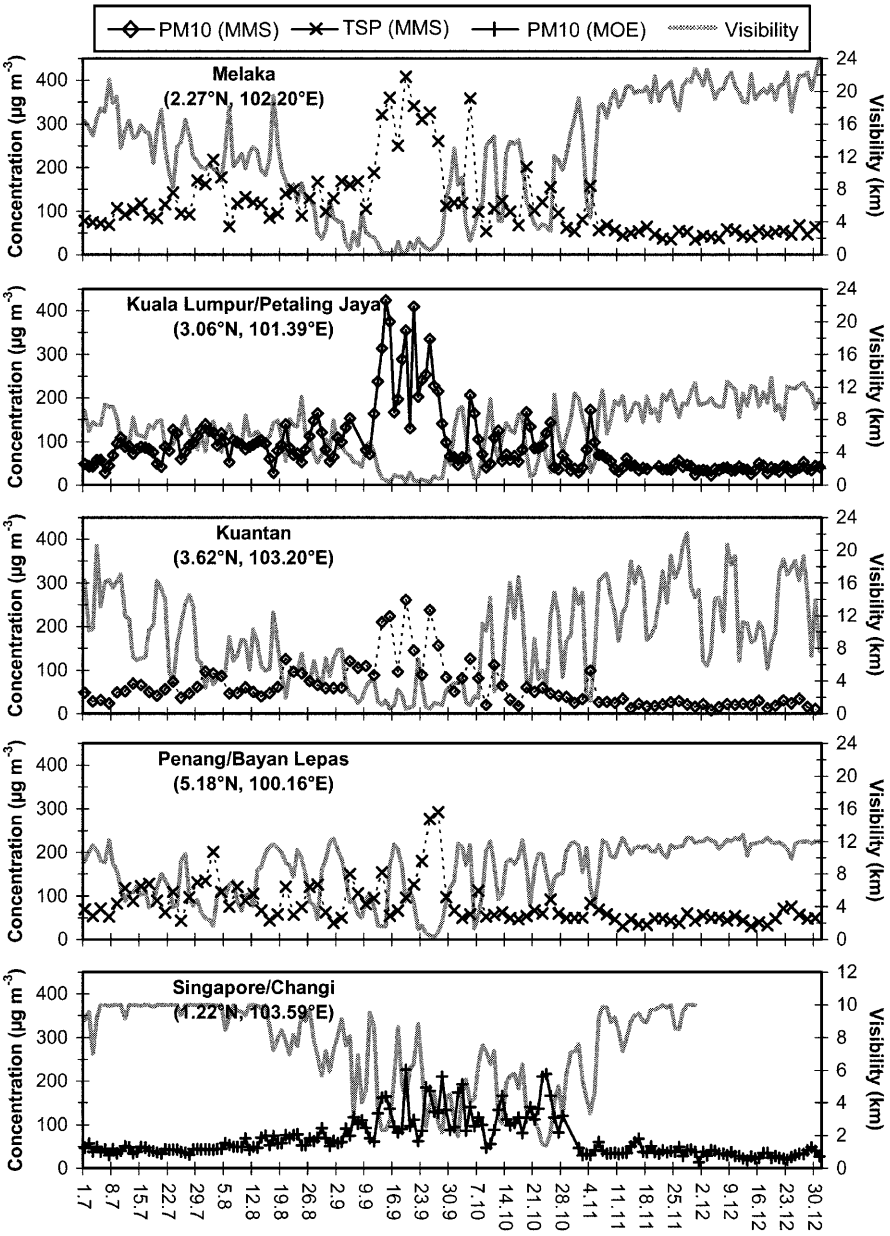

Fig. 5
Development of ambient particle concentration (TSP and PM_{10}) and daily mean horizontal visibility at selected locations in Peninsular Malaysia as well as in Singapore during the second half of 1997. *Dotted line* if records every second day only. (Data source: MMS, MSS, MoE)

529 µg m^{-3} TSP on 24 August. Inversely, daily mean horizontal visibility declined from above 18 km to below 2 km during that period. After an intermediate decline in early September, TSP concentration rose sharply above 590 µg m^{-3} between 17 and 25 September. On 23 and 24 September, a peak concentration of 1,030 µg m^{-3} TSP was recorded; the Ministry of Environment reported 930 µg m^{-3} PM_{10} on 24 September (Brauer 1997). Daily mean visibility during this peak episode was below 0.5 km, with hourly minima below 100 m. In the subsequent time until mid-November, TSP concentration fluctuated between 40 and 300 µg m^{-3} (mean of 100 µg m^{-3} TSP) and finally returned to rainy season background conditions from mid-November onwards.

Similar to the development in Kuching, particle concentration at all locations in Peninsular Malaysia exhibited a distinct rise during September, notably between 11 and 28 September (Fig. 5). It was preceded by a gradual, but highly fluctuating increase from July till August. From October to mid-November, particle concentration decreased all over, though still exhibiting high fluctuations, and remained almost constant at approximate background levels in the subsequent period. The highest particle concentration in September was recorded at Melaka (TSP) and Petaling Jaya/Kuala Lumpur (PM_{10}), both at the southern west coast of Peninsular Malaysia approximately 400–800 km north of the main fire activity in Sumatra. Peak values ranged between 300 and 420 µg m^{-3} on several days, and monthly mean particle concentration in September between 210 and 240 µg m^{-3} TSP/PM_{10}, compared to 40–50 µg m^{-3} in December. At both locations, monthly visibility averaged 2.2–2.3 km in September, with daily minima below 0.4 km during the peak episode. In Petaling Jaya, a total of 22 days exceeded 150 µg m^{-3} PM_{10}

('unhealthy'), 4 days of which were in the 'very unhealthy' to 'hazardous' range (PM_{10} above 350 μg m^{-3}).
More distant from fires, at Bayan Lepas/Penang, around 270 km north-north-west of Kuala Lumpur, particle concentration exhibited a lower increase than in the south. Particle concentration averaged 125 μg m^{-3} TSP in September, compared to 50 μg m^{-3} TSP in December. Accordingly, the impairment of visibility in September (average 4.8 km) was less pronounced at Bayan Lepas.
Kuantan, on the east coast of Peninsular Malaysia, exhibited a particle development similar to Petaling Jaya, but at a lower concentration range. Monthly mean particle concentration in September in Kuantan was 135 μg m^{-3} PM_{10} (maxima between 210 and 260 μg m^{-3} PM_{10}), compared to 20 μg m^{-3} in December.
Contrary to the development at all selected locations in Malaysia, particle concentration in Singapore was slightly higher in October (mean of 120 μg m^{-3} PM_{10}) than in September (110 μg m^{-3} PM_{10}). In September, it was also lower than in Petaling Jaya, Melaka or Kuantan, in spite of Singapore's close position to fires in Kalimantan and Sumatra. Consistently, horizontal visibility exhibited its low in October, averaging 4.3 km at Changi Station and 2.6 km at Tengah Station in Singapore's west. On 12 days, particle concentration was between 151 and 226 μg m^{-3} PM_{10} ('unhealthy') in Singapore during the smoke-haze episode.
Figures 4 and 5 show that day-to-day particle concentrations vary substantially in response to spatial and temporal changes of meteorological factors, such as wind conditions and intermediate rainfall, and of fire activity. However, throughout the fire episode, particularly between July and September, the southern Peninsular Malaysia locations Petaling Jaya, Melaka and Kuantan exhibited a largely coherent particle concentration development with correlation coefficients r above 0.7. This suggests that these locations were influenced by a similar wind and transmissions pattern. Such a correlation could not be found for Singapore, indicating that it was influenced by a special wind and transmission pattern.
In September and October, monthly mean surface wind speed was below 1.6 m s^{-1} at all sites, as displayed in Figures 4 and 5, except at Singapore Changi Station in September (3.2 m s^{-1}). These predominantly light surface wind conditions, characteristic for the transitional monsoonal period (Ramage 1971), provided unfavourable conditions for the dispersion of advected pyrogenic pollutants and of local vehicular or industrial emissions. The smoke-haze layer may also have contributed to the accumulation of pollutants near the surface by lowering radiative daytime warming of the surface and a decreasing convective mixing.
Though fire activity [by fire counts (Makarim et al. 1998)] and thus emission production were approximately similar in September and October, particle concentration at all locations in Malaysia was lower in October. This indicates a weakened cross-equatorial transport of pyrogenic emissions to Malaysia along with the retreating influence of the southerly monsoonal flow. According to von Hoyningen-Huene et al. (1999), the general weather situation in August and September was influenced by more frequent south-southeasterly winds compared to October, when a southeasterly flow was predominant. Back trajectory calculations made by the MMS indicate that in October southeasterly winds mainly transported pyrogenic emissions from fires in southern Kalimantan to Peninsular Malaysia, while south-southeasterly wind directions in August and September also transported stronger haze from fires at Sumatra to the Malaysian Peninsular (von Hoyningen-Huene et al. 1999). Considering the long distance from fires in Kalimantan to Peninsular Malaysia, increased dispersion and physicochemical removal processes of smoke plume constituents during transport may have contributed to lower ambient particle concentrations in October.
It appears that tropical cyclones in the South-China Sea generally enhancing the southerly monsoonal flow (Ramage 1971) contributed to an intermediate strengthening of the cross-equatorial transport of pyrogenic emissions during the smoke-haze episode (Awang 1998; Phonboon 1998). For instance, the simultaneous peak in particle concentration recorded at all locations in Malaysia and southern Thailand in late September as well as the final peak on 4 November (Fig. 5) coincided with a developing tropical cyclone close to Vietnam. Such a connection between tropical cyclones and increased particle concentration was also observed during the 1994 smoke-haze event (Singapore Meteorological Service 1995).

Physicochemical characteristics of the smoke-haze particles

The particle size distribution of the 1997 smoke-haze, an important parameter with respect to health impacts, atmospheric residence time and visibility impairment, was poorly investigated. Simultaneous PM_{10} and TSP measurements at the MMS site in Petaling Jaya/Kuala Lumpur show a clear trend to higher PM_{10}/TSP ratios when PM_{10} concentration increased during the smoke-haze episode 1997. Table 1 shows that from July to mid-November ('haze episode'), the PM_{10} fraction contributed on average 66% to the TSP mass. At concentrations exceeding 150 μg m^{-3} PM_{10} ('PM_{10} >150'), the PM_{10}/TSP ratio ranged between 70 and 93% (mean 78%). During 'post-haze' conditions (mid-November to December), it was only 46%. The fraction TSP minus PM_{10} remained almost constant during and after the smoke-haze episode

Table 1
Concentrations of PM_{10} and TSP during and after the smoke haze episode at Petaling Jaya, 1997 (see text). Mean (and range) concentrations in μg m^{-3}

	Haze (1 Jul–15 Nov)		Post-haze (16 Nov–31 Dec)
	Total	PM_{10} >150	Total
PM_{10}	107 (28–424)	247 (153–424)	38 (22–56)
TSP	155 (52–525)	314 (204–525)	83 (51–117)
PM_{10}/TSP (%)	66 (26–93)	78 (70–93)	46 (33–70)

(48 versus 45 μg m^{-3}); apparently, the increase in TSP concentration was almost entirely attributed to the PM_{10} fraction.

Tang and Orlic (unpublished data) monitored $PM_{2.5}$ and PM_{10} from January 1996 to December 1997 in Singapore. Before the smoke-haze episode, the $PM_{2.5}/PM_{10}$ ratio averaged 54% (mean $PM_{2.5}$=27 μg m^{-3}, mean PM_{10}=50 μg m^{-3}), whereas the ratio increased to 81% during the smoke-haze episode (mean $PM_{2.5}$=89 μg m^{-3}, mean PM_{10}=110 μg m^{-3}). In agreement, sky radiance measurements in Singapore and Kuala Lumpur showed that the volume size distribution of the smoke-haze aerosols tended to have a submicron peak around 0.25 μm (von Hoyningen-Huene et al. 1999; Nakajima et al. 1999). These size distribution measurements clearly indicate that higher TSP levels during the 1997 smoke-haze event were mainly attributed to the finer particle fraction ($PM_{2.5}$ and PM_{10}, respectively), resulting in higher PM_{10}/TSP and $PM_{2.5}/PM_{10}$ ratios than normal.

Inorganic and organic components of airborne particulate matter were analysed in Singapore and Kuala Lumpur (Fang et al. 1999; Narukawa et al. 1999; Orlic et al. 1999). During the smoke-haze episode, an increase in typical tracer for biomass burning, such as potassium (K), and vascular plant wax was observable, while typical vehicular or terrestrial fingerprint remained almost constant or decreased; apparently, related particle sources did not increase during the haze episode. Consequently, it was suggested that biomass burning made up a substantial contribution to the local aerosol loading.

Impacts of the smoke-haze event

The 1997 smoke-haze episode constituted an acute health risk to the public (World Health Organization 1998), exposing almost 100 million people in five countries in Southeast Asia to increased air pollution (Phonboon 1998). An estimated 20 million suffered from respiratory problems in Indonesia alone (World Health Organization 1998). The pollutant of major concern in respect to adverse health outcomes was particulate matter (World Health Organization 1998), especially the fine particle fraction.

Numerous recent epidemiological studies (e.g. Ostro 1993; Dockery and Pope 1994; Schwartz 1994) have shown consistent, statistically significant associations between increased daily aerosol loadings at levels typical of modern cities and morbidity and mortality – with no apparent threshold. They came to the conclusion that a 10-μg m^{-3} increase in PM_{10} is associated with a 1% increment in daily mortality. Schwartz et al. (1996) suggested that increased daily mortality is specifically related to $PM_{2.5}$, and not to the coarse fraction of PM_{10} ($PM_{10-2.5}$). Fine particles may penetrate into the lower respiratory tract ('respirable fraction'), where they are retained for a long period, whereas the larger particles are predominantly deposited in the upper respiratory system (Deutsches Institut für Normung 1996). Acute morbidity outcomes resulting from the exposure to particulate air pollution include respiratory symptoms, cardiovascular diseases and decreased lung function. For instance, studies have observed increases in respiratory hospital admissions and emergency department visits by ~1% per 10-μg m^{-3} PM_{10} increment (Dockery and Pope 1994). In addition to the acute effects of particulate exposure, chronic respiratory diseases such as chronic bronchitis and permanently decreased lung function are likely to follow (Schwartz 1993). Generally, individuals with pre-existing respiratory or cardiac diseases, but also elderly people and children, are most susceptible to adverse health outcomes (Schwartz 1994). Responding to these epidemiological findings, the US Environmental Protection Agency revised the national air quality standards for particulate matter and included thresholds for $PM_{2.5}$ (e.g. 65 μg m^{-3} $PM_{2.5}$ as 24-h average) (US Environmental Protection Agency 1999).

While biomass burning particles were not specifically tested in the above (or other) epidemiological studies they could certainly have similar health impacts. Not surprisingly, an increase in adverse health outcomes was observed in all countries affected by the 1997 smoke-haze event (Brauer 1997; Awang et al. 1998; Emmanuel and Lim 1998; Kandun 1998; World Health Organization 1998). The most frequent symptoms were asthma, upper respiratory tract illness and eye and skin irritations. In Kuching, outpatient visits increased two- to threefold during the main haze episode, and daily respiratory disease outpatient visits to Kuala Lumpur General Hospital rose from 250 to 800 (World Health Organization 1998). In Singapore, hospital attendances for haze-related conditions rose by 30%; an increase in PM_{10} levels from 50 to 150 μg m^{-3} was associated with increases of 12% of upper respiratory tract illness, 19% of asthma and 26% of rhinitis (Emmanuel and Lim 1998).

To alleviate the health impact, the governments recommended the public to remain indoors as much as possible, use air conditioning, wear respiratory masks and avoid physical exertion (World Health Organization 1997). In Sarawak (Borneo), the Malaysian province most severely affected by pyrogenic emissions, a state of emergency was proclaimed on 19 September 1997 for 10 days, during which schools, public offices and factories were closed (Department of Environment 1998). However, it is uncertain to what extent these measures can provide protection (Brauer 1998; World Health Organization 1998). Moreover, large parts of the population can neither afford to refrain from outdoor work nor to purchase protective tools. Finally, some regional governments and populations may consider these health impacts to be minor in the context of widespread sub-optimal nutrition, starvation, malaria, cholera, dengue fever, typhoid fever and other diseases.

Besides health impacts, impaired visibility seriously affected the economies of Indonesia, Singapore and Malaysia. Land, air and marine traffic was restricted, tourism revenues, industrial activity and fishing declined (Economy and Environment Program for South East Asia/World

Wide Found for Nature 1998; Hassan et al. 1998). An airline crash in September in northern Sumatra caused 234 deaths and ship collisions in the Strait of Malacca killed dozens; all were partly attributed to impaired visibility (Simons 1998). A reduction of the downward solar flux due to the smoke-haze layer (Nichol 1997; Herman et al. 1999; Ilyas et al. 1999) may also affect crop growth. For instance, Davies and Unam (1999) observed a 45–92% reduction in photosynthetically active radiation on hazy days in Kuching in 1997.

The Economy and Environment Program for South East Asia/World Wide Found for Nature (1998) roughly estimated the economic value of the damages caused by the 1997 fires and haze. They attributed 1 billion US$ to haze-related damages for Indonesia alone and for Malaysia and Singapore 0.4 billion US$. Including the fire-related damages, the total damages amount to 4.5 billion US$. However, due to insufficient data for Indonesia and parts of Malaysia, air pollution levels used for the assessment of the short-term health effects were derived from TOMS aerosol index maps, which do not necessarily reflect the real exposure during the smoke-haze.

Conclusions and recommendations

The transboundary character of the 1997 smoke-haze event reveals that land and forest fires in Indonesia have an important international dimension in relation to severe air pollution. In Indonesia and parts of Malaysia, particulate air pollution reached levels considered as an imminent and substantial endangerment to public health (PSI=500). However, due to the scarcity of air pollution data and health statistics, notably for Indonesia, an assessment of the exposure and adverse health outcomes resulting from the 1997 smoke-haze episode is limited. Nevertheless, there is every indication that the increased particle exposure during the smoke-haze also brought about premature deaths, in addition to the observed morbidity outcomes. Whereas the risk of long-term effects due to a single smoke-haze air pollution episode is even more difficult to detect than acute health outcomes, the repeated exposure of the Southeast Asian population to smoke-haze merits attention (World Health Organization 1998). Furthermore, these episodes add to the already existing air pollution emanating from other sources in this region, which, in turn, is expected to aggravate along with the continuing industrial development (Arndt et al. 1997; van Ardenne et al. 1999). For instance, already now, annual mean TSP and $PM_{2.5}$ in the city centre of Jakarta exceeds 400 and 50 $\mu g\ m^{-3}$, respectively (World Health Organization and United Nations Environmental Programme 1992; Gras and Cohen 1997). However, in regions in Brazil and Africa heavily influenced by biomass burning, $PM_{2.5}$ concentration may even reach $\sim$5,000 $\mu g\ m^{-3}$ (R. Yokelson, personal communication). Further epidemiological studies are required to assess the extent of the smoke-haze-related health impacts. Recent information is provided by the World Health Organization "Guidelines for Vegetation Fire Events", including the background papers by Goh et al. (1999) and Schwela et al. (1999).

The limited data available on the status of air quality in Indonesia and other countries affected by the smoke-haze demonstrates the need for a general upgrade of the national air quality monitoring facilities. This also applies to health statistics and the meteorological network. Enhanced co-ordination and networking among the smoke-haze-affected countries, including a standardisation of measurement and reporting procedures, could improve the management of smoke-haze events and support decision-making. Consistent region-covering air quality information and health statistics will not only provide the basis for an assessment of the health effect; the dissemination of real-time air quality information to the public may also contribute to increased transparency and environmental awareness in respect of fire-related air pollution and air pollution in general.

Of particular concern regarding adverse health impacts is the predominance of fine, respirable particles ($PM_{2.5}$) in the smoke-haze. Due to the resulting above-normal $PM_{2.5}$/PM_{10} and PM_{10}/TSP ratios, ambient air quality reporting and standards based only on PM_{10} – and especially TSP – may be inadequate for smoke-haze episodes and may give a false sense of security. It would therefore be necessary to elaborate adequate PM_{10} and/or TSP standards for smoke-haze conditions; the best would be to measure and report $PM_{2.5}$ directly.

Even though most of the impacts of the 1997 fire and smoke-haze episode remain unknown, the observed ones call for an immediate revision of the current land conversion and fire-use policies to prevent the reoccurrence of similar episodes. Ground-based and airborne investigations of the smoke-haze in 1997 indicated that fires on peat swamp vegetation made a substantial contribution to the smoke-haze development, but, however, are estimated to have contributed only 20% to the total area burnt. Given this apparent particular relevance of peat swamp fires to the development of transboundary smoke-haze, emission reduction and control strategies will have to focus on the prevention of fires in this type of vegetation as a matter of priority. Controlling future smoke-haze events and air pollution not only will be crucial for public health, but also represents a beneficial factor for economic prosperity in the future.

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