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ORIGINAL ARTICLE

Indonesian peat and vegetation fire emissions: Study on factors influencing large-scale smoke haze pollution using a regional atmospheric chemistry model

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Abstract Numerical modelling of fire-related smoke haze episodes in Southeast Asia is important for both prediction and assessment of atmospheric impacts, especially when observational data are fragmentary, as is the case in Indonesia. This work describes the atmospheric fate of smoke particles emitted during the 1997 Indonesian fires modelled with a regional atmospheric chemistry model. We established a new fire emission inventory and calculate that 55 teragram (Tg) of particulate matter and 1098 Tg of carbon were released during this fire episode. Our emission estimate is an intermediate value compared with other studies. Utilising different scenarios, we demonstrate the variable atmospheric impacts of surface vegetation fires and peat soil fires separately and also investigate the sensitivity of smoke dispersion to the differing meteorological conditions of an El Niño and a normal year. When peat fires are included in the emission inventory, modelled ambient particle concentrations exceed the ambient air quality standard across transboundary scales. In a scenario including only surface vegetation fires, ambient air quality standards are exceeded only in areas close to the main fires. This scenario demonstrates the prominent role of fires in peat areas in causing regional air pollution episodes. In years with normal meteorological conditions, intermittent precipitation and associated wet deposition during the dry season are predicted to remove most of the particulate emissions close to the sources. Strongly reduced rainfall and generally stronger southeasterly winds during El Niño years provide favourable conditions for larger scale smoke haze pollution.

Keywords Air pollution · El Niño · Regional atmospheric chemistry model · Smoke dispersion · Southeast Asia · Vegetation and peat fires

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1. Introduction

Vegetation and peat fires in Indonesia are an important factor when dealing with transboundary air pollution in the Southeast Asian region. Particulate matter emitted by the fires is the dominant pollutant causing exceedances of ambient air quality thresholds on a regional scale (e.g., Heil and Goldammer 2001). In the El Niño year 1997, Indonesia experienced abnormal drought conditions, and the number of land clearing fires by far exceeded the normal annual dry season's burning. Land clearing fires mainly in southern Kalimantan, Sumatra, and Irian Jaya, which started with the onset of the relatively dry season in May/June 1997, progressively raged out of control in the following months and affected the surrounding vegetation. Kirono et al. (1999) noted that during the 1997 El Niño, virtually the entire country had rainfall below the 10th percentile, with many locations receiving the lowest rainfall on record since 1950. These conditions contributed to a pronounced lowering of the water table in peat soils (Usup et al. 2000), making not only drained but also undrained peat soils susceptible to shallow peat fires (Zoltai et al. 1998).

The emissions released by the 1997 fires caused a regional air pollution episode with tremendous impacts on human health, visibility, and economy, and influenced regional to possibly global climates (ADB/BAPPENAS 1999; Rosenfeld 1999; Heil and Goldammer 2001; Page et al. 2002). Up to 300 million people across the Southeast Asian region were exposed to elevated particle levels during this episode. Up to five times the normal number of cases of respiratory diseases were observed in Malaysia in September alone (Awang et al. 2000). Severe transboundary smoke haze episodes have been recorded in earlier El Niño years as well. Particulate matter levels during the 1991 and 1994 smoke haze episodes in the Malaysian Klang Valley region, for example, were more than two times the ambient air quality standard for PM_{10} (particulate matter smaller than 10 μm diameter) (Soleiman et al. 2003). Even in 'normal' (non-El Niño) years, fires in Indonesia adversely affect particulate air quality in Indonesia and in neighbouring countries. The atmospheric impacts of these smoke haze events are less severe, but they remain important for public health, as any increase in airborne particle levels enhances the risk of exposed populations to increased morbidity and mortality – even at concentrations below regulatory limits. A 10 $\mu g/m^3$ increase in daily PM_{10} levels, for example, has been found to increase daily mortality by around 0.5% and hospital admissions for respiratory diseases by up to around 1.5% (Brunekreef and Holgate 2002, and references therein). Several studies have demonstrated that fires in peat areas are of particular importance for overall fire emission production as fires in peat areas may release up to 50 times (and more) higher emissions per unit area burnt than fires in surface vegetation (Levine 1999; Page et al. 2002). Peat areas have been estimated to account for 3% of the total area burnt in 1994, yet to produce 55% of total soot emissions (Nichol 1997), and to account for 20% of the total area burnt in 1997 while producing 94% of total emissions (Levine 1999). Page et al. (2002) have estimated that 480–2570 Tg of carbon (C) were released during the 1997 peat and forest fires, with the overlying vegetation contributing only 19%. For smoke haze management and mitigation measures it is important to discriminate between fires from surface vegetation and peat soil. To learn more about each type of fire we modelled the atmospheric impacts of emissions from each source separately.

Modelling the atmospheric distribution of fire aerosols from Indonesian fires is particularly important for air quality forecasts and impact assessment because region-covering, continuous, and directly accessible air quality information is lacking. Several numerical models have been applied to investigate the smoke haze in this region. An extensive discussion is provided in Radojevic (2003). For example, Koe et al. (2001) and Roswintiarti and Raman (2003) modelled the transport of emissions from the main fire locations in Indonesia in 1997.

These studies did not, however, establish a quantitative emission scenario and therefore did not model absolute concentrations of pollutants. The same applies to the model study on smoke dispersion during 1998 to 2000 by Keywood et al. (2003). All of these studies confirmed the large-scale transport of fire emissions from Indonesia to neighbouring countries. Recently, Langmann and Heil (2004) investigated the atmospheric implications of a lower and high emission scenario, which largely followed the estimate of Levine (1999) and Page et al. (2002). In this study, we model the atmospheric impacts of the 1997 Indonesian fires using an intermediate emission scenario and address in detail the influence of the climate factor El Niño on smoke haze distribution.

2. Methods

2.1. Model description

REMO (REgional MOdel), a three-dimensional regional scale atmospheric chemistry module (Langmann 2000), is applied to study the atmospheric transport and removal of aerosols emitted from the Indonesian fires in the second half of 1997. In this setup, REMO determines at each model time step the physical and chemical state of the model atmosphere, while the dynamical part of the model uses physical parameterisations from the global ECHAM4 model (Roeckner et al. 1996; Jacob 2001). REMO has three types of convection: penetrative, shallow, and mid-level convection. Only one scheme is allowed in a grid cell. The parameterisation of the convective clouds is based on the mass flux concept from Tiedtke (1989) with changes in the deep convection. In the current model setup, atmospheric aerosol is the only prognostic species included, which is represented without further differentiation according to chemical composition and size distribution. Although secondary aerosol formation may play an important role, it is not included in the present study.

The particle transport is determined by horizontal and vertical advection according to the algorithm of Smolarkiewitz (1983), convective up- and downdraft by a modified scheme of Tiedtke (1989), and vertical diffusion after Mellor and Yamada (1974). Because of the elevated sulphur content and hygroscopicity of Indonesian vegetation and peat fire aerosols (Ikegami et al. 2001) particle deposition is calculated as for sulphate. Dry deposition velocities are determined as described by Walcek et al. (1986), dependent on friction velocities and stability of the lowest model layer. Wet deposition is computed according to Walcek and Taylor (1986) by integrating the product of the grid-averaged precipitation rate and the mean cloud water concentration, assuming 100% solubility of the particles. The REMO model was applied with 20 vertical layers of increasing thickness between the Earth's surface and the 10 hPa pressure level using terrain following hybrid pressure-sigma coordinates. In this study, we assume that aerosols emitted by fires are released into the lowest model layer.

The model domain expands over entire Indonesia covering an area from 19°S to 8°N and 91°E to 141°E (around 18 million km^2) with a horizontal resolution of 0.5° (∼55 km). A basic model time step of 5 minutes was chosen. In this study, REMO is run in a forecast mode (restart every 30 hours) which is initialised and driven (nudged at the lateral boundary every 6 hours) by the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis while aerosol processes are calculated continuously (cf. Langmann and Heil 2004). By restarting the model every day the internal model variability is suppressed with the purpose of forcing the model to stay close to the observed weather situation (ECMWF analysis) and thereby to model particle transport and removal processes as close to reality as possible.

Previous studies with the REMO atmospheric chemistry model (e.g., Langmann et al. 1998, 2003; Chevillard et al. 2002; Langmann and Heil 2004) give confidence in the ability of the model to reproduce the physicochemical state of the atmosphere. Aldrian et al. (2004) validated REMO performance in simulating the Indonesian rainfall and found good agreement between simulated and observed rainfall variability, particularly over southern Sumatra and Kalimantan. They found that REMO systematically overestimates the amount of rainfall over the ocean surrounding the Indonesian archipelago by up to 70%, but reproduces it well over land with a bias of less than 5% for Kalimantan and Sumatra. Generally, predictability is highest during the normal annual dry season (June–September), notably in regions affected by El Niño – Southern Oscillation (ENSO) events. In view of precipitation directly determining the magnitude of removal of airborne particles by wet deposition (Grantz et al. 2003) and the main fire episode being in the dry season, this is a promising prerequisite for using the model in wide-range smoke haze pollution monitoring and prediction scenarios. However, REMO is likely to overpredict the removal of smoke particles by wet deposition particularly during transport over the ocean and outside the main dry season.

2.2. Emission inventory

The current study builds on previous work described in Langmann and Heil (2004), which has been modified to more realistically represent an intermediate emission scenario by using different parameters for emission calculation such as biomass load and emission factors and an improved map of peat soil distribution.

2.2.1. Distribution of surface and subsurface fuels and emission factors

In this study, the different surface vegetation types from the land cover data set of Loveland et al. (2000) are aggregated into three main surface fuel classes (Figure 1a–c). We use a version of this data set that has been processed for climate modelling into $0.5^\circ \times 0.5^\circ$ fractional vegetation cover data by Hagemann (2002). The fire emission inventory only includes fires occurring in the subarea of the model domain from 10.5°S to 7.0°N, (i.e., including Indonesia and Malaysia but excluding Australia). Within this inventory area, forest makes up 60% of the total area of surface vegetation (2.3 million km^2), while agriculture, grassland, and savannah make up 32%, and fragmented forests and plantations 8%.

We also include emissions from subsurface fires in organic peat soils, which we calculate separately from the surface fire emissions. Estimates of the areas covered by peatland in Indonesia are highly uncertain. The most commonly cited area estimates for Indonesian ‘predisturbance peatland’ (prior to large-scale drainage for agriculture and forestry) range from 170,000 to 270,000 km^2. The main uncertainty in this estimate is the definition of peatland, as the definition of minimal depth varies greatly from 0.2 m to 0.6 m (Immirzi et al. 1992). Current estimates of peatland in this region are on average 216,000 km^2 (Immirzi et al. 1992; Page et al. 1999). We derived the distribution of peat soils from areas designated as reference soil group Histosol (HS) in the World Reference Base (WRB) Map of World Soil Resources (FAO 2003). The WRB system defines the soil type histosol as a soil having an organic soil material horizon (histic or folic) of at least 0.1–0.4 m thickness, dependent on the properties of the underlying horizon (FAO 1998). The total area of soils classified as reference soil group HS in the inventory area is 436,000 km^2, twice the cited area estimate of peatland in this region (216,000 km^2) of Immirzi et al. (1992) and Page et al. (1999). Its spatial distribution corresponds well with the drawing of Indonesian peat areas by Rieley et al. (1997). HS mapped in the inventory area using the WRB classification system also includes soil units where histosols are associated with gleysols, which may partly explain the higher value. To account for this overestimation, we assume that 50% of the HS mapped is

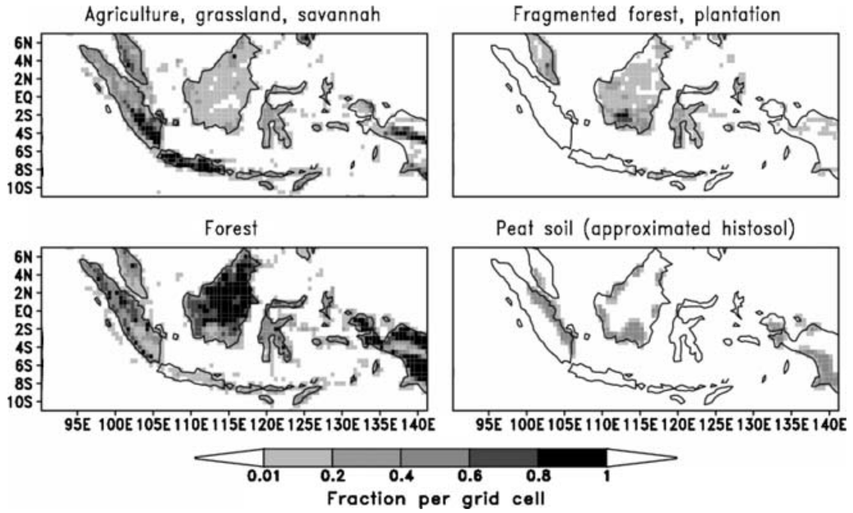

Fig. 1 Fractional distribution of the aggregated fuel classes used in our study as fraction per grid area based on Hagemann (2002) and FAO (2003): (a) agriculture, grassland, and savannah; (b) fragmented forests, plantations; (c) forest; (d) peat soil

peat, resulting in a total peat soil area of 218,000 km^2, of which 30% is on Sumatra/Peninsular Malaysia, 34% on Borneo, and 36% on Irian Jaya (d).

The above- and belowground biomass densities determine the amount of fuel per unit area that can potentially burn in a fire event. The burning efficiency β (frequently also referred to as combustion factor) describes how much of the biomass available is actually consumed during a fire event, i.e., converted into gases and aerosols. The emission factor (EF_x) determines the mass of compound $\times$ emitted per mass of fuel consumed by the fire (gram $\times$/kg dry fuel). The total emissions of $\times$ are calculated from the product of area burnt and the corresponding biomass loading, burning efficiency, and emission factor EF_x. Table 1 summarises the parameters used for calculating emissions of PM_{10} for different fuel classes based on a literature study. For later discussion, Table 1 also includes other selected trace species. The parameters for surface fuel classes are relatively well documented, but with large ranges. These parameters are, however, poorly investigated for Indonesian or tropical peat in general. Neither the average depth of Indonesian peat soils nor the average depth of peat burnt has been explored in a consistent way that representatively covered the different types of peat areas in this region. For our modelling, we assume a mean peat depth of 2.3 m, which is a reduced estimate for average peat thickness found in Central Kalimantan by Page et al. (2002). The only published study on peat depths burnt in Indonesia found a mean peat depth burnt in Central Kalimantan of 0.51 m in 1997 (range from 0.25 m to 0.85 m) (Page et al. 2002), which we use in this study.

An extensive review of emission factors for different biomes by Andreae and Merlet (2001) includes tropical forest and grassland/savannah, but not peat. Christian et al. (2003) provides the first detailed description of emission factors for gaseous compounds and aerosol chemical constituents from Indonesian peat combustion while particulate emission factors (PM_{10}) of Indonesian peat were only recently analysed within the EFEU (Impact of Vegetation Fires on the Composition and Circulation of the Atmosphere) project (Wurzler et al. 2001) (cf. Table 1). Our peat emission inventory rests on the two latter studies, which represent a

Table 1 Biomass density, burning efficiency, carbon content, and emission factors used for the four fuel classes used in this study to calculate fire emissions

	Agriculture, grassland, savannah	Fragmented forest, plantation	Forest	Peat soil
Biomass density [t/km^2]	4,035[a]	20,000[b]	50,400[c]	293,825[d]
Burning efficiency [%]	93[e]	54[f]	39[g]	22[h]
Carbon content [%]	50[i]	50[i]	50[i]	54[j]
Emission factors (EF) in g/kg dry fuel consumed:[k]				
Particulate matter $d < 10\,\mu$m	5.9[l]	9.9[l]	9.9[l]	38.0[m]
Particulate organic carbon	3.4	5.2	5.2	6.0
Particulate elemental carbon	0.5	0.7	0.7	0.04
Carbon dioxide	1,613	1,580	1,580	1,703
Carbon monoxide	65	104	104	210

[a] Average aboveground biomass of grasslands and annual crops in Indonesia (Lasco 2002)

[b] Aboveground biomass of plantations (Mudiyarso and Wasrin 1995)

[c] Average aboveground biomass of undisturbed and logged rainforests (Lasco 2002)

[d] Average peat depth (conservative approach) in Kalimantan (Page et al. 2002), biomass load calculated with average bulk density for Indonesian peat of 0.13 g/m^3 (Shimada et al. 2001)

[e] Burning efficiency of pasture/grass (Fearnside 2000)

[f] Mean burning efficiency of secondary forest (Fearnside 2000)

[g] Mean burning efficiency of original forest (Fearnside 2000)

[h] Derived from ratio of mean peat depth entirely burnt in Central Kalimantan 1997 (0.5 m) and a conservative estimate of mean peat thickness (2.3 m) (Page et al. 2002)

[i] Carbon content of 50% assumed (Fearnside 2000)

[j] Mean carbon content of peat cores sampled in Kalimantan (Shimada et al. 2001)

[k] Emission factors for agriculture, savannah, and grassland are taken from emission factors for savannah and grassland (Andreae and Merlet 2001). Emission factors for both forests and fragmented forests/plantations correspond to emission factors for tropical forest in Andreae and Merlet (2001). Emission factors for Indonesian peat are taken from Christian et al. (2003), except for PM_{10}. When emission factors are given as range, average is used

[l] PM_{10} emission factors derived from $PM_{2.5}$-emission factor given in Andreae and Merlet (2001) using a mean $PM_{2.5}/PM_{10}$ ratio of 0.92 found for burning different forest types by Peterson and Ward (1993)

[m] PM_{10} emission factor of a composite sample of Sumatran peat obtained during the EFEU-campaign (O. Schmid, Max-Planck-Institute for Chemistry, Mainz, Germany personal communication, 16.04.2004)

substantial progress for adequately inventorying aerosol and trace gas emission for peat fires in Indonesia. In the absence of these data, previous studies have estimated the emissions from Indonesian peat fires using emission factors for organic soils in extratropical regions (e.g., Levine 1999), which, however, are generally moss-derived in contrast to woody peat in the tropics.

2.2.2. Area burnt estimate and distribution of surface and below-ground fuels

In this study, we use the area burnt estimate of Tacconi (2003) and redistribute this area estimate in space and time using fire count data retrieved from the Along Track Scanning Radiometer (ATSR) satellite instrument (Arino and Rosaz 1999). The area burnt estimate is an update of the area burnt estimate for Indonesia for different vegetation types by ADB/BAPPENAS (1999), which compiled the various data sources available on area burnt based on satellite data, aerial surveillance, and ground assessments. We use this approach because continuous and time-resolved information on the spatial extent of the fire-affected areas in 1997 is not available for entire Indonesia.

So-called ‘hotspot’ or fire count data can provide information on the spatial and temporal occurrence of an active fire event, but not on the area burnt within an individual fire count pixel (Malingreau 1990). We use nighttime data from the ATSR World Fire Atlas (Arino and Rosaz 1999) and aggregate them into $0.5^\circ \times 0.5^\circ$ cells on a weekly basis. Only fires occurring in the inventory area are included. A weekly mean is used to smoothen out the three-day acquisition frequency of the ATSR sensor at equatorial latitude to assure that at least two overpasses are included in each time step. The ATSR thermal $3.7\,\mu$m channel detects active fires through the induced changes in Earth’s radiative temperature using two algorithms: Algorithm 1 identifies a so-called hotspot when the surface temperature is above 312° Kelvin, while the threshold is 308° Kelvin for Algorithm 2. We used Algorithm 2 data in our study because of the resulting enhanced sensitivity to lower-temperature fires (e.g., smouldering peat fires) (Malingreau 1990). Compared with other satellite products, Stolle et al. (2004) found that ATSR data for Indonesia are a fair temporal proxy for area burnt, despite existing commission and omission errors. ATSR data show a high correlation with burn scar area maps ($R = 0.82$ for Algorithm 2), albeit largely but consistently underrepresenting the number of active fires in Indonesia. Figure 2a shows the distribution of ATSR Algorithm 2 fire counts as number per model grid cell from July to December 1997. There is widespread occurrence of fires on Sumatra, Kalimantan, and Irian Jaya and an increasing fire intensity towards the southern coastal areas.

The total area burnt estimate of Tacconi (2003) for 1997/1998 divided by the total number of ATSR Algorithm 2 fire counts detected over Indonesia from July 1997 to June 1998 (39,240 counts) results in a mean area burnt of $3.0\,\text{km}^2$ per fire count. This ratio, which is around three times the ATSR pixel size, may partly be explained by the ATSR sensor covering Indonesia only every third day. Evaluating TRMM (Tropical Rainfall Measuring Mission)-fire counts, van der Werf et al. (2003) showed that the ratio of area burnt per fire count increases with decreasing percentage of tree cover. We therefore use estimated fuel type dependent ratios to approximate the area burnt estimate of Tacconi (2003). We scaled them to $2.3\,\text{km}^2$, $2.9\,\text{km}^2$, and $4.5\,\text{km}^2$ burnt per fire count for the fuel classes forest and peat soil, fragmented forest/plantation, and agriculture/grassland/savannah, respectively.

Table 2 shows the approximated area burnt for the four fuel classes derived from the scaled ATSR fire counts for 1997. Although we exclusively focus on the 1997 fires in this study, the 1997/1998 area burnt approximation is shown to allow a comparison with the area burnt

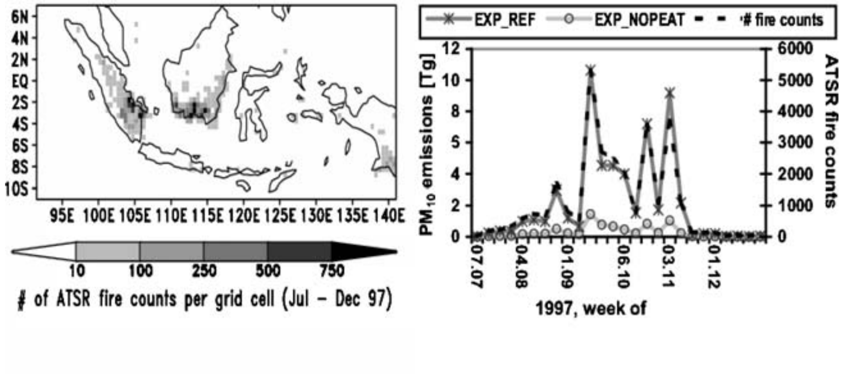

Fig. 2 (a) Total number of ATSR Algorithm 2 fire counts recorded in the second half of 1997 per 0.5° × 0.5° model grid; (b) weekly total PM_{10} emissions in the second half of 1997 calculated for all fuel classes (EXP_REF) and for all fuel classes except peat (EXP_NOPEAT). On the secondary axis, the weekly number of ATSR Algorithm 2 fire counts is shown

estimate for 1997/1998 by Tacconi (2003), which was used to scale the area burnt per fire count.

The total area burnt approximation for the different fuel classes for 1997/1998 corresponds well with the estimate of Tacconi (2003). However, there are distinct deviations of the area of surface fuel classes burnt on Sumatra, Kalimantan, and Irian Jaya, resulting in a two times larger area of surface vegetation burnt on Sumatra in our approximation compared with Tacconi (2003), while it is around 30% lower on Kalimantan and Irian Jaya. Compared with 110,000 km^2 approximated area burnt for 1997/1998, 80,000 km^2 (73%) burnt in 1997. Our approximation of 19,000 km^2 of burnt peat soil in 1997 is close to the intermediate estimate of 24,000 km^2 of peat area burnt in 1997 by Page et al. (2002).

2.2.3. *Calculated emission*

The emissions of PM_{10} and of other selected species calculated for the Indonesian fires in the second half of 1997 are summarised in Table 3 as total amount and as relative contribution of the different fuel classes. We calculate that the 1997 Indonesian fires released 55 Tg of PM_{10} to the atmosphere. Fires in peat soil contribute 86% (47 Tg) to the total PM_{10} emissions, while fires in surface vegetation contribute only 14% although the area of surface vegetation burnt was four times larger than the area of peat soil burnt. Total C released from burning surface vegetation and peat soil in the second half of 1997 is estimated to be 1098 Tg C, most (672 Tg C) of which resulted from peat fires. Total C and PM_{10} emitted from surface fires stem mainly from forest fires (64%–68%). While the other surface vegetation classes contribute 75% to the total area of surface vegetation burnt, their emissions are less because of lower biomass densities (Table 1).

Compared with other estimates of total C released during these fires, our estimate represents an intermediate value: Levine (1999) calculated 245 Tg C, Duncan et al. (2003) reported around 700 Tg C, and Page et al. (2002) provided a range from 480 Tg C to 2570 Tg C for a lower and upper estimate. There are several indications that the upper estimate of Page et al. (2002) is too high (Duncan et al. 2003; Roedenbeck et al. 2003; Langmann and Heil 2004; van der Werf et al. 2004). Via global inversion of atmospheric transport of carbon dioxide

Table 2 Estimate of area burnt 1997 and 1997/1998 in this study and estimates of other studies for comparison

	Fuel class region	Agriculture, grassland, savannah	Fragmented forest, plantation	Forest	Total surface vegetation	Peat soil
Area burnt 1997,	Total area (km^2)	35,986	15,922	27,922	79,830	19,092
approximation (this study)	(% of total area)	(45)	(20)	(35)	(100)	(24)
Area burnt 1997	Total area (km^2)	22,800	11,400	11,400	45,600	9,120
(Liew et al. 1998)[a]	(% of total area)	(50)	(25)	(25)	(100)	(20)
Area burnt 1997	Total area (km^2)	56,500	20,000	55,300	131,800	–
(Fuller and Fulk 2001)[b]	(% of total area)	(43)	(15)	(42)	(100)	–
Area of peat burnt 1997	Total area (km^2)		Lower estimate			14,500
(Page et al. 2002)			Intermediate estimate			24,410
			Upper estimate			68,047
Area burnt 1997/98,	Total area (km^2)	42,737	18,590	48,605	109,932	23,005
approximation (this study)	(% of total area)	(39)	(17)	(44)	(100)	(21)
Area burnt 1997/98	Total area (km^2)	49,678	21,105	46,201	116,984	21,240
(Tacconi 2003)[c]	(% of total area)	(42)	(18)	(39)	(100)	(18)

[a] Vegetation type agricultural and plantation areas is aggregated into fuel class agriculture/grassland/savannah; vegetation type forests and bushes as well as peat swamp forests are distributed equally on the fuel classes fragmented forest/plantation and forest

[b] Area of unspecified land cover type is aggregated into fuel class fragmented forest/plantation

[c] Vegetation type agriculture and dry scrub and grass is aggregated into the fuel class agriculture/grassland/savannah; vegetation type timber plantation and estate crop is aggregated to fragmented forest/plantation, while montane and lowland forest are aggregated to the fuel class forest; vegetation type peat and swamp forest is equally distributed among the three surface fuel classes

Table 3 Particulate and gaseous emissions from 1997 Indonesian vegetation and peat fires

	Contribution of fuel class to total emission [%]				
Specie	Total fire emissions 1997 [Tg]	Agriculture, grassland, savannah	Fragmented forest, plantation	Forest	Peat soil
Particulate matter $d < 10\,\mu$m	55	1	3	10	86
Particulate organic carbon	12	4	8	24	64
Particulate elemental carbon	1	11	19	61	9
Total carbon released[a]	1,098	6	8	25	61
Carbon dioxide	3,470	6	8	25	61
Carbon monoxide	345	3	5	17	76

[a] Total carbon released is calculated from biomass carbon densities and burning efficiencies. Sum of carbon in the carbon-containing species emitted (derived from emission factors) is larger than calculated total carbon released because of rounding errors and differences in data sources

(CO_2), for example, Roedenbeck et al. (2003) retraced an estimated flux anomaly of around 1000 Tg C in 1997 from the Indonesian fires, which is in the lower region of the range given by Page et al. (2002), and which is in good agreement with our estimate.

PM_{10} emission fluxes show high variability throughout the main fire episode from August to November 1997 (Figure 2b). PM_{10} emissions peak at 10.6 Tg in the third week of September when both surface and subsurface fires are considered (EXP_REF). The temporal spacing of weekly total PM_{10} emissions is largely congruent with the weekly number of fire counts recorded, indicating a relatively homogenous distribution of fires in the different fuel classes over time. The emissions from surface fires largely follow the temporal development of total emissions from surface and subsurface fires ($R = 0.92$), but are generally six times smaller.

The presence of a dense, persistent smoke layer over the main fire areas in Kalimantan during the smoke haze period may have strongly impaired the consistent detection of fires by satellite (Siegert and Hoffmann 2000). Compared with Kalimantan, the smoke haze layer over Sumatra was much less pronounced, resulting in a lower underrepresentation of fire counts for the latter region. We therefore consider our ATSR fire count–based approach for establishing the emission inventory (see methods) to result in a potential underestimate for Kalimantan and overestimate for Sumatra.

The ignition probability of peat soils by surface fires increases with decreasing soil moisture (Frandsen 1997), e.g., with persistent dry conditions during the fire season. We used constant factors for the ignition probability of peat soils by surface fires throughout the entire fire season, resulting in a likely overestimation of peat fire emissions in the earlier fire season and a likely underestimation in the later fire season. Further misclassifications of fuel type burnt may also result from shortcomings in the land cover and peat soil distribution information used. Misclassified peat fires in our emission inventory could result in up to 55 times larger emissions than actually produced.

The estimated 55 Tg PM_{10} of fire aerosols released from the 1997 Indonesian fires are equivalent to roughly one third of the annual global anthropogenic emissions of primary particles into the atmosphere in the 1980s (Kiehl and Rodhe 1995). Simultaneously, around 3470 Tg CO_2 and 345 Tg carbon monoxide (CO) were released, about 15% and 130%, respectively, of the global emissions of these species produced in 1990 by fossil fuel combustion (Olivier et al. 1999; Marland et al. 2003). Estimated emissions of particulate organic carbon (OC) of 11.7 Tg and elemental carbon (EC) of 0.6 Tg are equivalent to around 115% and

Table 4 Experimental setup for scenario runs conducted for this study

Model run	Description
EXP_REF	Reference run with REMO from July to December 1997 driven by corresponding ECMWF-analysis. A medium estimate of PM_{10} emissions from fires in surface vegetation and peat is used as model input
EXP_NOPEAT	Same experimental setup as EXP_REF, with emissions from only surface fires included in fire emission inventory; peat fire emissions excluded
EXP_MET96	Same experimental setup as EXP_REF, with the ECMWF meteorological conditions from July to December 1996 (still incorporating the 1997 fire emissions)

10% of global emissions of these species in 1984 from fossil fuel combustion, respectively (Cooke et al. 1999).

In contrast to these values, Duncan et al. (2003) estimated lower CO_2 and CO emissions of 2300 Tg and 130 Tg, respectively, and distinctively higher OC and EC emissions of 18.5 Tg and 2.6 Tg, respectively. One reason for this discrepancy is that, in the absence of other information, Duncan et al. (2003) assumed that the biomass burnt during the 1997 Indonesian fires was forest and not peat. We applied specific emission factors for peat combustion, which is characterised by a predominant smouldering, low-efficiency combustion with a higher CO/CO_2 and lower EC/OC ratio than typical for the more flaming combustion processes in surface vegetation (Christian et al. 2003; see also Table 1). As a result, we calculate a CO/CO_2 (EC/OC) ratio around two to three times lower (higher) than in the study by Duncan et al. (2003). We think our approach provides a more realistic emission estimate of the absolute and relative abundance of species emitted by the fires.

2.3. Scenario runs

To investigate various influences on smoke dispersion and ambient air quality, we performed three model experiments (Table 4). In addition to an experimental scenario using a medium fire emission estimate (EXP_REF), two extreme scenarios were simulated: one neglecting emissions from fires in peat areas (EXP_NOPEAT), the other using 1996 meteorology and still incorporating the 1997 fire emissions (EXP_MET96). The year 1996 was chosen to represent the meteorological conditions of a normal year, i.e., when ENSO-related anomalies from the long-term average are small (McPhaden 1999). Both extreme scenarios are unrealistic, because (a) fires do not affect only surface vegetation, but also the underlying peat soil, rendering this an underestimation of fire emissions and (b) 1996 had much fewer fires than the extreme fire event of 1997, rendering this simulation an overestimation of fire emissions for 1996.

3. Results and discussion

3.1. Modelled PM_{10} levels for the different scenarios in the near-surface model layer

Monthly mean PM_{10} concentration modelled for the three scenario runs in the first vertical model layer above the surface is shown in Figure 3. The first vertical model layer (ground to ~50 m altitude) can be used as a proxy for near surface or ambient air quality. The PM_{10}

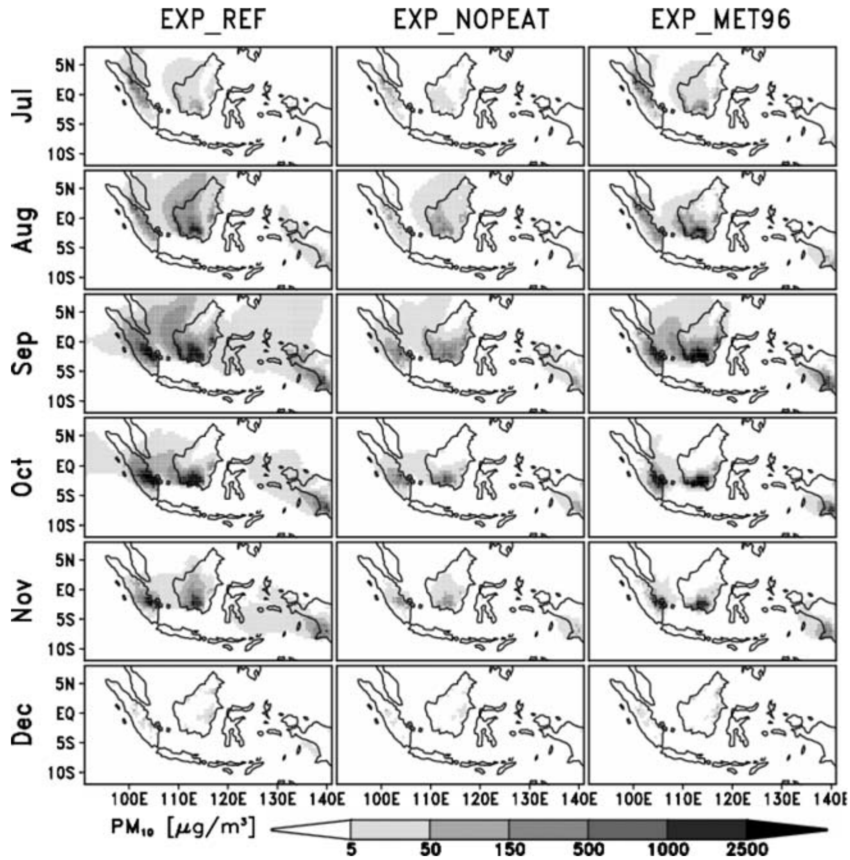

Fig. 3 Monthly mean PM_{10} concentration modelled for the lowest model layer for the scenario runs EXP_REF (left column), EXP_NOPEAT (middle column) and EXP_MET96 (right column)

air quality standard for Indonesia, Singapore, and Malaysia is 150 μg/m^3 as a daily average (ASEAN 2001).

All scenario runs show an increase in the extent and intensity of the smoke haze layer from July to October 1997, followed by a subsequent decrease. Maximum PM_{10} concentration is modelled above the main fire areas in southern Sumatra, Kalimantan, and Irian Jaya and the adjacent areas to the northwest (Figure 2a). The spatial extent and PM_{10} concentrations are greatest in the reference run (EXP_REF, Figure 3 left column). PM_{10} concentrations in the main fire areas generally range between 3000 μg/m^3 and 9000 μg/m^3 and gradually decrease with the west- and northward expansion of the smoke haze layer. From August to November, monthly mean PM_{10} concentrations above 250 μg/m^3 are modelled for large areas of Sumatra, Kalimantan, and Irian Jaya. Fire-related PM_{10} levels in peninsular Malaysia (including Singapore) are generally in the range of 5 μg/m^3 to 50 μg/m^3, except in September, when they reach 50 μg/m^3 to 150 μg/m^3. An increase in monthly mean PM_{10} concentrations above 5 μg/m^3 is modelled for most of insular Southeast Asia during the fire episode.

The spatial and temporal smoke haze distribution modelled with REMO in 1997 largely reproduces the TOMS (Total Ozone Mapping Spectrometer) Aerosol Index observational data (Herman et al. 1999), as shown in a qualitative comparison by Langmann and Heil (2004).

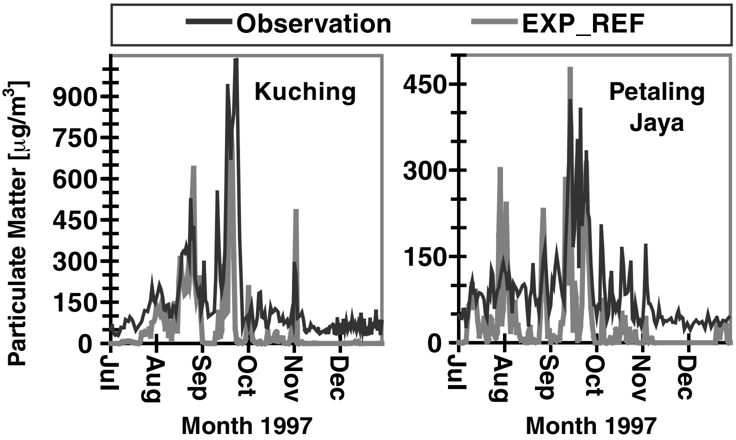

Fig. 4 Daily mean PM_{10} concentrations modelled in the lowest model layer in EXP_REF and ambient particle measurements at (a) Kuching (total particulate matter TPM) and (b) Petaling Jaya/Kuala Lumpur (PM_{10}) (data source: Malaysian Meteorological Services). Modelled PM_{10} concentrations are directly compared with TPM measurements

shows a quantitative comparison of modelled daily mean PM_{10} concentrations and measurements made at two Malaysian stations, Kuching on Sarawak-Malaysia (1.5°N, 110.3°E) and Petaling Jaya/Kuala Lumpur on peninsular Malaysia (3.1°N, 101.4°E), located around 400–800 km downwind from the main source areas of emissions. Measured particle levels at these stations include the particle background concentration (about 40–60 μg/m^3) and input from Indonesian fires, while the modelled particle levels include only fire emissions. Of the Malaysian stations for which measurements exist, these two stations were the most severely affected by the 1997 smoke haze (Heil and Goldammer 2001). Kuching was influenced only by emissions from fires in southern Kalimantan, whereas advected emissions from fires in Sumatra, and to a lesser extend Kalimantan, influenced Petaling Jaya (Koe et al. 2001).

Observed daily mean particle concentrations at these stations increase gradually, with large daily fluctuations, from an approximate background level in early July to maximum values in September of around 350 μg/m^3 in Petaling Jaya and 1000 μg/m^3 in Kuching (Figure 4). Particle concentrations return to background values by mid-November. The reference model experiment (EXP_REF) reproduces observed particle levels at both stations fairly well, as well as the main temporal characteristics. The predicted duration of the main haze episode during September, however, is shorter than observed, notably at Kuching. The shortfall likely stems from an underestimation of fire emissions from Kalimantan in our emission inventory. There is a distinct overprediction (factor of 2–3) of observed concentrations in late July to early August at Petaling Jaya, possibly because of misclassification of fires on Sumatra.

Comparison of the reference run (EXP_REF) and the experiment excluding peat fire emissions (EXP_NOPEAT) (Figure 3, middle column) demonstrates the relative importance of surface fires and peat fires in creating smoke haze episodes. Monthly mean PM_{10} concentrations in EXP_NOPEAT show a spatial and temporal pattern largely similar to that of EXP_REF, but with much lower values. In EXP_NOPEAT, populated areas of northern Sumatra and peninsular Malaysia (including Singapore) are almost entirely spared the exposure to smoke particles in EXP_NOPEAT (Figure 3), whereas distinct increases in particle concentration are predicted for these areas in EXP_REF.

The comparison of EXP_REF and EXP_MET96 (Figure 3, right column) demonstrates the influence of meteorological conditions prevailing during an El Niño year (EXP_REF)

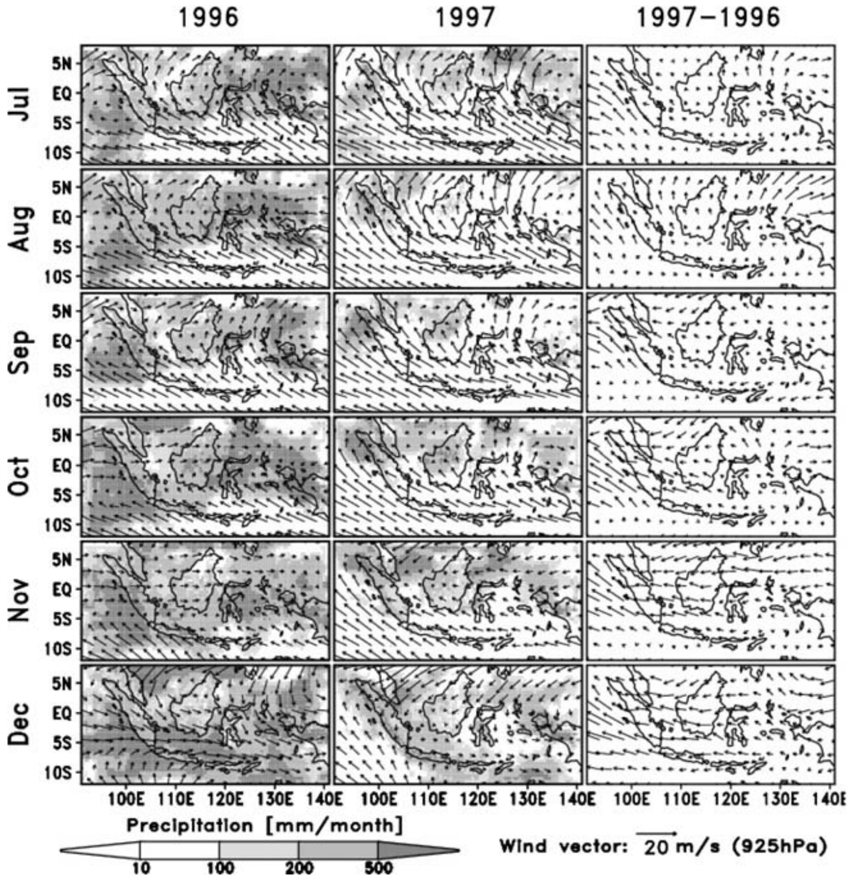

Fig. 5 Monthly total precipitation and monthly mean wind vectors at 925 hPa for July to December 1996 (left column) and 1997 (middle column). The right column illustrates wind vector differences between 1997 and 1996

and a normal year (EXP_MET96) on smoke haze dispersion. Modelled PM_{10} concentrations in the main source areas of emissions in the scenario run EXP_MET96 are largely similar to EXP_REF. The spatial expansion of the smoke haze layer is reduced in EXP_MET96, particularly in October and November, when the monsoon started in 1996. Concentrations are distinctively lower in the northwest regions adjacent to the main fire area in EXP_MET96 than in EXP_REF. Transport of fire emissions to peninsular Malaysia generally results in monthly mean PM_{10} concentrations of less than 15 μg/m^3. At Kuching and Petaling Jaya, modelled daily mean PM_{10} concentrations in EXP_MET96 (not shown) show a greatly different temporal pattern contrasted with the 1997 meteorology (EXP_REF) (Figure 4). Daily mean modelled PM_{10} levels are well below 100 μg/m^3, except for a few days in late August and September at Kuching and in late July and early August at Petaling Jaya. The peak in late July to early August at Petaling Jaya in EXP_MET96 is also demonstrated in EXP_REF and is attributed to the northward expansion of the smoke haze layer originating from fires in southern Sumatra. Compared with EXP_REF, the northward expansion of the smoke haze layer in EXP_MET96 is largely suppressed in the subsequent period (Figure 3), resulting in distinctively lower advection of PM_{10} to Petaling Jaya. In summary, the spatial extent in

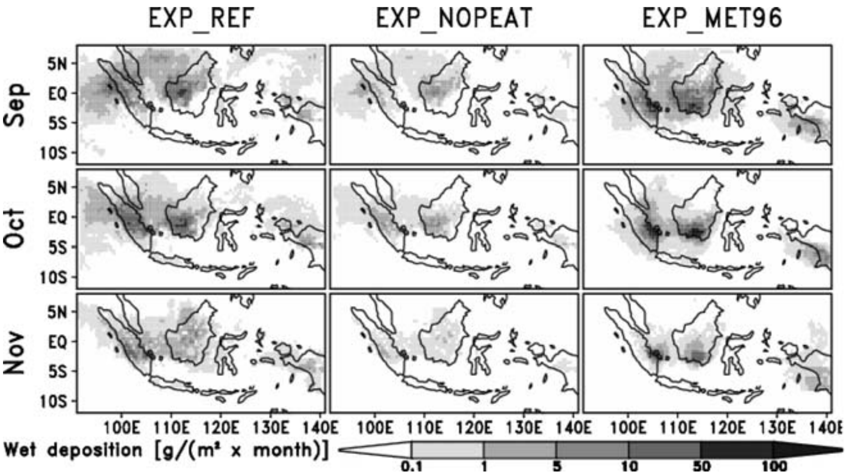

Fig. 6 Monthly total wet deposition modelled for the scenario runs EXP_REF (left column), EXP_NOPEAT (middle column), and EXP_MET96 (right column)

the EXP_MET96 model run is distinctively lower than in the EXP_MET96 run. The meteorological conditions of a normal year are predicted to result in much smaller increases in particulate air pollution in the highly populated areas of northern Sumatra and peninsular Malaysia (including Singapore).

In our model scenarios, we only predict increases of airborne particles from primary aerosols emitted by the fires. Aged smoke plumes, however, show a significant enrichment in secondary aerosols formed from precursor gases (organic and inorganic gases emitted by the fires) during transport, which may increase total aerosol burden by up to 50% and more (Reid et al. 2004). For this reason, we expect modelled particle levels in smoke plumes downwind of the fires to present a lower boundary. Due to the model's overprediction of wet deposition especially over the ocean, we expect underprediction of particle levels to be most pronounced after a cross-ocean transport, e.g. on peninsular Malaysia.

3.2. Influence of meteorology on PM_{10} dispersion

3.2.1. Meteorological conditions

In this section, we compare the meteorological conditions of 1996 and 1997 from model simulations only. Meteorological conditions between 1996 and 1997 are used to explain the discrepancies of model results between EXP_REF and EXP_MET96. Whereas 1996 is considered a normal, non-ENSO year, 1997 is an El Niño year. Figure 5 displays monthly total rainfall and mean wind vectors at 925 hPa for model simulations for July to December 1996 (left column) and 1997 (middle column), as well as the wind vector differences between 1997 and 1996 (right column). We chose the 925 hPa level because mean transport of the smoke haze was found to occur at around this mark (Koe et al. 2001).

Precipitation patterns are distinctively different in these years because the El Niño phenomenon in 1997 brought strongly reduced precipitation over all Indonesia. Discrepancies occur particularly in regions south of the equator, and the largest differences occur in August and September, when the total dry condition (<10 mm/month) reaches southern Kalimantan

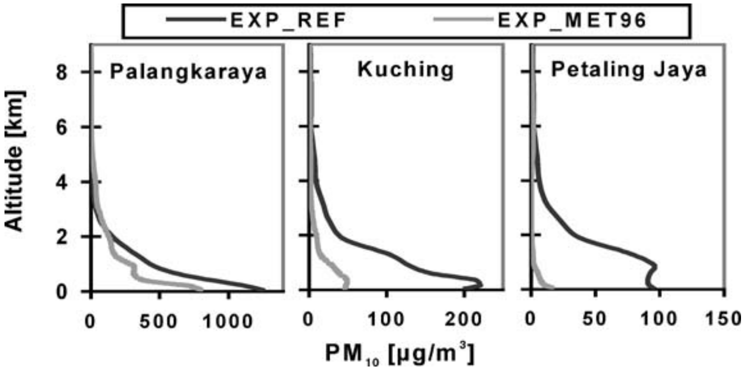

Fig. 7 Monthly mean vertical distribution of PM_{10} modelled for the scenario runs EXP_REF and EXP_MET96 for September over (a) Palangkaraya, (b) Kuching, and (c) Petaling Jaya/Kuala Lumpur

and Sumatra. In agreement with Aldrian and Susanto (2003) and references therein indicated, two dominant rainfall climatic regions in the eastern and southern part of Indonesia experience lower amounts of rainfall in El Niño years during the dry period from April to October. During the rainy season, however, the impact of El Niño is unnoticeable. In 1996, the extension of dry area reached out to only the southern Lesser Sunda Islands. The dry season extended until November in 1997 compared with September in 1996. The unusual dryness in 1997 affected three major peat locations in southern Sumatra, southern Kalimantan, and southern Irian Jaya (Figure 1d). In these areas, fire intensity and emission release were highest during the 1997 fire episode (Figure 2a).

Compared with the relatively normal wind conditions in 1996, wind over large parts of Southeast Asia north of around 3° south, including the main fire areas on Sumatra and Kalimantan, were more southeasterly in 1997 (Figure 5). Especially during July to October 1997 the region exhibited a stronger cross-equatorial flow from southern Sumatra and Kalimantan to peninsular Malaysia and points north. This particular wind pattern during El Niño 1997 provided favourable conditions for an enhanced transport and dispersion of emissions from fires in southern Kalimantan and Sumatra to populated areas in the northwest. Parameswaran et al. (2004) found that strong easterly winds at the equatorial Indian Ocean in 1997 were responsible for the transport of the smoke haze layer to the tropical Indian Ocean (Figure 3).

3.2.2. Particle removal by wet deposition

In both EXP_REF and EXP_NOPEAT model experiments, modelled maximum wet deposition is shifted around 400 km northwestward from the main source areas of emissions, i.e., the fires cluster in southeastern Sumatra, southern Kalimantan, and southwestern Irian Jaya (Figure 6). Wet deposition in the EXP_MET96 model experiment is largely confined over the main source area of emissions and shows higher deposition rates. Maximum wet deposition simulated in EXP_REF of up to $120\,\mathrm{g}/(\mathrm{m}^2 \times \mathrm{month})$ is lower by a factor of 3.5 than the one for EXP_MET96 in October because of rainfall being around five times more intense in 1996 than in 1997 over the main source areas of emissions. With the EXP_NOPEAT scenario, spatial distribution of the wet deposition is similar to EXP_REF, but shows much lower fluxes.

The spatial distribution of the wet deposition differs from the spatial distribution of PM_{10} concentration at the lowest model layer (Figure 3) because wet deposition is a function of the entire vertical aerosol column burden and the rainfall. Unfortunately, observational wet deposition data for comparison are unavailable. Figure 6 illustrates the influence of different wind patterns in 1996 and 1997 on wet deposition. As mentioned earlier, more southeasterly winds prevailed in 1997, which contributed to the transport of emissions from main fire areas northwestward. Using meteorological conditions representing a normal year (EXP_MET96), there is less transport of fire emissions away from the main source areas of emissions. Large portions of the fire emissions are then removed from the atmosphere by wet deposition directly over the source regions. Figure 6 also illustrates the importance of the quality of rainfall predictions because rainfall determines the amount of wet deposition, which strongly influences the amount of particulate matter remaining in the atmosphere.

As noted earlier, we generally expect to overestimate the wet deposition of PM_{10} because of the model's overprediction of precipitation. The effects of fire aerosols on cloud formation, rainfall, and wet deposition, however, are neglected in this study. Several studies have shown that fire aerosols suppress cloud formation and rainfall by a set of complex radiative and cloud microphysical interactions (Graf 2004). Rosenfeld (1999) evidenced that high concentrations of small fire aerosols result in small cloud droplets, which precipitate less efficiently. This microphysical effect strongly depends on particle hygroscopicity, i.e., potential to act as cloud condensation nuclei (CCN) (Reid et al. 2004, and references therein). Because of their high OC/EC ratio and hygroscopicity, Indonesian peat fire aerosols are very efficient CCN (Christian et al. 2003; Reid et al. 2004; see also Table 1) and are expected to suppress cloud formation in a significant manner. It is therefore expected that including these interactions into the model's calculations would partially compensate for overprediction of precipitation and particle removal by wet deposition.

3.2.3. *Vertical distribution of PM_{10}*

The vertical distribution of monthly mean PM_{10} concentration in September for the scenario runs EXP_REF and EXP_MET96 is shown in Figure 7 for three locations. Palangkaraya (2.2°S, 113.7°E) is in the vicinity of the main source area of emissions in southern Kalimantan, while Kuching and Petaling Jaya are located around 400 to 800 km north from the fires in southern Kalimantan and Sumatra, respectively.

PM_{10} levels are higher in EXP_REF than EXP_MET96 at all locations and all vertical levels. Fire-related PM_{10} concentration generally decreases with height and reaches very low concentrations at around 4500 m at all locations, the strongest decrease occurring below 2000 m. The relative difference in particle concentration between EXP_MET96 and EXP_REF increases with distance of the locations from the main source area of emissions, i.e., 64% at Palangkaraya and around 20% at the other locations. The strong relative reduction of particulate matter concentration up to 1000 m height at Palangkaraya is higher in EXP_REF than EXP_MET96. Since emission strengths are similar in both experiments, and rainfall-associated wet deposition is much more reduced in EXP_REF, this result indicates a strong transport away from the source by the enhanced wind in 1997 (see Figure 5). Near the source area, EXP_REF shows low vertical mixing, indicating the presence of a strong subsidence. In contrast, the particle concentration reaches higher altitude (2000 m) in locations farther away from the main source area, indicating stronger atmospheric mixing. Koe et al. (2001) found a similar vertical profile of the haze along Singapore with indication of trapping because of inversion at around 1000–1500 m. Parameswaran et al. (2004) also found the smoke haze layer to be generally confined to the lower troposphere (mainly below ~1500 m).

4. Conclusions and outlook

The Indonesian fires in 1997 released pyrogenic aerosols in the order of around 55 Tg PM_{10} into the atmosphere, equivalent to around one third of the annual global anthropogenic emissions of primary particles. Using a regional atmospheric chemistry model, we investigated the influence of meteorological conditions and fuel type burnt on large-scale smoke haze pollution.

The particular meteorological conditions prevailing during an El- Niño year strongly aggravate smoke distribution to wider areas, including densely populated areas of northern Sumatra and peninsular Malaysia including Singapore. Compared to normal years with similar fire emissions, El Niño conditions strongly reduce removal of particles by wet deposition and favour the cross-equatorial transport of fire emissions. The study also illustrates the dominant role of peat fire emissions in creating severe transboundary air pollution episodes. If peat fires are excluded, ambient air quality standards are exceeded only in areas close to the main fires. Including peat fires, however, air quality standards are exceeded on transboundary scales. During El Niño years, the risk of large-scale, sustained peat fires is much higher because the areas in Sumatra and Kalimantan that experience abnormal dryness contain exceptionally large portions of peat soil. Prevention of fires in peat areas, particularly during El Niño years, is therefore of major importance to the mitigation of adverse health impacts from smoke haze pollution.

The largest uncertainties in model simulation of atmospheric impacts of Indonesian fire emissions stem from missing validated spatio-temporal information on area and depth of peat burnt. Substantial uncertainty also comes from the omission of interactions between fire aerosols and clouds, and of secondary aerosol formation in model studies conducted so far. Further research will address this issue by specifically adapting the regional atmospheric chemistry model REMO to model fire emission dispersion over Indonesia. Such a regional model will be useful for both smoke and fire management and is a promising tool for future impact and mitigation studies.

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