Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia

C L Reddington[1], M Yoshioka[1], R Balasubramanian[2], D Ridley[3], Y Y Toh[4], S R Arnold[1] and D V Spracklen[1]

[1] Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, UK
[2] Department of Civil and Environmental Engineering, National University of Singapore, Singapore
[3] Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, USA
[4] Environmental Studies Division, Malaysian Meteorological Department, Malaysia

E-mail: c.l.s.reddington@leeds.ac.uk

Abstract

Smoke haze, caused by vegetation and peat fires in Southeast Asia, is of major concern because of its adverse impact on regional air quality. We apply two different methods (a chemical transport model and a Lagrangian atmospheric transport model) to identify the locations of fires contributing to the increased mass concentration of particulate matter with diameters less than 2.5 μm (PM$_{2.5}$) in Singapore over the period 2004–09. We find that fires in southern Sumatra account for the greatest percentage of the total fire enhancement to PM$_{2.5}$ concentrations in Singapore (42–62%), with fires in central Sumatra and Kalimantan contributing 21–35% and 14–15%, respectively. Furthermore, we find that fires in these regions also increase PM$_{2.5}$ concentrations in other major cities across Southeast Asia. Our results suggest that acting to reduce fires in southern and central Sumatra (specifically in the eastern parts of the provinces of Jambi, South Sumatra, Lampung and Riau) and southwest Kalimantan (the southern extent of the provinces of West, Central and South Kalimantan) would have the greatest benefit to particulate air quality in Singapore and more widely across Southeast Asia.

S Online supplementary data available from stacks.iop.org/ERL/9/094006/mmedia

Keywords: air quality, particulate matter, vegetation fires, aerosol, Southeast Asia, air pollution, smoke transport

1. Introduction

Vegetation and peat fires occur across Southeast Asia due to a combination of El Niño-induced droughts and anthropogenic land-use change (van der Werf *et al* 2008). These fires result in deforestation and forest degradation (Langner *et al* 2007, Carlson *et al* 2012), and release large quantities of CO$_2$ (Page *et al* 2002) and other atmospheric pollutants, degrading regional air quality and negatively impacting human health (Emmanuel 2000, Kunii *et al* 2002, Johnston *et al* 2012).

The mass concentration of particulate matter (PM) with diameters less than 2.5 μm (PM$_{2.5}$) is associated with adverse health effects and increased mortality (e.g., Ostro *et al* 1999). Most previous attention has been on health impacts of PM$_{2.5}$ from fossil fuel combustion (e.g., Lim *et al* 2012), but particulates from vegetation and peat fires are also thought to be harmful to human health (Frankenberg *et al* 2005, Emmanuel 2000, Johnston *et al* 2012, Pavagadhi *et al* 2013). During large fire years, particulate emissions from fires across Southeast Asia have been estimated to cause 10 800 premature deaths in the region each year (Marlier *et al* 2012).

Particulate emissions from vegetation and peat fires result in substantial concentrations of PM$_{2.5}$ across large regions of Southeast Asia, including the Indochina peninsula (See *et al* 2006, Gautam *et al* 2013, Huang *et al* 2013) and

southern China (Fu *et al* 2012). This study focuses on Singapore, which regularly experiences substantial $PM_{2.5}$ concentrations resulting from a combination of local emissions from industry and transportation sectors as well as long-range transport of smoke from fires (Balasubramanian *et al* 2003, See *et al* 2006). Observed 24 hr average $PM_{2.5}$ concentrations in Singapore vary from $\sim 10\,\mu g\,m^{-3}$ on clean days to between ~ 40 and $\sim 300\,\mu g\,m^{-3}$ on polluted days (Balasubramanian *et al* 2003, See *et al* 2006, Atwood *et al* 2013, Salinas *et al* 2013, Betha *et al* 2014). Atmospheric back trajectory methods have been used to show that both increased $PM_{2.5}$ concentrations (Balasubramanian *et al* 2003, Betha *et al* 2014) and poor visibility (See *et al* 2006) in Singapore occur when air masses pass over regions with fires. Elevated $PM_{2.5}$ concentrations in Singapore are coincident with elevated concentrations of levoglucosan, a tracer for biomass burning (Atwood *et al* 2013, Engling *et al* 2014), providing further evidence of a large contribution from fires.

Vegetation and peat fires in Southeast Asia rarely occurred before human influence (Goldammer 2006, Schultz *et al* 2008) and the majority of present day fires in the region are intentionally lit. Fires are used to clear forests to make way for agriculture (Langner *et al* 2007, Carlson *et al* 2012) as well as an agricultural management tool. Extensive drainage has also made peatlands susceptible to fires (van der Werf *et al* 2008). In Sumatra, large fires have occurred since at least 1960 whereas the first large fires in Kalimantan occurred in the 1980s, reflecting the different historical pattern of land-use change across the two regions (Field *et al* 2009). Future patterns of land-use change will play an important role in determining the extent of future fires across the region (Carlson *et al* 2012).

Regional scale air pollution and the transport of smoke from vegetation fires across national boundaries have resulted in substantial regulatory interest and attempts to manage and control these fires. For example, the Association of Southeast Asian Nations Agreement on Transboundary Haze Pollution commits the member countries to tackle transboundary haze pollution caused by vegetation and peat fires. Understanding the varying contribution of fires across different regions to particulate pollution is critical to future efforts to monitor and reduce fire.

In this study, we explore the contribution of vegetation and peat fires in different regions across Southeast Asia to $PM_{2.5}$ concentrations in Singapore over a six-year period (2004–09). Our aim is to provide quantitative information on the locations of fires that contribute most to $PM_{2.5}$ concentrations in Singapore and other large cities in Southeast Asia. This is the first study to quantify the regional contribution of fires to $PM_{2.5}$ in Southeast Asia over a multi-year period. Whilst the location of fires is well known, the impact of fires on air quality depends both on fire location combined with subsequent atmospheric transport of the smoke. Identifying the locations of fires causing the greatest air quality degradation will help prioritize action to combat fires and formulate sustainable land-use policy.

2. Methods

We applied two different methods to identify the regions that make the largest contribution to $PM_{2.5}$ concentrations in Singapore.

Firstly, we applied a 3D global aerosol model, GLOMAP (Mann *et al* 2010) (described in section S1 of the supplementary material), which simulates black carbon (BC), particulate organic matter, sulfate, sea spray and dust with a horizontal resolution of 2.8° by 2.8°. GLOMAP is driven by analyses from the European Centre for Medium-Range Weather Forecasts, meaning our simulations are consistent with the large-scale atmospheric flow from the assimilated observations. The model includes detailed aerosol processes, simulating the evolution of aerosol particles from emission/production to removal from the atmosphere. Our previous work has demonstrated the ability of GLOMAP to capture observed aerosol concentrations in diverse atmospheric environments (e.g. Spracklen *et al* 2007, 2010, 2011a, 2011b, Mann *et al* 2010, 2012). For the analysis, we performed a series of simulations over the period January 2004–December 2009 in which we switched off emissions from fires occurring in specific regions (defined in figure 1). To evaluate the model against observations (section 3.1), we performed two simulations over the period January 2000–December 2011 (one control simulation including all global fire emissions and one simulation where no fire emissions were included).

Secondly, we applied a Lagrangian atmospheric transport model, ROTRAJ (Methven *et al* 2003) (described in section S2), to calculate the history of air masses arriving in Singapore (figure S3). We calculated the cumulative exposure of air masses to fire emissions of carbon monoxide (CO) over five days of atmospheric transport to Singapore. These five-day atmospheric back trajectories were calculated every six hours (0, 6, 12, 18 h UTC) for the period of January 2004–December 2007. The results from the back-trajectory analysis were aggregated for monthly or annual means and averaged over the eight regions shown in figure 1. The resolution of the ROTRAJ model is determined by the resolution of wind fields (1.0125°) used to drive the transport of the air masses (section S2) and the emission database (0.5° × 0.5°), both of which have a higher spatial resolution than GLOMAP. Thus, results from the ROTRAJ model will complement those from GLOMAP, which contains more detailed aerosol processes but coarser spatial resolution.

In both methods we used fire emissions from the Global Fire Emissions Database (GFED3; van der Werf *et al* 2010) (described in section S3). For use in the global model, the emissions are split by region (figure 1) on a 0.5° by 0.5° grid (the resolution of the GFED3 emissions) and then degraded to the resolution of the global model (2.8° by 2.8°). Figure 2(a) shows the GFED3 fire emissions flux of BC over Southeast Asia. The largest BC emission fluxes over this region are from fires located in central and southern Sumatra and southwest Kalimantan. Figure 2(b) shows the dominant fire type in each grid cell, indicating that these large emission fluxes mainly arise from deforestation and peat fires, which dominate emissions from fires over Southeast Asia (van der
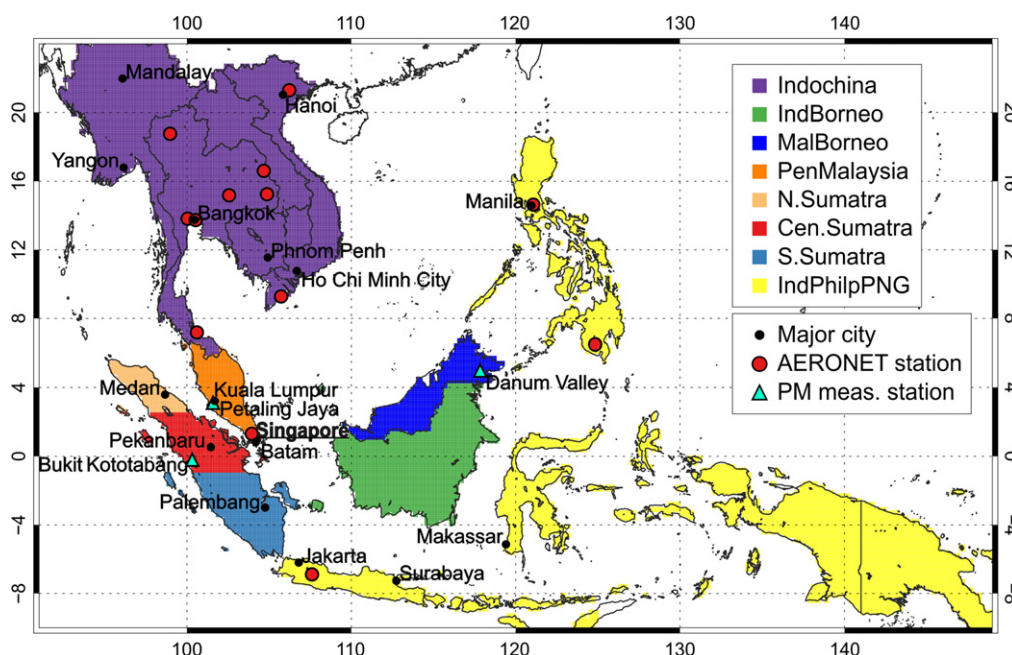
Figure 1. Map of the eight regions where fire emissions are 'switched off' in the global model simulations. The regions are: 'Indochina' (Thailand, Cambodia, Vietnam, Laos, and Myanmar); 'IndBorneo' (Indonesian Borneo/Kalimantan); 'MalBorneo' (Malaysian Borneo/East Malaysia); 'PenMalaysia' (Peninsula Malaysia); 'N.Sumatra' (northern Sumatra; above 2.5°N); 'Cen.Sumatra' (central Sumatra; between 2.5°S and 1°S); 'S.Sumatra' (southern Sumatra; below 1°S); 'IndPhilpPNG' (Indonesia (excluding Sumatra and Kalimantan), Philippines and Papua New Guinea). The red dots and cyan triangles show the locations of 4 PM measurement stations and 13 AERONET stations, respectively (see table S1). The black dots show 15 major cities (with populations greater than 1 million) selected for analysis in section 3.4.

Werf *et al* 2010). Strong emission fluxes of BC also arise from deforestation fires in western Malaysian Borneo, deforestation and agricultural fires in Cambodia, Laos and Myanmar, and savannah-type fires in northern Australia.

3. Results

3.1. Evaluation of modelled aerosol over Southeast Asia

Figure 3 shows a Taylor Diagram (Taylor 2001) summarizing the evaluation of monthly-mean PM and aerosol optical depth (AOD) simulated by GLOMAP against observations. The locations of *in-situ* observations of $PM_{2.5}$ (Singapore) and PM_{10} (Petaling Jaya, Danum Valley and Bukit Kototabang) and the 13 AERONET stations are shown in figure 1. The length of observation period varies by site (for PM, mean = 3 years; AOD, mean = 4.6 years) and is detailed in table S1. In a Taylor diagram, the agreement between model and observations is quantified in terms of their correlation (R), their centred root mean square error (RMSE) and the ratio of their standard deviations, called the normalized standard deviation (NSD). The observations are represented by a point on the horizontal axis at unit distance from the origin; points closer to this represent better agreement between modelled and observed values.

Figure 3 demonstrates the importance of fires in controlling variability in PM concentrations across the region: the simulated variability in monthly-mean PM when the model includes GFED3 fire emissions (R = 0.75–0.89; NSD =

0.23–0.58) is improved compared to a model simulation without fire emissions (R = −0.18–0.77; NSD = 0.12–0.30) (figure 3(a)). Similarly, the model with GFED3 fire emissions better captures variability in observed AOD (440 nm) (R = 0.29–0.85; NSD = 0.44–1.15) compared to the simulation without fires (R = 0.09–0.68; NSD = 0.33–0.90) (figure 3(b)). The positive correlation between the model (with fires) and observations shows that the model framework is able to capture the seasonal and inter-annual variability in AOD and PM that is driven by variability in fire emissions combined with the vertical and horizontal transport of emissions from their source and the microphysical processing of the aerosol particles.

Particulate emissions from fires are uncertain, so we compared simulated aerosol with GFED3 emissions against a simulation using emissions from the National Centre for Atmospheric Research Fire Inventory (FINNv1; Wiedinmyer *et al* 2011) (described in section S3). At the eight AERONET stations in northern Thailand and Vietnam, where agricultural fires dominate emissions (figure 2(b)), the model with FINNv1 emissions better captures AOD (R = 0.80–0.92, NSD = 0.62–0.98) compared to GFED3 (R = 0.29–0.85, NSD = 0.44–0.74). Improved agreement with FINNv1 emissions at these sites is likely because emissions from small fires, which dominate emissions in agriculture fire regions, are not well represented in GFED3 (Randerson *et al* 2012). At the five other AERONET stations, located in regions mainly influenced by deforestation and peat fire emissions (figure 2(b)), model performance with GFED3 (R = 0.33–0.59, NSD = 0.54–1.15) is more comparable to that
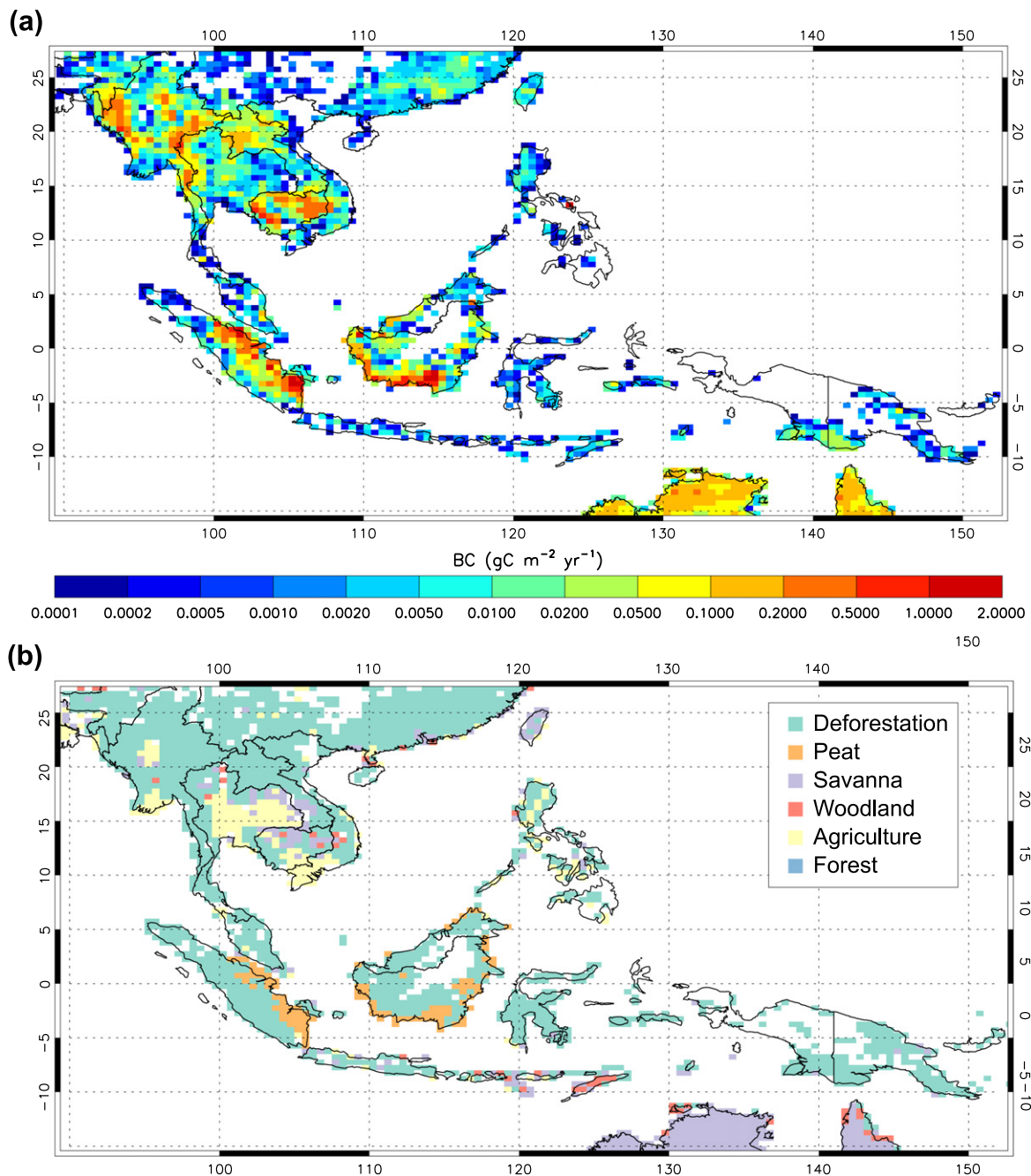
Figure 2. (a) Map of the 2004–09 mean biomass burning emissions flux of BC (in g(C) m^{-2} yr^{-1}) over Southeast Asia from GFED3. (b) Map of the dominant fire type for biomass burning emissions of BC over Southeast Asia; derived by calculating the maximum GFED3 BC emissions flux for each fire type in each 0.5° × 0.5° grid cell over the period 2004–09. Information on specific source category is from van der Werf *et al* (2010).

with FINNv1 ($R = 0.45$–0.59, NSD $= 0.51$–1.28). Additionally, when evaluated against PM observations located in regions dominated by deforestation and peat fire emissions, the model with GFED3 emissions ($R = 0.77$–0.89, NSD $= 0.23$–0.58) is comparable to the model with FINNv1 emissions ($R = 0.71$–0.89; NSD $= 0.39$–0.57). We use GFED3 fire emissions for the rest of this analysis as this dataset is available for 2000–11 (FINNv1 is only available for 2002–12) and we have shown that the two datasets are

comparable in regions dominated by deforestation and peat fires which are of most interest to this study.

GLOMAP (with GFED3 emissions) underpredicts observed annual mean PM concentrations in both urban (Singapore, normalized mean bias (NMB) $= -64\%$; Petaling Jaya, NMB $= -77\%$) and rural locations (mean NMB $= -56\%$). GLOMAP is also negatively biased against observed AOD (mean NMB $= -29\%$). In urban locations, underprediction of PM and AOD with a coarse resolution ($\sim$300 km) global model is expected because urban scale
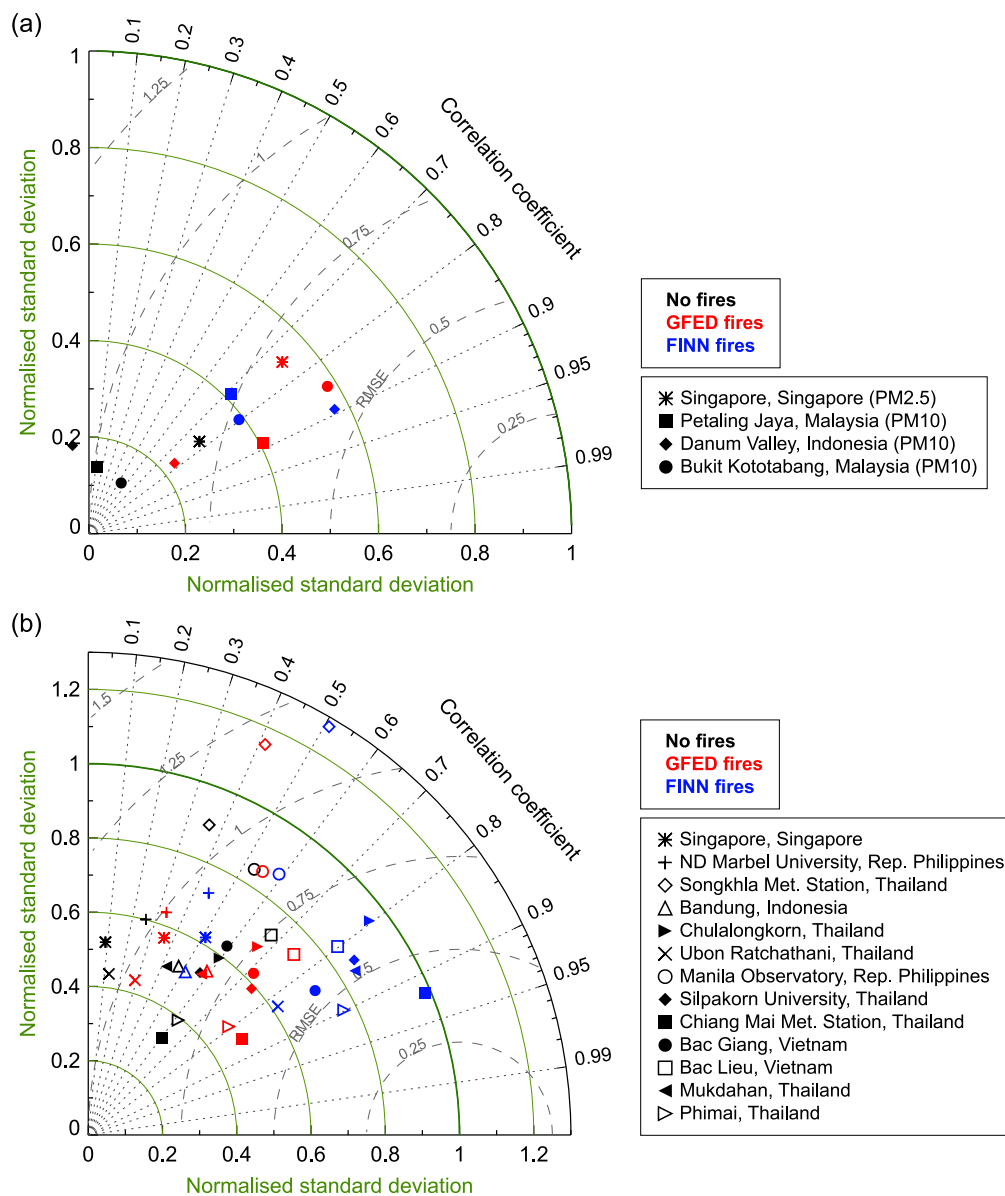
Figure 3. Taylor diagrams comparing monthly-mean modelled (GLOMAP) and observed (a) $PM_{2.5}$ and PM_{10} at four aerosol measurement stations in Singapore, Malaysia and Indonesia; and (b) AOD (440 nm) at 13 AERONET stations located across Southeast Asia (locations shown in figure 1 and time periods in table S1). The modelled and observed monthly-mean AOD was calculated using daily means, with days corresponding to missing AERONET data removed prior to calculating the monthly-mean value. The observations are represented by a point on the x-axis at unit distance from the y-axis. Results are shown for three model simulations: (i) without fire emissions ('No fires'); (ii) with GFED3 fire emissions ('GFED'); (iii) with FINNv1 fire emissions ('FINN') (this simulation cannot be compared with $PM_{2.5}$ observations in Singapore because FINN emissions are not available for the year 2000). The model standard deviation and RMSE are normalized by dividing by the corresponding observed standard deviation. The normalized standard deviation and RMSE values are marked by the green-solid and grey-dashed lines respectively.

pollution is not resolved. Underprediction in rural areas is consistent with previous studies that have found a persistent underestimation of AOD in biomass burning influenced regions, requiring a scaling factor of ~2–5 to be applied to fire emissions (e.g. Kaiser *et al* 2012, Tosca *et al* 2013, Marlier *et al* 2012). We do not scale fire emissions in this analysis since there is considerable uncertainty associated with this scaling factor, which is likely to have large spatial variability. Since we underpredict PM concentrations, particularly in urban locations, we do not focus on the fractional contribution of fires to total $PM_{2.5}$. Instead, the focus of our study is to

compare the relative contributions of fires from different regions to $PM_{2.5}$ concentrations and explore how these contributions change over the seasonal cycle and between different years.

3.2. Regional contribution of fires to $PM_{2.5}$ over Singapore

Figure 4(a) shows the simulated contribution of fire emissions to monthly-mean surface $PM_{2.5}$ in Singapore over the period 2004–09. The average simulated contribution to 2004–09 monthly-mean $PM_{2.5}$ varies from 0.3 to 10.7 $\mu g\,m^{-3}$, with the
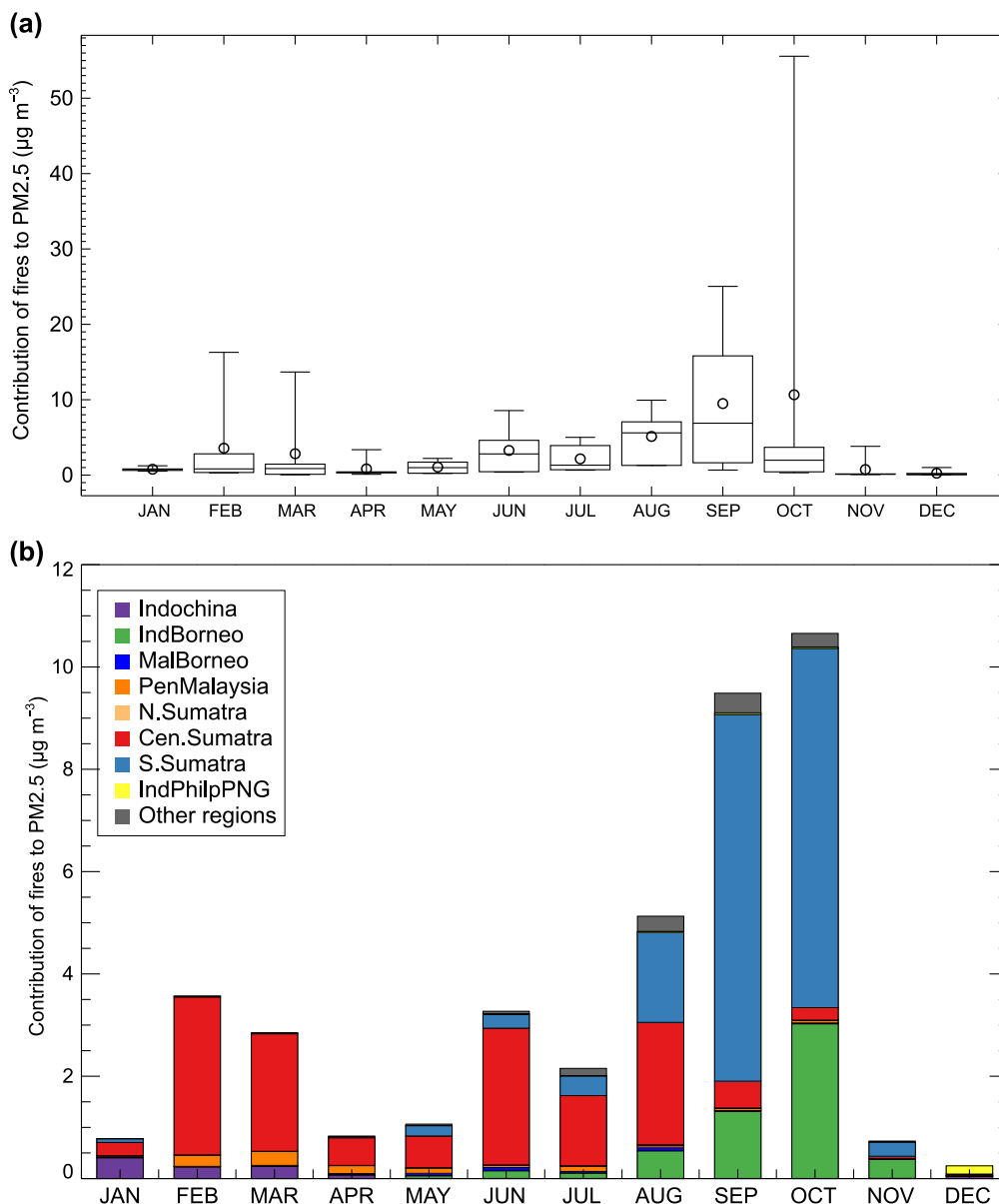
Figure 4. (a) The long-term (January 2004–December 2009) mean (open circles), median (horizontal line), 25th and 75th percentiles (lower and upper box edges), and minimum and maximum (whiskers) contributions of all fire emissions to simulated monthly-mean PM$_{2.5}$ concentrations over Singapore. (b) The long-term mean contributions of fire emissions to PM$_{2.5}$ from different regions in Southeast Asia (defined in figure 1).

largest contribution in October. There are also substantial contributions from fires in August (mean 5.1 μg m^{-3}) and September (mean 9.5 μg m^{-3}). During these months, the Southwest Monsoon predominates over Southeast Asia, with much of the southern part of the region experiencing dry season conditions conducive to fires. Fires contribute little to PM$_{2.5}$ during November–January when the Northeast Monsoon brings heavy rain to the region, reducing the susceptibility of vegetation to burning. Towards the end of the Northeast Monsoon season and during the onset of the Southwest Monsoon season, fires contribute moderately to monthly-mean PM$_{2.5}$ over Singapore, particularly in February (mean 3.6 μg m^{-3}), March (mean 2.8 μg m^{-3}) and June (mean 3.3 μg m^{-3}).

There is considerable inter-annual variability in the contribution of fires to simulated monthly-mean PM$_{2.5}$ in Singapore: in October fires contribute as little as 0.3 μg m^{-3} to as much as 55.6 μg m^{-3} depending on the year (figures 4(a) and S1). Although anthropogenic land-use change is the underlying cause of the majority of vegetation and peat fires occurring over Southeast Asia (Langner *et al* 2007, Carlson *et al* 2012), the frequency and magnitude of these fires are linked to inter-annual variability in sea surface temperature and atmospheric conditions, namely El Niño Southern Oscillation (ENSO) (van der Werf *et al* 2004, Field and Shen 2008, Logan *et al* 2008, Shi *et al* 2014). During El Niño years, rainfall over Southeast Asia decreases, which can lead to drought conditions increasing the susceptibility of

vegetation to burning (e.g. Siegert *et al* 2001, Wooster *et al* 2012). Fire emissions in Southeast Asia have been observed to be up to a factor of 50 greater in El Niño years compared to La Niña (van der Werf *et al* 2010). Satellite observations show that ENSO has a substantial effect on the number of fire plumes and the aerial extent of smoke clouds observed over Borneo (Tosca *et al* 2011). The westward transport of smoke from Sumatra is also thought to be greater during El Niño years, particularly during October–November, due to the combination of higher smoke-plume injection heights and anomalous easterlies over tropical Southeast Asia (Xian *et al* 2013). The plume injection heights are fixed in our model, but a strong increase in $PM_{2.5}$ over Singapore is simulated in October 2006 due to the combination of an increase in GFED3 fire emissions and the prevailing wind direction (specified by analysed meteorological fields).

Figure S1 shows that contributions from fires to simulated $PM_{2.5}$ in Singapore are substantially higher in dry season months with a positive Oceanic Niño Index (ONI; indicating El Niño conditions) relative to those with negative ONI values (indicating La Niña conditions). In the weak to moderate El Niño years of 2004, 2006 and 2009, the mean simulated contribution of fires emissions to $PM_{2.5}$ in Singapore ($5.0 \, \mu g \, m^{-3}$) is a factor of ~7 larger than in the La Niña years of 2007 and 2008 ($0.7 \, \mu g \, m^{-3}$). Note that 2005 is not included here as this year experienced mixed conditions with a positive ONI in the first half of the year and a relatively strong negative ONI for the remainder of the year.

Another important contributing factor to drought conditions, and subsequently the frequency and magnitude of fires in Southeast Asia (particularly in Indonesia) is the Indian Ocean Dipole (IOD; Saji *et al* 1999, Field and Shen 2008, Field *et al* 2009, Nassar *et al* 2009). When a positive phase of the IOD coincides with El Niño, severe drought conditions can occur in Sumatra and Kalimantan leading to extremely high fire emissions, for example during 1997 (Saji *et al* 1999) and 2006 (Field and Shen 2008). The combined effects of positive IOD conditions and El Niño are evident in figure S1, where the simulated total contribution from fires in October 2006 is a factor of ~20 higher than in October 2009, despite the weaker El Niño (ONI of 0.8° in 2006 compared with 1.1° in 2009).

Figure 4(b) shows the contribution from fires occurring in different regions (defined in figure 1) to simulated $PM_{2.5}$ concentrations in Singapore. Fires in southern Sumatra make the largest contribution to monthly-mean $PM_{2.5}$ in Singapore with long-term mean contributions of $7.2 \, \mu g \, m^{-3}$ (max. $20.7 \, \mu g \, m^{-3}$) in September and $7.0 \, \mu g \, m^{-3}$ (max. $37.7 \, \mu g \, m^{-3}$) in October. As a fractional contribution, fires in southern Sumatra account for 76% of total enhancement to $PM_{2.5}$ from fires in September and 66% in October. In these months, fires occurring in Indonesian Borneo make the second largest contribution to $PM_{2.5}$ (mean $3.0 \, \mu g \, m^{-3}$, max. $17.3 \, \mu g \, m^{-3}$ in October), accounting for 12% of the total fire enhancement in September and 28% in October. From February to August, fires in central Sumatra make the largest contribution to $PM_{2.5}$, peaking in February (mean $3.1 \, \mu g \, m^{-3}$). During this period, the fractional contributions from fires in central

Sumatra range from 87% in February to 47% in August. There is a small contribution to $PM_{2.5}$ from fires in Indochina in January, February and March (max. $0.9 \, \mu g \, m^{-3}$), during which the Indochina region experiences relatively dry conditions. Fires occurring outside the regions discussed above have minor impacts on air quality in Singapore.

Over the whole study period (2004–09), fires in southern Sumatra account for the largest fraction of the total fire enhancement to $PM_{2.5}$ in Singapore (42%), with fires in central Sumatra and Indonesian Borneo contributing 35% and 14%, respectively. During El Niño years (2004, 2006, 2009) there are greater fractional contributions from fires in southern Sumatra (54%) and Indonesian Borneo (17%) relative to the La Niña years (29% and 9%, respectively). The fractional contribution from fires in central Sumatra remains similar between the El Niño (22%) and La Niña (26%) years, but is particularly large during 2005 (84%) due to the persistence of El Niño conditions throughout the 2004/2005 winter wet season, leading to drought conditions in this region (Yulianti *et al* 2013). Fires occurring in Peninsular Malaysia and Indochina account for a relatively small fraction (~2–3%) of the total fire enhancement to $PM_{2.5}$ between 2004 and 2009, with slightly larger fractional contributions in La Niña years (4 and 12%, respectively).

3.3. Atmospheric back trajectory results

We used atmospheric back trajectories to further explore the relative contributions from fires in different regions to smoke transported to Singapore. Figure 5 shows the relative contributions from each region to fire-emitted CO transported to Singapore for the period January 2004 and December 2007. The largest amount of fire emission transported to Singapore occurs in September and October with the greatest contribution from fires in southern Sumatra and a secondary contribution from fires in Indonesian Borneo. Fires in central Sumatra result in transport of fire emissions to Singapore during March–October, with the greatest contributions in March, June and August. This analysis demonstrates substantial seasonal (figure S3) and inter-annual variability in the transport of fire emissions to Singapore with maximum contributions simulated in September and October 2006, matching the variability simulated by the global model (figure S1).

Over the whole study period (2004–07), fires in southern Sumatra make the largest relative contribution to the total fire-emitted CO transported to Singapore (62%). This is consistent with previous work that demonstrated that more than 90% of hazy days in Singapore (visibility < 8000 m) occurred when back trajectories passed over southern Sumatra on days with fire hot spots (See *et al* 2006). Fires in central Sumatra and Indonesian Borneo contribute 21% and 15%, respectively of the total fire emissions transported to Singapore. We note that whilst this analysis accounts for locations of fires and the atmospheric transport of emissions, it does not account for variations in atmospheric residence time driven by changes in deposition of particulates. Assuming an infinite residence time of the fire-emitted CO, this method predicts a larger relative contribution from fires in southern Sumatra (thus a
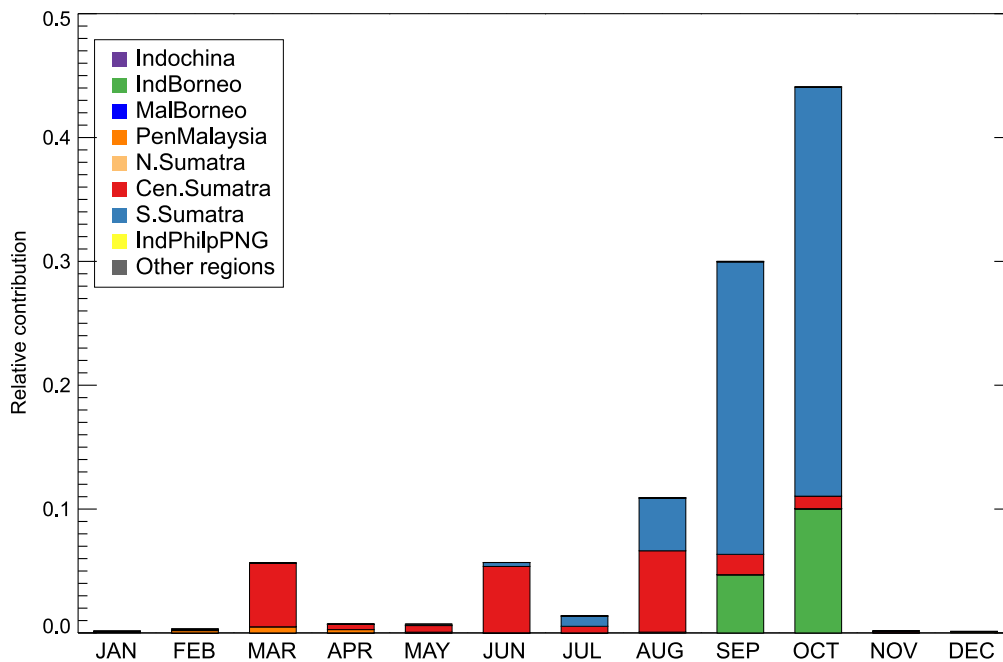
Figure 5. Regional relative contributions to fire-emitted CO transported to Singapore between January 2004 and December 2007. Relative contributions are calculated as the total CO from each emission region emitted into air parcels arriving at Singapore as a fraction of the total CO emitted into all air parcels over the entire period and domain. Regions are displayed in figure 1.
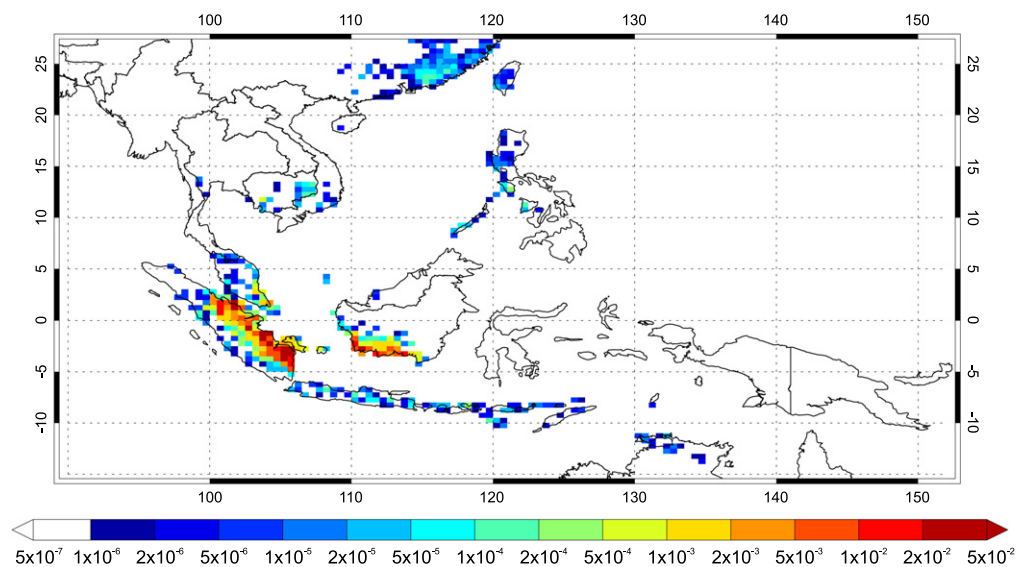

Figure 6. Gridded relative contributions to fire-emitted CO transported to Singapore between January 2004 and December 2007. Relative contributions are calculated as the total CO from each emission grid cell emitted into air parcels arriving at Singapore as a fraction of the total CO emitted into all air parcels over the entire period and domain. Emission from grid cells into each air mass trajectory is calculated as the emission flux at the grid cell over which the trajectory passes multiplied by the residence time of the trajectory over the grid cell.

smaller relative contribution from fires in central Sumatra) compared to the global model where changes in residence times are explicitly simulated.

Figure 6 shows the spatial distribution of fire emissions transported to Singapore during 2004–07. Fires in southern Sumatra, central Sumatra and southwest Kalimantan are the largest contributors of fire-emitted CO transported to Singapore, matching the results from the global model. However, the higher spatial resolution of this analysis compared to the

global model simulations allows finer scale features to be resolved. The fires in southern Sumatra are located in the eastern part of the province of South Sumatra and the southeastern parts of the provinces of Jambi and Lampung. The fires in central Sumatra are located in the eastern part of the province of Riau, and the fires in southern Borneo are located in the southern extent of the provinces of West, Central and South Kalimantan.
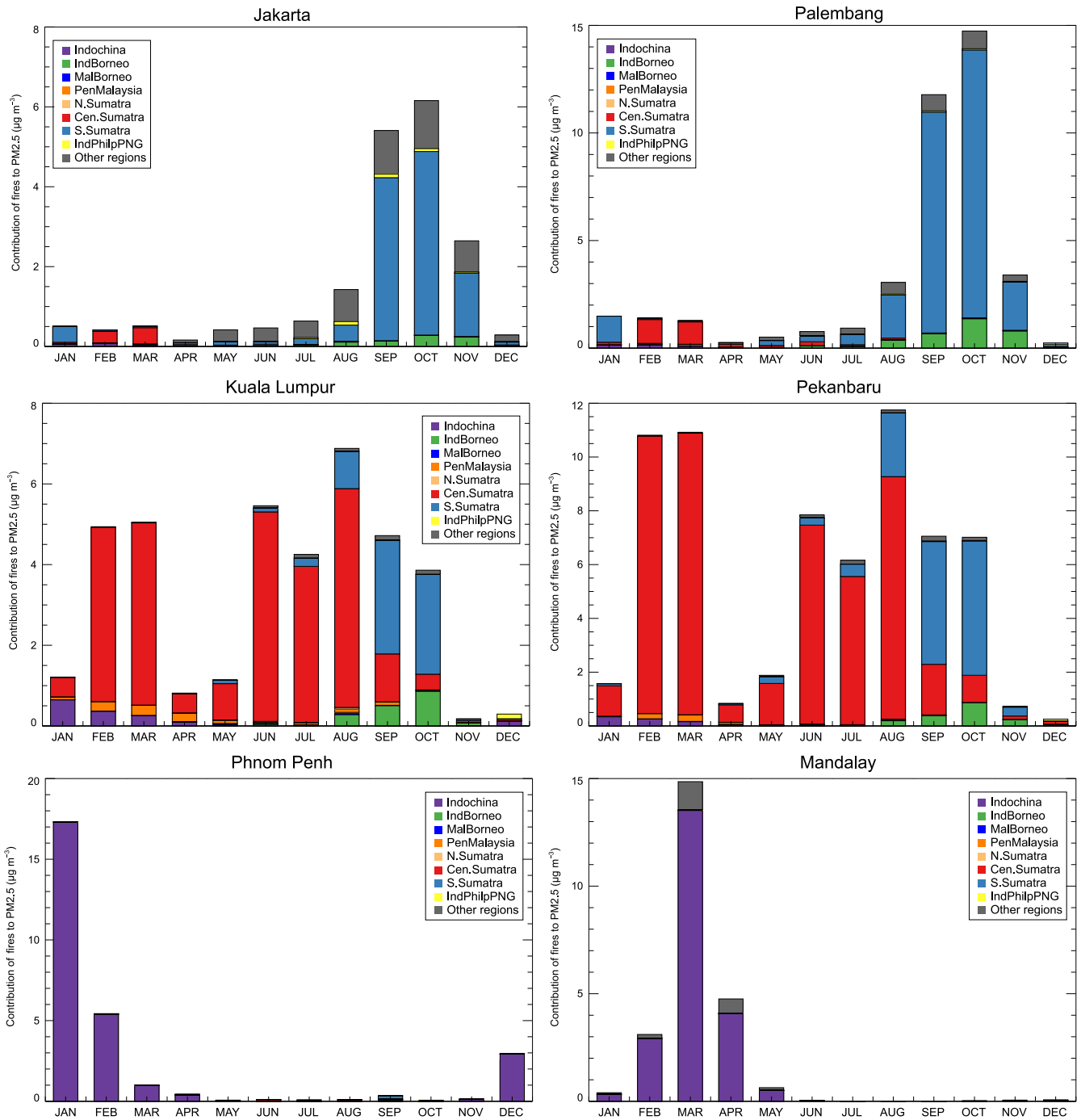
Figure 7. The long-term (January 2004–December 2009) mean contribution of fire emissions from different regions in Southeast Asia (defined in figure 1) to simulated monthly-mean PM$_{2.5}$ concentrations over Jakarta, Palembang and Pekanbaru in Indonesia; Kuala Lumpur, Malaysia; Phnom Penh, Vietnam; and Mandalay, Myanmar.

3.4. Contribution of fires to PM$_{2.5}$ in other major cities in Southeast Asia

To explore the impact of fire emissions over the wider region of Southeast Asia, we used the GLOMAP model to simulate the contribution of fire emissions to PM$_{2.5}$ concentrations in 15 cities across the region with a population greater than one million (locations shown in figure 1). Figure 7 shows the simulated long-term (2004–09) mean contribution of fires to monthly-mean PM$_{2.5}$ concentrations in six of these cities. It is

important to highlight that the simulated enhancement to PM$_{2.5}$ concentrations from fires is greater in four of these cities (Palembang, Pekanbaru, Phnom Penh and Mandalay) than in Singapore; due to their closer proximity to biomass burning regions.

Cities in southern Sumatra (Palembang) and western Java (Jakarta) are affected by fires in a similar way to Singapore, with peak contributions from fires to PM$_{2.5}$ in September (mean Palembang: 11.8 μg m^{-3}; Jakarta: 5.4 μg m^{-3}) and October (Palembang: 14.7 μg m^{-3}; Jakarta: 6.2 μg m^{-3}).

PM$_{2.5}$ concentrations are dominated by emissions from southern Sumatra, except in February–March where emissions from central Sumatra dominate. Between 2004 and 2009, fires in southern Sumatra account for 60–74% of the total fire enhancement to PM$_{2.5}$ in Jakarta and Palembang, with 5–7% from fires in central Sumatra. Fires in regions located outside those defined in figure 1 (e.g. northern Australia) account for 8–27% of the total fire enhancement to PM$_{2.5}$.

In Kuala Lumpur (Peninsula Malaysia) and Pekanbaru (Riau, central Sumatra) there is a considerable contribution from fires to PM$_{2.5}$ throughout the year with the largest contribution from fires in central Sumatra (69–74% of the total fire enhancement). Both cities are also impacted by fire emissions from southern Sumatra during August–October (17–20% of the total fire enhancement).

The contribution of fires to PM$_{2.5}$ in Batam, Riau Islands (not shown in figure 7) is similar to Singapore, with the largest contribution from fires in southern Sumatra (51% of the total fire enhancement to PM$_{2.5}$) and secondary contributions from fires in central Sumatra (23%) and Indonesian Borneo (15%). The cities of Singapore and Batam are close together and are affected by similar wind patterns and transport pathways of smoke emissions. Simulated long-term mean contributions of fires to PM$_{2.5}$ over the other analysed cities in Indonesia (Surabaya, Medan and Makassar) and Manila in the Philippines are relatively small (mean $\leqslant 2\,\mu\mathrm{g\,m^{-3}}$).

Simulated PM$_{2.5}$ concentrations over cities in Indochina (Hanoi, Ho Chi Minh, Yangon, Mandalay, Phnom Penh, and Bangkok) are affected by local fire emissions from January to April, with little contribution from fires during May–November. The two cities with the largest contributions from fires, Phnom Penh and Mandalay, are shown in figure 7. Contributions to PM$_{2.5}$ concentrations from fires in this region (dominated by deforestation and agricultural fires) show less inter-annual variability than the contributions from fires in Sumatra and Borneo (dominated by peat and deforestation fires).

4. Conclusions and implications

We have used two complementary methods to explore the contribution of smoke from vegetation and peat fires across Southeast Asia to PM$_{2.5}$ concentrations in Singapore. Firstly, we used a global aerosol model to simulate PM$_{2.5}$ concentrations and investigate the contributions from different defined regions by switching off fire emissions from one region at a time. Secondly, we used a Lagrangian atmospheric transport model to simulate the transport of fire emissions to Singapore. Both methods used fire emissions derived from satellite remote sensing. Our global model simulations are restricted to a coarse spatial resolution meaning that the model is unable to resolve urban scale pollution and absolute PM$_{2.5}$ concentrations in Singapore are underpredicted. We are therefore not able to quantify the fractional contribution of fires to total PM$_{2.5}$ concentrations in Singapore. Despite the coarse spatial resolution of our model, it is able to capture

observed seasonal and inter-annual variability in observed PM and AOD. Future work should repeat our analysis with regional atmospheric models with higher spatial resolution. Nevertheless, our two methods produced consistent results providing additional confidence in our conclusions.

Over the studied period (2004–09), we found that Singapore is impacted by smoke from vegetation and peat fires predominantly in June–October and February–March, with the largest contribution from fires occurring in September and October. We found that fires in southern Sumatra account for the largest percentage of the total fire enhancement to PM$_{2.5}$ in Singapore (42–62%), with fires in central Sumatra and Indonesian Borneo (Kalimantan) contributing 21–35% and 14–15%, respectively. Therefore, fires in central Sumatra that are closest to Singapore were not the dominant source of fire-induced PM$_{2.5}$ pollution in Singapore between 2004 and 2009. Instead, fires in South Sumatra (located ∼550 km from Singapore) contributed more to PM$_{2.5}$ pollution in Singapore. Establishing this source-receptor relationship in a quantitative manner provides useful information for policy makers in the region to develop appropriate air quality management strategies to protect public health. Our work suggests that preventing fires occurring in southern Sumatra (in the eastern part of the provinces of Jambi, South Sumatra and Lampung), central Sumatra (in the eastern part of the province of Riau) and southwest Kalimantan (in the southern extent of the provinces of West, Central and South Kalimantan) would result in the largest benefit to particulate air quality over Singapore.

We also explored the impact of vegetation and peat fires on PM$_{2.5}$ concentrations across other major cities in the region. We found the fires that contributed most to PM$_{2.5}$ concentrations in Singapore also contributed substantially to PM$_{2.5}$ concentrations across the rest of the region. Jakarta, Palembang and Batam are mostly impacted by fires in southern Sumatra (accounting for 51–74% of the total fire enhancement to PM$_{2.5}$), whereas Kuala Lumpur and Pekanbaru are impacted most by fires in central Sumatra (accounting for 69–74% of the total fire enhancement to PM$_{2.5}$). Therefore, targeting fire reduction efforts to improve air quality in Singapore will also improve air quality in other major cities in Indonesia and Malaysia.

The large fire emissions from central and southern Sumatra and Kalimantan that are causing air quality issues in Singapore are coincident with ongoing deforestation and expansion of oil palm plantations (Koh *et al* 2011, Miettinen *et al* 2011, Ramdani and Hino 2013). Forest cover in Southeast Asia declined by 1.45 million hectares per year over the period 2000–10 (Stibig *et al* 2014), with natural forest largely being replaced by oil palm plantations (Koh *et al* 2011). The extent of future fires in the Southeast Asia region will be linked to patterns of land-use change (Carlson *et al* 2012), potentially exacerbated by changing climate conditions (Field *et al* 2009). In particular, the expansion of large-scale oil palm plantations, which have been linked to the use of fire for land clearing activities (Varkkey 2013), is likely to be a key driver of future fires. Future land use change, under business as usual scenarios, includes continued

expansion of oil palm plantation in regions that we have identified to be crucial for air quality in Singapore: southern Kalimantan (Carlson et al 2012) and central to southern Sumatra (e.g. Wicke et al 2011, Miettinen et al 2012). In Kalimantan, 79% of allocated oil palm leases remain undeveloped (Carlson et al 2013), creating the potential for large future expansion of this land use type. In this region, rates of deforestation are significantly greater in oil palm concessions compared to natural forest timber concessions or protected areas (Gaveau et al 2013), suggesting that maintenance and expansion of protected areas and natural forest timber concessions would help reduce deforestation and prevent future fires. Strict enforcement of regulations prohibiting the use of fire to prepare lands for plantation agriculture may mitigate smoke emissions and improve regional air quality. However, plantation agriculture on peatlands requires extensive drainage (Carlson et al 2012) creating conditions conducive to the spread of accidental fire during El Niño droughts (Field et al 2009). Furthermore, oil palm plantations have been linked to enhanced regional ozone concentrations due to altered emissions of biogenic volatile organic compounds from vegetation and emissions of oxides of nitrogen from agro-industrial activity (Hewitt et al 2009, Warwick et al 2013). To ensure improved air quality in Singapore and surrounding regions, fire management needs to be combined with sustainable agricultural expansion that does not lead to deforestation, forest degradation or peatland drainage (Smit et al 2013).

Acknowledgements

References

Atwood S A, Reid J S, Kreidenweis S M, Yu L E, Salinas S V, Chew B N and Balasubramanian R 2013 Analysis of source regions for smoke events in Singapore for the 2009 El Niño burning season Atmos. Environ. **78** 219–30

Balasubramanian R, Qian W-B, Decesari S M C, Facchini M C and Fuzzi S 2003 Comprehensive characterization of PM2.5 aerosols in Singapore J. Geophys. Res. **108** 4523

Betha R, Behera S N and Balasubramanian R 2014 Southeast Asian smoke haze: fractionation of particulate-bound elements and associated health risk Environ. Sci. Technol. **48** 4327–35

Carlson K M, Curran L M, Asner G P, McDonald Pittman A, Trigg S N and Adeney J M 2013 Carbon emissions from forest conversion by Kalimantan oil palm plantations Nat. Clim. Change **3** 283–7

Carlson K M, Curran L M, Ratnasari D, Pittman A M, Soares-Filho B S, Asner G P, Trigg S N, Gaveau D A, Lawrence D and Rodrigues H O 2012 Committed carbon emissions, deforestation, and community land conversion from oil plam plantation expansion in West Kalimantan, Indonesia Proc. Natl. Acad. Sci. USA **109** 7559–64

Emmanuel S C 2000 Impact to lung health of haze from forest fires: the Singapore experience Respirology **5** 175–82

Engling G, He J, Betha R and Balasubramanian R 2014 Assessing the regional impact of Indonesian biomass burning emissions based on organic molecular tracers and chemical mass balance modeling Atmos. Chem. Phys. Discuss **14** 8043–54

Field R D and Shen S S P 2008 Predictability of carbon emissions from biomass burning in Indonesia from 1997 to 2006 J. Geophys. Res. **113** G04024

Field R D, van der Werf G R and Shen S S P 2009 Human amplification of drought-induced biomass burning in Indonesia since 1960 Nat. Geosci. **2** 185–8

Frankenberg E, McKee D and Thomas D 2005 Health consequences of forest fires in Indonesia Demography **42** 109–29

Fu J S, Hsu N C, Gao Y, Huang K, Li C, Lin N-H and Tsay S-C 2012 Evaluating the influences of biomass burning during 2006 BASE-ASIA: a regional chemical transport modeling Atmos. Chem. Phys. **12** 3837–55

Gautam R, Hsu N C, Eck T F, Holben B N, Janjai S, Jantarach T, Tsay S-C and Lau W K 2013 Characterization of aerosols over the Indochina peninsular from satellite-surface observations during biomass burning pre-monsoon season Atmos. Environ. **78** 51–9

Gaveau D L A et al 2013 Reconciling forest conservation and logging in Indonesian Borneo PLoS One **8** e69887

Goldammer J G 2006 History of equatorial vegetation fires and fire research in Southeast Asia before the 1997–98 episode: a reconstruction of creeping environmental changes Mitigation Adapt. Strateg. Glob. Change **12** 13–32

Hewitt C et al 2009 Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution Proc. Natl. Acad. Sci. USA **106** 18447–51

Huang K, Fu J S, Hsu N C, Gao Y, Dong X, Tsay S-C and Lam Y F 2013 Impact assessment of biomass burning on air quality in Southeast and East Asia during BASE-ASIA Atmos. Environ. **78** 291–302

Johnston F H, Henderson S B, Chen Y, Randerson J T, Marlier M, Defries R S, Kinney P, Bowman D M and Brauer M 2012 Estimated global mortality attributable to smoke from landscape fires Environ. Health Perspect. **120** 695–701

Kaiser J W et al 2012 Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power Biogeosciences **9** 527–54

Koh L P, Miettinen J, Liew S C and Ghazoul. J 2011 Remotely sensed evidence of tropical peatland conversion to oil palm Proc. Natl. Acad. Sci. **108** 5127–32

Kunii O, Kanagawa S, Yajima I, Hisamatsu Y, Yamamura S, Amagai T and Ismail I T 2002 The 1997 haze disaster in Indonesia: its air quality and health effects Arch. Environ. Health **57** 16–22

Langner A, Miettinen J and Siegert F 2007 Land cover change 2002–2005 in Borneo and the role of fire derived from MODIS imagery Glob. Change Biol. **13** 2329–40

Lim S S, Vos T, Flaxman A D, Danaei G, Shibuya K, Adair-Rohani H and Amann M Ezzati M 2012 A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010 Lancet **380** 2224–60

Logan J A, Megretskaia I A, Nassar R, Murray L T, Zhang L, Bowman K W, Worden H M and Luo M 2008 Effects of the 2006 El Niño on tropospheric composition as revealed by data from the Tropospheric Emission Spectrometer (TES) *Geophys. Res. Lett.* **35** L03816

Mann G W *et al* 2012 Intercomparison of modal and sectional aerosol microphysics representations within the same 3D global chemical transport model *Atmos. Chem. Phys.* **12** 4449–76

Mann G W, Carslaw K S, Spracklen D V, Ridley D A, Manktelow P T, Chipperfield M P, Pickering S J and Johnson C E 2010 Description and evaluation of GLOMAP-mode: a modal global aerosol microphysics model for the UKCA composition-climate model *Geosci. Model Dev.* **3** 519–51

Marlier M E, DeFries R S, Voulgarakis A, Kinney P L, Randerson J T, Shindell D T, Chen Y and Faluvegi G 2012 El Niño and health risks from landscape fire emissions in southeast Asia *Nat. Clim. Change* **3** 131–6

Methven J, Arnold S R, O'Connor F M, Barjat H, Dewey K, Kent J and Brough N 2003 Estimating photochemically produced ozone throughout a domain using flight data and a Lagrangian model *J. Geophys. Res.* **108** 4271

Miettinen J, Hooijer A, Shi C, Tollenaar D, Vernimmen R, Liew S C, Malins C and Page S E 2012 Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections *GCB Bioenergy* **4** 908–18

Miettinen J, Shi C and Liew S C 2011 Deforestation rates in insular Southeast Asia between 2000 and 2010 *Glob. Change Biol.* **17** 2261–70

Nassar R, Logan J A, Megretskaia I A, Murray L T, Zhang L and Jones D B A 2009 Analysis of tropical tropospheric ozone, carbon monoxide, and water vapor during the 2006 El Niño using TES observations and the GEOS-Chem model *J. Geophys. Res.* **114** D17304

Ostro B, Chestnut L, Vichit-vadakan N and Laixthai A 1999 The impact of particulate matter on daily mortality in Bangkok, Thailand *J. Air Waste Manage.* **49** 100–7

Page S E, Siegert F, Rieley J O, Boehm H D V, Jaya A and Limin S 2002 The amount of carbon released from peat and forest fires in Indonesia during 1997 *Nature* **420** 61–5

Pavagadhi S, Betha R, Venkatesan S, Balasubramanian R and Hande M P 2013 Physiochemical and toxicological characteristics of urban aerosols during a recent Indonesian biomass burning episode *Environ. Sci. Pollut. R.* **20** 2569–78

Ramdani F and Hino M 2013 Land use changes and GHG emissions from tropical forest conversion by oil palm plantation in Riau Province, Indonesia *PLOS ONE* **8** e70323

Randerson J T, Chen Y, van der Werf G R, Rogers B M and Morton D C 2012 Global burned area and biomass burning emissions from small fires *J. Geophys. Res.* **117** G04012

Salinas S V, Chew B N, Miettinen J, Campbell J R, Welton E J, Reid J S, Yu L E and Liew S C 2013 Physical and optical characteristics of the October 2010 haze event over Singapore: a photometric and lidar analysis *Atmos. Res.* **122** 555–70

Saji N H, Goswami B N, Vinayachandran P N and Yamagata T 1999 A dipole mode in the tropical Indian Ocean *Nature* **401** 360–3

Schultz M G, Heil A, Hoelzemann J J, Spessa A, Thonicke K, Goldammer J G, Held A C, Pereira J M C and van het Bolscher M 2008 Global wildland fire emissions from 1960 to 2000 *Global Biogeochem. Cycles* **22** GB2002

See S W, Balasubramanian R and Wang W 2006 A study of the physical, chemical and optical properties of ambient aerosol particles in Southeast Asia during hazy and nonhazy days *J. Geophys. Res.* **111** D10S08

Shi Y, Sasai T and Yamaguchi Y 2014 Spatio-temporal evaluation of carbon emissions from biomass burning in Southeast Asia during the period 2001–2010 *Ecol. Modell.* **272** 98–115

Siegert F, Ruecker G, Hinrichs A and Hoffmann A A 2001 Increased damage from fires in logged forests during droughts caused by El Niño *Nature* **414** 437–40

Smit H H, Meijaard E, van der Laan C, Mantel S, Budiman A and Verweij P 2013 Breaking the link between environmental degradation and oil palm expansion: a method for enabling sustainable oil palm expansion *PLoS ONE* **8** e68610

Spracklen D V *et al* 2010 Explaining global surface aerosol number concentrations in terms of primary emissions and particle formation *Atmos. Chem. Phys.* **10** 4775–93

Spracklen D V, Carslaw K S, Pöschl U, Rap A and Forster P M 2011a Global cloud condensation nuclei influenced by carbonaceous combustion aerosol *Atmos. Chem. Phys.* **11** 9067–87

Spracklen D V *et al* 2011b Aerosol mass spectrometer constraint on the global secondary organic aerosol budget *Atmos. Chem. Phys.* **11** 12109–36

Spracklen D V, Pringle K J, Carslaw K S, Mann G W, Manktelow P and Heintzenberg J 2007 Evaluation of a global aerosol microphysics model against size-resolved particle statistics in the marine atmosphere *Atmos. Chem. Phys.* **7** 2073–90

Stibig H-J, Achard F, Carboni S, Raši R and Miettinen J 2014 Change in tropical forest cover of Southeast Asia from 1990 to 2010 *Biogeosciences* **11** 247–58

Taylor K E 2001 Summarizing multiple aspects of model performance in a single diagram *J. Geophys. Res.* **106** 7183–92

Tosca M G, Randerson J T, Zender C S, Nelson D L, Diner D J and Logan J A 2011 Dynamics of fire plumes and smoke clouds associated with peat and deforestation fires in Indonesia *J. Geophys. Res.* **116** D08207

Tosca M G, Randerson J T and Zender C S 2013 Global impact of smoke aerosols from landscape fires on climate and the Hadley circulation *Atmos. Chem. Phys.* **13** 5227–41

van der Werf G R *et al* 2008 : Climate regulation of fire emissions and deforestation in equatorial Asia *Proc. Natl. Acad. Sci. USA* **105** 20350–5

van der Werf G R, Randerson J T, Collatz G J, Giglio L, Kasibhatla P S, Arellano A F, Olsen S C and Kasischke E S 2004 Continental-scale partitioning of fire emissions during the 1997 to 2001 El Niño/La Niña period *Science* **303** 73–6

van der Werf G R, Randerson J T, Giglio L, Collatz G J, Mu M, Kasibhatla P S, Morton D C, DeFries R S, Jin Y and van Leeuwen T T 2010 Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009) *Atmos. Chem. Phys.* **10** 11707–35

Varkkey H 2013 Patronage politics, plantation fires and transboundary haze *Environ. Hazards* **12** , 200–17

Warwick N J *et al* 2013 A global model study of the impact of land-use change in Borneo on atmospheric composition *Atmos. Chem. Phys.* **13** 9183–94

Wicke B, Sikkema R, Dornburg V and Faaij A 2011 Exploring land use changes and the role of palm oil production in Indonesia and Malaysia *Land Use Policy* **28** 193–206

Wiedinmyer C, Akagi S K, Yokelson R J, Emmons L K, Al-Saadi J A, Orlando J J and Soja A J 2011 The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning *Geosci. Model Dev.* **4** 625–41

Wooster M J, Perry G L W and Zoumas A 2012 Fire, drought and El Niño relationship on borneo (Southeast Asia) in the Pre-MODIS era (1980–2000) *Biogeosciences* **9** 317–40

Xian P, Reid J S, Atwood S A, Johnson R S, Hyer E J, Westphal D L and Sessions W 2013 Smoke transport patterns over the maritime continent *Atmos. Res.* **122** 469–85

Yulianti N, Hayasaka H and Sepriando A 2013 Recent trends of fire occurrence in Sumatra (analysis using MODIS hotspot data): a comparison with fire occurrence in Kalimantan *Open J. Forestry* **3** 129–37