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# Sensitivity of population smoke exposure to fire locations in Equatorial Asia

Patrick S. Kim [a,*], Daniel J. Jacob [a,b], Loretta J. Mickley [b], Shannon N. Koplitz [a], Miriam E. Marlier [c], Ruth S. DeFries [c], Samuel S. Myers [d,e], Boon Ning Chew [f], Yuhao H. Mao [g,h]

[a] Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA
[b] School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA
[c] Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York, NY, USA
[d] Department of Environmental Health, Harvard School of Public Health, Harvard University, Cambridge, MA, USA
[e] Harvard University Center for the Environment, Harvard University, Cambridge, MA, USA
[f] Centre for Remote Imaging, Sensing and Processing, National University of Singapore, Singapore
[g] Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA
[h] Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, CA, USA

## HIGHLIGHTS

- Smoke exposure sensitivity to Equatorial Asian fires computed with adjoint model.
- Protecting Sumatran peatswamp forests is key to future regional air quality.
- The GEOS-Chem adjoint can provide guidance for targeted land conservation.

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## ABSTRACT

High smoke concentrations in Equatorial Asia, primarily from land conversion to oil palm plantations, affect a densely populated region and represent a serious but poorly quantified air quality concern. Continued expansion of the oil palm industry is expected but the resulting population exposure to smoke is highly dependent on where this expansion takes place. We use the adjoint of the GEOS-Chem chemical transport model to map the sensitivity of smoke concentrations in major Equatorial Asian cities, and for the population-weighted region, to the locations of the fires. We find that fires in southern Sumatra are particularly detrimental, and that a land management policy protecting peatswamp forests in Southeast Sumatra would be of great air quality benefit. Our adjoint sensitivities can be used to immediately infer population exposure to smoke for any future fire emission scenario.



## 1. Introduction

Global palm oil production has more than doubled since 2000 in response to soaring demand (FAO, 2013). Indonesia and Malaysia together account for 86% of the world's production and Indonesia plans to further double its output by 2020 (AFP, 2009; Koh and Ghazoul, 2010). The demand for palm oil is driving rapid deforestation to clear land for new plantations (Koh et al., 2011; Mietinen et al., 2012). The area covered by oil palm plantations in Indonesia tripled from 2000 to 2012 (FAO, 2013). The land is mainly cleared and managed by fire. The resulting smoke pollutes the airshed of one of the most densely populated regions of the world. According to Marlier et al. (2013), the unusually large fire season of 1997 resulted in 10,000 excess deaths from smoke exposure in Equatorial Asia. More recently, Sumatran fires in June 2013 caused a 24-h maximum particulate matter (PM) concentration of 300 μg $m^{-3}$

* Corresponding author. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA.
*E-mail address:* kim68@fas.harvard.edu (P.S. Kim).

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in Singapore, far exceeding the 25 μg m$^{-3}$ air quality guideline from the World Health Organization (WHO, 2006).

The fire season in Equatorial Asia is typically July–November (dry season), with large interannual variation in intensity (van der Werf et al., 2010) driven in part by the El Nino-Southern Oscillation and associated dryness (Reid et al., 2012, 2013). Presently there is less interannual variability in the location of the fires, with land conversion mostly occurring in the South Sumatran lowlands and the southern and western coasts of Borneo (Miettinen et al., 2010).

The fire plumes are transported by the prevailing southwesterly flow (Fig. 1) such that some population centers are minimally affected by the smoke (e.g., Jakarta), while others are heavily affected (e.g., Singapore). Fires in different areas have very different air quality implications depending on the population downwind. Public health costs could be reduced by targeting sensitive areas for conservation while allowing palm oil development in other areas. Previous studies have examined the transport of smoke in Equatorial Asia using chemical transport model (CTM) simulations (Heil et al., 2007; Hyer and Chew, 2010; Wang et al., 2013) and trajectory analyses (Koe et al., 2001; He et al., 2010; Atwood et al., 2013). They have highlighted the importance of peat burning in Sumatra and Borneo on downstream surface air quality (Heil et al., 2007) as well as the complexity of local scale meteorological phenomena, including the sea-breeze effect and surface topography (Wang et al., 2013).

Here we use the adjoint of the GEOS-Chem CTM (Bey et al., 2001; Henze et al., 2007) to map the sensitivity of smoke concentrations to fire location for selected urban receptor locations in Equatorial Asia as well as for the entire population of the region. The adjoint is the transpose of the CTM, allowing model sensitivities to be tracked back in time through the CTM fields (Kopacz et al., 2011). It is a computationally efficient method to determine the sensitivity of model output to many input parameters (Errico and Vukicevic, 1992). Our work provides a basis to identify where fires could most effectively be restricted to reduce population exposure, and to readily determine the exposure associated with any future land management scenario.

## 2. Materials & methods

We examine here the sensitivity of different population centers (receptor sites) in Equatorial Asia to the geographical distribution of smoke emissions throughout the region. Our analysis is based on meteorological data for July–November 2006 and is applied to different present and future fire scenarios. The smoke simulation uses the GEOS-Chem CTM and is evaluated with a surface network of observations in Malaysia and Singapore. Sensitivity of receptor sites to different fire locations is computed with the GEOS-Chem adjoint.

### *2.1. The GEOS-Chem CTM and its adjoint*

We use GEOS-Chem v8-02-01 (www.geos-chem.org) driven by assimilated meteorological data from the Goddard Earth Observing System (GEOS-5) of the NASA Modeling and Assimilation Office (GMAO). The data have a native horizontal resolution of 0.50° × 0.67° with 72 pressure levels and 6-h temporal frequency (3-h for surface variables and mixing depths). We focus on simulating primary PM (smoke) emitted by the fires as organic and black carbon (OC/BC). The OC/BC simulation in GEOS-Chem is described by Wang et al. (2011). Open fire emissions are from the GFED3 inventory (Giglio et al., 2010; van der Werf et al., 2010) with monthly resolution. The standard GFED3 product does not consider small fires, which account for one third of total fire emissions in Equatorial Asia (Randerson et al., 2012). We therefore increase the GFED3 emissions by 50%.

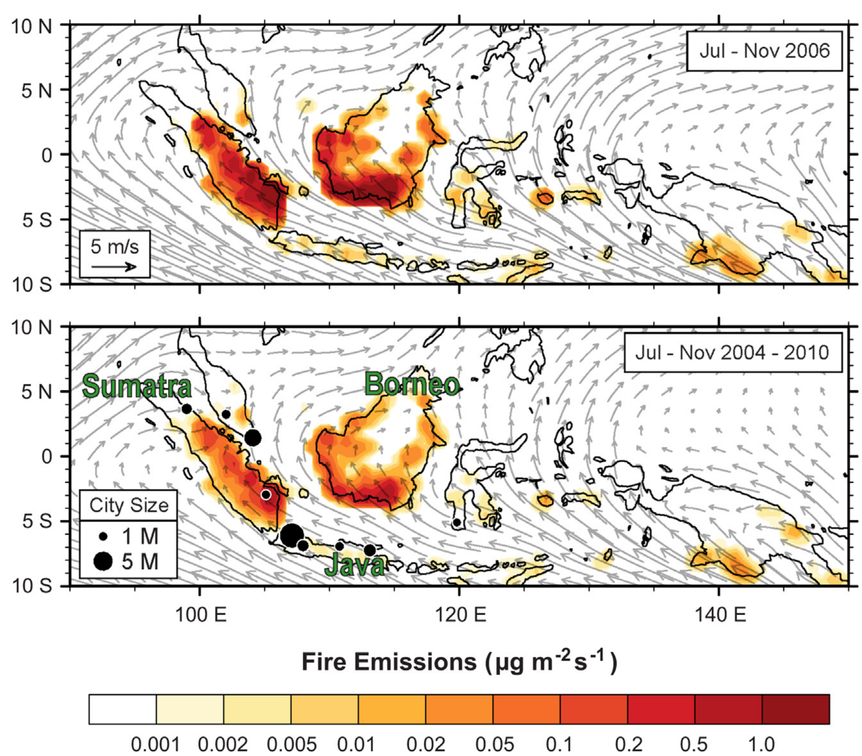


**Fig. 1.** Fire emissions and mean 0–1 km vector winds in Equatorial Asia in July–November. The top panel is for 2006 (a high fire year) and the bottom panel is the 2004–2010 mean. Fire emissions are from the GFED3 inventory, increased by 50% to account for small fires (see text). Winds are from GEOS-5 assimilated meteorological data. Also shown are the locations of cities with more than one million people.

Fig. 1 shows the spatial distribution of fire emissions in Equatorial Asia for 2006 and for 2004–2010, and Fig. 2 (top panel) shows the interannual variability in total fire emissions for the region. 2006 was a high fire year associated with El Nino conditions (van der Werf et al., 2010; Reid et al., 2012) while 2010 had almost no fires. The fires are mainly in Sumatra and Borneo for all years. Sumatra accounts for 36–60% of total regional emissions depending on the year (2004–2009). Emissions are highest in the peatlands of southeastern Sumatra and southern Borneo.

The GEOS-Chem results presented here are for a simulation with the native 0.50° × 0.67° horizontal resolution over East Asia [70°–150° E, 11° S–55° N] (Chen et al., 2009), nested within a global simulation with 4° × 5° horizontal resolution that provides dynamic boundary conditions. We focus on the 2006 fire season (July–November) following a 1-year initialization. As shown in Fig. 1, the boundary layer winds (0–1 km) in 2006 were typical of the 2004–2010 mean.

We use the GEOS-Chem adjoint version 34 (Kopacz et al., 2011) for source attribution of the simulated smoke concentrations at selected receptor sites (Singapore, Palembang, and Jakarta) and for the whole population-weighted Equatorial Asia region (population distribution from http://web.ornl.gov/sci/landscan). The adjoint simulation is conducted for the July–November duration of the fire season $[t_0, t_1]$. A single simulation with the adjoint model operating backward in time over $[t_1, t_0]$ yields the complete time-dependent footprint of sources contributing to the smoke concentrations at a particular receptor site and for any averaging time. The GEOS-Chem adjoint has previously been used in this manner to determine source contributions to BC/OC aerosol concentrations in the Himalayas (Kopacz et al., 2011).

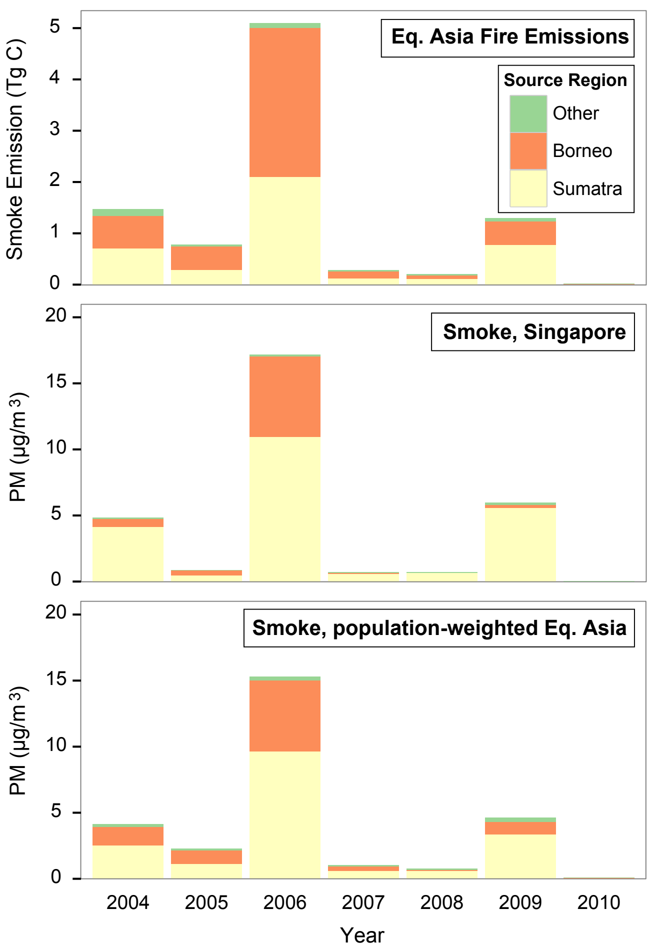


**Fig. 2.** Interannual variability in smoke emissions and associated population exposure in Equatorial Asia (domain of Fig. 1). The top panel shows total July–November emissions and the bottom panels show mean July–November smoke concentrations for Singapore and for population-weighted Equatorial Asia computed from the GEOS-Chem adjoint (Equation (1)) with 2006 meteorology. The smoke concentrations are partitioned into contributions from fires in Borneo, Sumatra, and other regions.

Smoke concentrations in GEOS-Chem are proportional to emissions so that the total smoke mass concentration $PM(\mathbf{x_R}, t')$ at receptor site $\mathbf{x_R}$ and time $t'$ is given by

$$\mathrm{PM}(x_R, t') = \int_{t_0}^{t'} \oiint_{x} \frac{\partial \mathrm{PM}(x_R, t')}{\partial E(x, t)} E(x, t)\mathrm{d}x\mathrm{d}t \tag{1}$$

where $E(\mathbf{x}, t)$ is the emission flux (g m$^{-2}$ s$^{-1}$) at location $\mathbf{x}$ and time $t < t'$, $t_0$ is the beginning of the fire season, and the spatial integration is over the entire emitting domain. One adjoint simulation conducted over the time period $[t_1, t_0]$ provides the ensemble of sensitivities $\partial PM(\mathbf{x_R}, t')/\partial E(\mathbf{x}, t)$ for $PM$ at a selected receptor site $\mathbf{x_R}$ and at all times $t'$ to the emissions for all domain grid squares ($\mathbf{x}$) and all prior times ($t < t'$). Instead of a single receptor location, the adjoint can also provide the same ensemble of sensitivities for the population-weighted mean smoke concentration ($\overline{\mathrm{PM}}$) over the entire Equatorial Asia domain (i.e. $\partial\overline{\mathrm{PM}}(t')/\partial E(\mathbf{x}, t)$).

### 2.2. Surface $PM_{10}$ observations

Measurements of 24-h mean $PM_{10}$ (mass concentration of particulate matter finer than 10 μm aerodynamic diameter) are available from a network of surface sites maintained by the Malaysian Department of the Environment (http://www.doe.gov.my/) and the Singaporean National Environment Agency (http://www.nea.gov.sg/) (Hyer and Chew, 2010). The site locations (marked on the map in Fig. 3) are predominantly in urban areas and away from the main fire locations. We estimate the smoke concentration at each site in the observations by subtracting as baseline the mean concentration for the bracketing non-burning months (June and December).

### 2.3. Future fire scenarios

The adjoint sensitivities $\partial \mathrm{PM}(\mathbf{x_R}, t')/\partial E(\mathbf{x}, t)$ described in Section 2.1 can be used with Equation (1) to immediately derive population exposure to smoke under any future emission scenario $E(\mathbf{x}, t)$. Here we examine the impact of two possible 2009–2032 future emission scenarios for Sumatra described by Marlier et al. (2014): a "High Oil Palm" scenario with continued rapid plantation expansion (including into peatswamps where fuel loads are particularly high), and a "Green Vision with Peat Protection" scenario that promotes sustainable development and where all remaining peatswamp forests are preserved. Marlier et al. (2014) give mean Sumatran emissions of 256 Gg a$^{-1}$ for present-day (2004–2010), 414 Gg a$^{-1}$ for the High Oil Palm scenario, and 186 Gg a$^{-1}$ for the Peat Protection scenario. Their present-day emission estimates are 40% lower than ours for the same time period, likely due to their explicit treatment of small fires compared to our application of a 50% increase to the standard GFED3 product. We have some confidence in our estimate on the basis of better comparisons to observed smoke concentrations (next section). The Marlier et al. (2014) present-day Sumatran emissions nevertheless serve as a baseline against which their future projections can be compared.

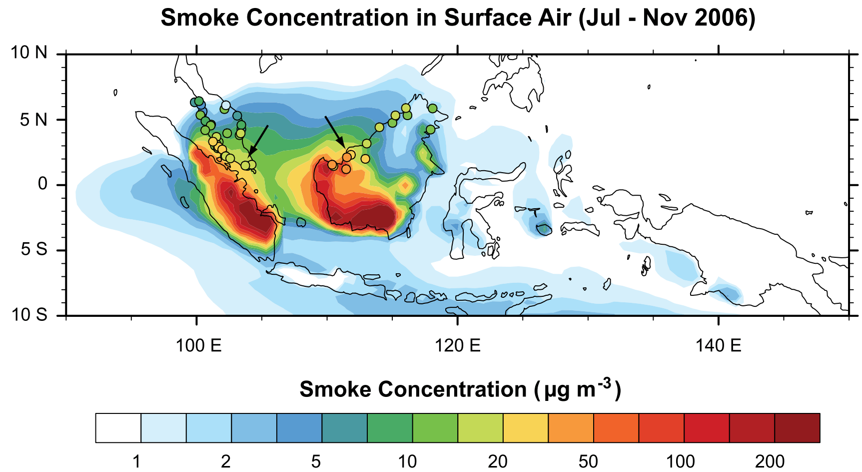


**Fig. 3.** Mean smoke concentration in surface air for July–November 2006, observed at a network of sites (circles; see text for details) and simulated by GEOS-Chem. Arrows point to the locations of Singapore and Sibu (western Borneo) for which time series of concentrations are shown in Fig. 4.

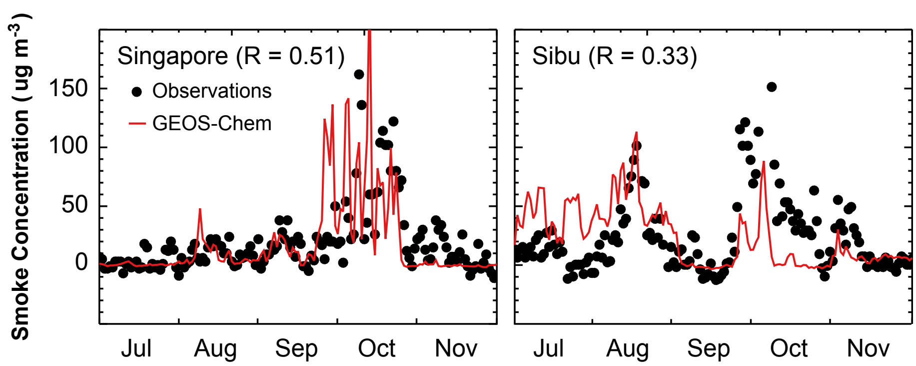


**Fig. 4.** Time series of observed and simulated 24-h surface mean smoke concentrations at Singapore and Sibu (western Borneo). Temporal correlation coefficients are inset. Site locations are indicated by arrows in Fig. 3.

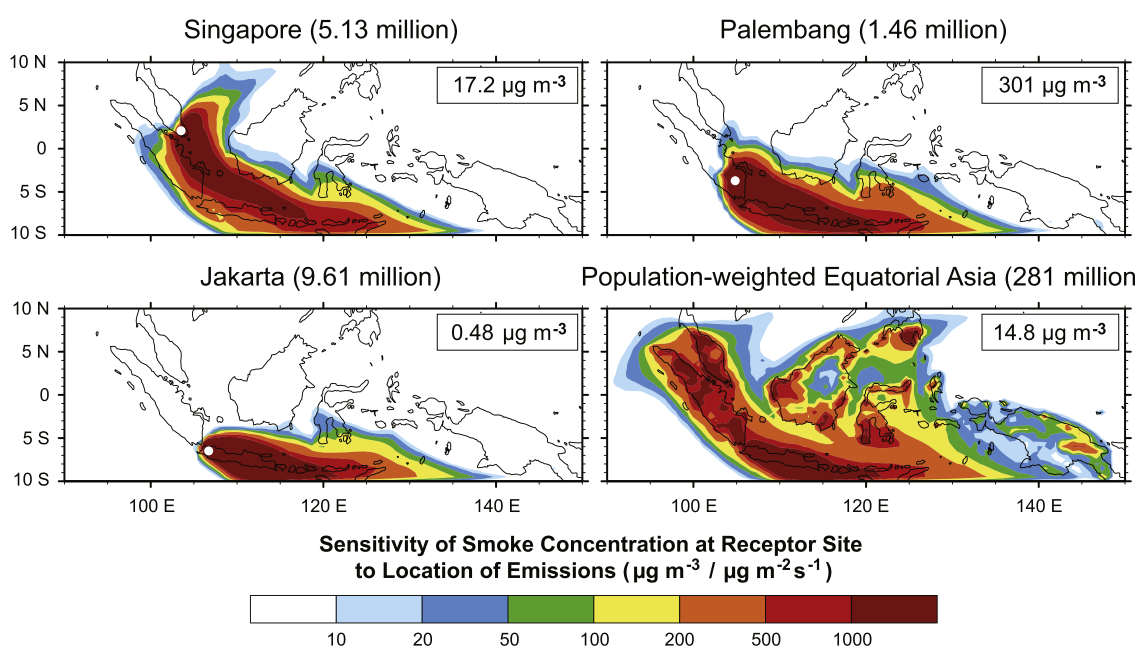


**Fig. 5.** Sensitivity of mean smoke concentrations in July–November 2006 to the location of fire emissions for three large cities and for all of Equatorial Asia weighted by population (city locations indicated by white circles, population in parentheses). Values are GEOS-Chem adjoint mean sensitivities. The simulated July–November mean smoke concentration for each receptor is shown inset.

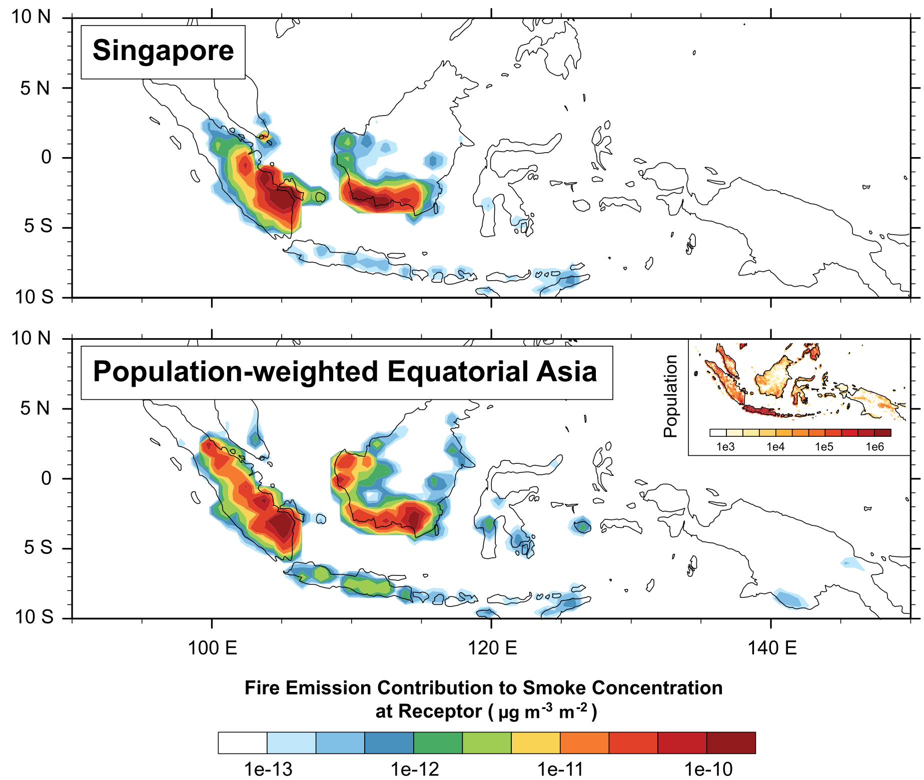


**Fig. 6.** Spatially resolved contributions of fire emissions to July–November 2006 mean smoke concentrations in Singapore (top) and for all of Equatorial Asia weighted by the population distribution shown inset (bottom).

## 3. Results and discussion

### 3.1. Smoke concentrations

Fig. 3 shows the mean surface air smoke concentrations in July–November 2006 observed at the surface monitoring stations and simulated by GEOS-Chem. The observed baseline $PM_{10}$ concentrations (mean concentrations in June and December when smoke influence is negligible) range from 21 to 71 μg $m^{-3}$ depending on the site. Mean smoke concentrations in July–November elevate this baseline by 10–50 μg $m^{-3}$ depending on the site. The observed smoke concentrations and spatial patterns are well captured by the model, with a mean relative bias of −27% and a spatial correlation coefficient $r = 0.84$ for the ensemble of sites

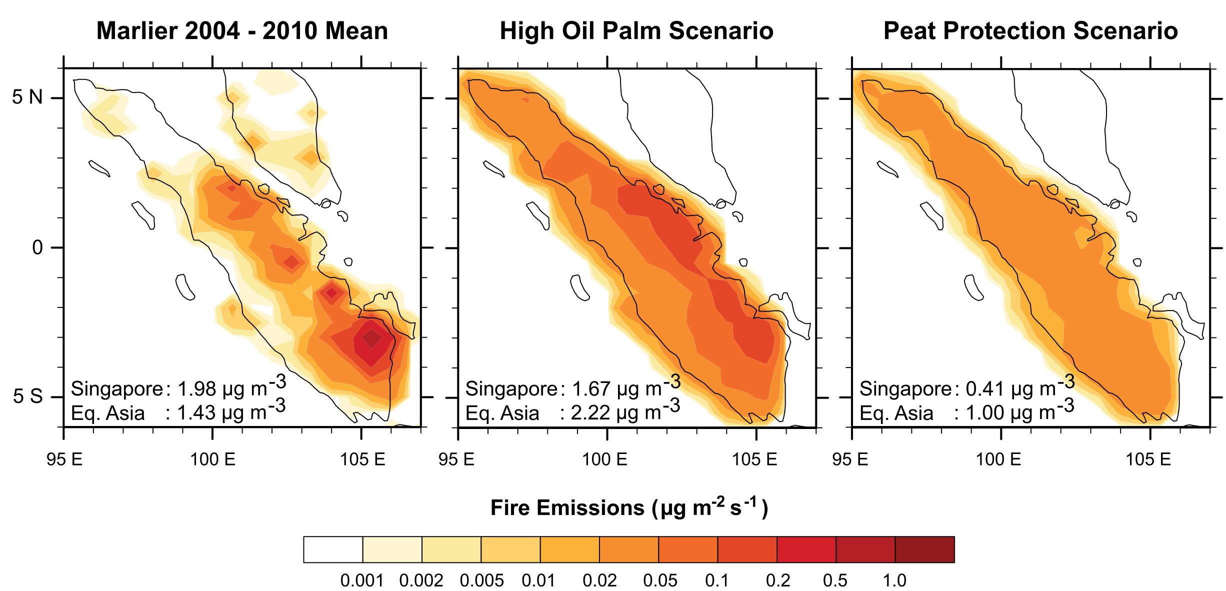


**Fig. 7.** Mean July–November fire emissions in Sumatra from Marlier et al. (2014) for the present (2004–2010) and for two future scenarios, “High Oil Palm” and “Green Vision with Peat Protection” (see text). The emissions are plotted on the same scale as Fig. 1. The Sumatran contribution to simulated July–November mean smoke concentration for Singapore and for population-weighted Equatorial Asia is shown inset.

($n = 50$). The model misses the smoke influence in northeastern Borneo and this likely reflects difficulty in simulating transport around the Tama Abu mountain range (Wang et al., 2013). The model simulates July–November mean concentrations in excess of 100 μg $m^{-3}$ in large areas of southern Sumatra and southern Borneo but no observations are available there. The city of Palembang (1.5 million people) in southern Sumatra experiences a seasonal mean concentration of 300 μg $m^{-3}$ in the model.

Time series of simulated and observed smoke concentrations are shown in Fig. 4 for Singapore and for Sibu (western Borneo, where mean observed smoke concentrations are particularly high as shown in Fig. 3). Time series for all other sites are in the Supplementary material. The model often does not capture the magnitude and timing of individual events and this is attributable at least in part to errors in the timing of emissions and in small-scale plume transport. The temporal correlation coefficient $r$ for 24-h smoke concentrations at individual sites ranges from 0.7 to no correlation (four sites in western Borneo).

### 3.2. GEOS-Chem adjoint sensitivities

Fig. 5 shows the sensitivities of mean smoke concentrations at Singapore, Palembang, Jakarta, and population-weighted Equatorial Asia during July–November 2006 to the mean fire emissions over the same time period. Sensitivities are generally largest for fires to the southeast, reflecting the prevailing flow (Fig. 1). Singapore is particularly sensitive to fires in southeastern Sumatra. Jakarta is not sensitive to fires in Sumatra or Borneo. The Equatorial Asian population as a whole is much more sensitive to fires in Sumatra than in Borneo. It is most sensitive to fires in Java because of high population density but fire activity there is low.

The sensitivities computed in this manner can be combined with knowledge of emission patterns to map the contributions from different source regions to the smoke concentrations at the receptor sites (Equation (1)). Fig. 6 shows the contributions to mean smoke concentrations in July–November 2006 at Singapore and for population-weighted Equatorial Asia. Sumatra was responsible for 37% of total fire emissions in Equatorial Asia in 2006 but contributed to 64% of the smoke concentration in Singapore and 63% of the smoke concentration to which the whole Equatorial Asian population was exposed. Suppressing fires in southeastern Sumatra would be of particular air quality benefit both for Singapore and for Equatorial Asia as a whole.

There is large year-to-year variability in present day fire emissions and the relative contributions from Sumatra and Borneo (Fig. 2). We applied Equation (1) to individual years of 2004–2010 and results are shown in the bottom panels of Fig. 2 as the regional contributions from Sumatra and Borneo to smoke concentrations at Singapore and for population-weighted Equatorial Asia. Despite this variability in fire emissions, we find that Sumatran fires contribute the majority of the smoke burden at Singapore and for population-weighted Equatorial Asia in all years in 2004–2009.

We can use the adjoint sensitivities to readily estimate the smoke exposure for any future land management scenario and this is illustrated in Fig. 7 with the Sumatra fire scenarios of Marlier et al. (2014). The Figure shows the fire emissions for the different scenarios, and inset are the mean July–November PM concentrations in Singapore and population-weighted Equatorial Asia contributed by the fires. Values are much lower than Fig. 1 because they are for an average fire season, consider only Sumatran fires, and assume a lower base emission estimate, as discussed above. The smoke concentration in Singapore drops for both future scenarios compared to present-day due to a shift of emissions away from Southeast Sumatra where Singapore is most sensitive (Fig. 5). By contrast, the population-weighted mean concentration increases by 60% under the High Oil Palm scenario. The Green Vision with Peat Protection scenario reduces mean smoke concentrations relative to the High Oil Palm scenario by a factor of 4 at Singapore and a factor of 2 for the population-weighted mean.

The adjoint sensitivities computed here (Fig. 5) allow immediate inference of smoke concentrations at selected receptor sites for any fire scenario. The smoke concentrations can be converted to public health costs using standard methods (Johnston et al., 2012; Marlier et al., 2013). In this manner and together with the work of Marlier et al. (2014), an integrated system can be developed for policy analysts to quantify the health cost endpoints of different land management options for the region. We plan to improve our tool in the future through the generation of adjoint sensitivities for other years to yield probability distribution functions of smoke concentrations that account for interannual variability in meteorology. Use of a finer-resolution regional CTM to generate the adjoint sensitivities could also provide an improved simulation of smoke transport and more geographically precise source–receptor relationships. A GEOS-Chem simulation capability at $0.25° \times 0.3125°$ ($25 \times 25$ $km^2$) horizontal resolution has recently been developed (Kim et al., 2014) and can be applied in the future.

## Acknowledgments

Data supporting Figs. 3 and 4 are available upon request to BNC. The GEOS-Chem code is available at http://geos-chem.org/. This work was funded by the Rockefeller Foundation and the Gordon and Betty Moore Foundation through the Health & Ecosystems: Analysis of Linkages (HEAL) program, and by a Department of Energy Office of Science Graduate Fellowship to PSK made possible in part by the American Recovery and Reinvestment Act of 2009, administered by ORISE-ORAU under contract no. DE-AC05-06OR23100. The authors would like to thank Singapore's National Environment Agency and Malaysia's Department of Environment for collecting and archiving the surface air quality data. We thank Zifeng Lu for his assistance with the population data. We thank two anonymous reviewers for their helpful comments that led to improvements to the manuscript.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2014.09.045.

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