Supplemental Material for:

"Public health impacts of the severe haze in Equatorial Asia in September-October 2015: Demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure"

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1. The GEOS-Chem adjoint

We use version 8-02-01 of the GEOS-Chem chemical transport model and its adjoint (Henze *et al* 2007, Kopacz *et al* 2011, Kim *et al* 2015) to quantify the source-receptor relationships relevant for smoke exposure in Equatorial Asia during large haze events. GEOS-Chem is driven by Goddard Earth Observing System (GEOS-5) assimilated meteorological data from the NASA Modeling and Assimilation Office (GMAO) at 0.5° x 0.67° native horizontal resolution with 72 vertical levels. Following Kim *et al* (2015), we use the GEOS-Chem adjoint (v34) to calculate the potential influence of smoke emissions in each 0.5º x 0.67º grid cell for the whole Equatorial Asia model domain [70°-150° E, 11° S-55° N] on population-weighted $PM_{2.5}$ concentrations in three receptor regions (Indonesia – 250 million people in 2015, Malaysia – 30 million people, and Singapore – 4 million people) for each month during July-October based on meteorology for 2006. Population weighting of the mean receptor concentrations was carried out by first weighting the smoke concentration of each grid cell by its fractional population within the receptor area, then taking the average concentration across those grid cells. The resulting sensitivities – i.e., the fractional contribution of each grid cell to smoke exposure at each receptor downwind – are applied to the fire emission inventory, yielding a gridded estimate of the monthly mean smoke-related $PM_{2.5}$ exposure that results from those emissions. We scale the resulting OC-related $PM_{2.5}$ by a factor of 2.1 to account for additional organic matter acquired through atmospheric processing (Turpin and Lim 2001). The fractional contributions to exposure from each grid cell are then summed together to estimate the total population-weighted exposure at each receptor. For this study, we apply the 2006 sensitivities to both the 2006 and 2015 emissions. This approach assumes that the smoke transport patterns for these two haze events are similar, which is likely given that they both occurred during similar phases of the ENSO and the IOD, the two major drivers of interannual meteorological variability in Equatorial Asia (Li *et al* 2003). Calculation of new adjoint sensitivities would require processing of 2015 GMAO meteorological fields and considerable computational expense, while our streamlined approach allows for near real-time assessment of smoke exposure and attribution to emission sources.

2. Health impact calculations

We estimate health impacts from smoke pollution using an approach similar to that in Anenberg *et al* (2012) and two studies quantifying the Global Burden of Disease (Lim *et al* 2012, Burnett *et al* 2014). We derive a concentration response relationship (CRF) between relative mortality and $PM_{2.5}$ from the epidemiological literature, modeling health impacts as a 1% increase in annual baseline all-cause mortality per 1 $\mu g\ m^{-3}$ increase in annual average $PM_{2.5}$ levels when annual average $PM_{2.5}$ concentrations are less than 50 $\mu g\ m^{-3}$ (Schwartz *et al* 2008, Anenberg *et al* 2012 and references therein, Lepeule *et al* 2012). Using annual average $PM_{2.5}$ exposure increases the likelihood of capturing the effects of both acute and chronic pollution exposure. In our calculations there were no locations where annual average concentrations exceeded this 50 $\mu g\ m^{-3}$ threshold, likely because our estimates reflect population-weighted exposures rather than actual smoke concentrations. Using gridded population data from the Center for International Earth Science Information Network (CIESIN; Columbia University 2005) and country-level data on baseline mortality rates and population age structure from the Global Burden of Disease for 2013 (the most recently available year; Lim *et al* 2012, Institute for Health Metrics and Evaluation 2015), we estimate the excess deaths attributable to smoke $PM_{2.5}$ as follows. We first calculate a July-October population-weighted average $PM_{2.5}$ exposure for each receptor country during both 2006 and 2015 (Section S1 above). We next convert these July-October average population-weighted smoke $PM_{2.5}$ exposures to annual average values. We then calculate the total population in each receptor country using the CIESEN population distributions, and apply the baseline mortality rate and age structure information for each country to calculate population over 25 years of age. Finally, we calculate the total mortality attributed to $PM_{2.5}$ from fires in each receptor country i using:

$$\begin{aligned} &Attributable\ Mortality[i] \\ &\quad = Baseline\ Mortality[i] \times Population[i] \times \beta \times Population \\ &\quad - weighted \Delta PM_{2.5}[i] \end{aligned}$$

where β is the CRF from epidemiological studies, corresponding to the slope of the relationship (1%) between pollutant concentration and mortality, and $\Delta PM_{2.5}$ is the estimated change in $PM_{2.5}$

from smoke pollution.

Previous estimates of excess deaths from smoke $PM_{2.5}$ pollution for the 1997 event range widely – e.g., 296,000 in Johnston *et al* 2012 and 13,200 in Marlier *et al* 2013. Our estimate of ~100 thousand in 2015 falls between these two extremes. Johnston *et al* (2012) included health impacts on the whole population, including children, and considered all causes of premature mortality, capping exposure above 50 μg m^{-3} in each model grid cell. In contrast, Marlier *et al* (2013) restricted their analysis to cardiovascular mortality in adults and used a different CRF form. In sensitivity analyses Marlier *et al* (2013) found that applying differently shaped CRFs to the same smoke concentrations yielded mortality increases up to four times higher than their reported estimate. Due to the lack of consistent emissions datasets, we cannot directly compare our estimate of excess mortality for 2015 to those reported for 1997. Nonetheless the fine spatial resolution of our approach likely better captures smoke exposure to peak pollution concentrations in populated areas. We also use more recent information about baseline mortality rates and population age structure.

3. High resolution FRP observations in concessions

Table S1. Average percent contributions of fire radiative power (FRP) on concessions and peatlands to total FRP observed by MODIS on the Aqua and Terra satellites during July-October in 2006 and 2015 over Sumatra and Kalimantan. The term "mixed" indicates regions in which boundaries of oil palm, timber, and/or logging concessions overlap. Estimates of percent contributions for peat take into account peatland areas both within and outside of concessions. All values are calculated using FRP Collection 6, and so differ slightly from those reported by Marlier *et al* (2015), who relied on Collection 5.

	Year	**Timber %**	**Oil Palm %**	**Logging %**	**Mixed %**	**Peat %**	**Total FRP (MW)**
Sumatra	2006	26.55	11.33	2.01	0.51	44.47	4.57E+06
	2015	55.07	4.72	1.32	0.44	71.76	6.46E+06
Kalimantan	2006	7.81	32.01	6.57	5.66	32.39	6.59E+06
	2015	9.62	20.06	8.97	3.99	42.85	5.67E+06

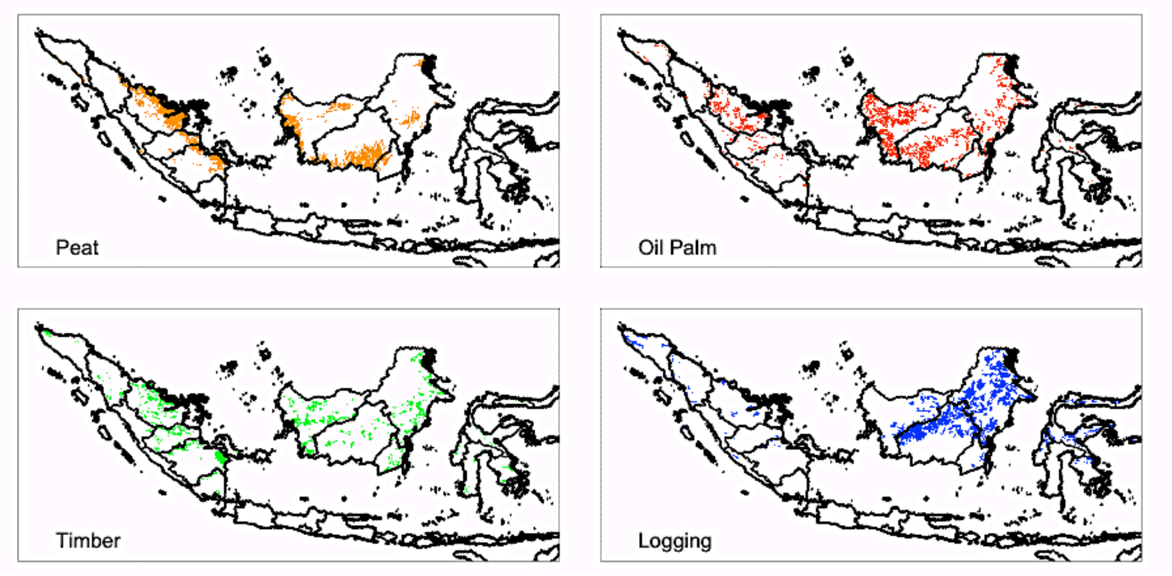

Figure S1. Distribution of peatlands and current or planned concession types in Indonesia as of 2010. The top left panel shows the peatland distribution in orange (Wahyunto and Subagjo, 2003,2004). The other three panels show land use distributions from the Global Forest Watch (World Resources Institute, 2015a,b,c); estimates are based on data provided by the Indonesian

Ministry of Forestry. Oil palm concessions are shown in the top right in red, timber in the bottom left in green, and logging in bottom right in blue. Spatial resolution in all panels is 5 x 5 km^2.

4. Province masks

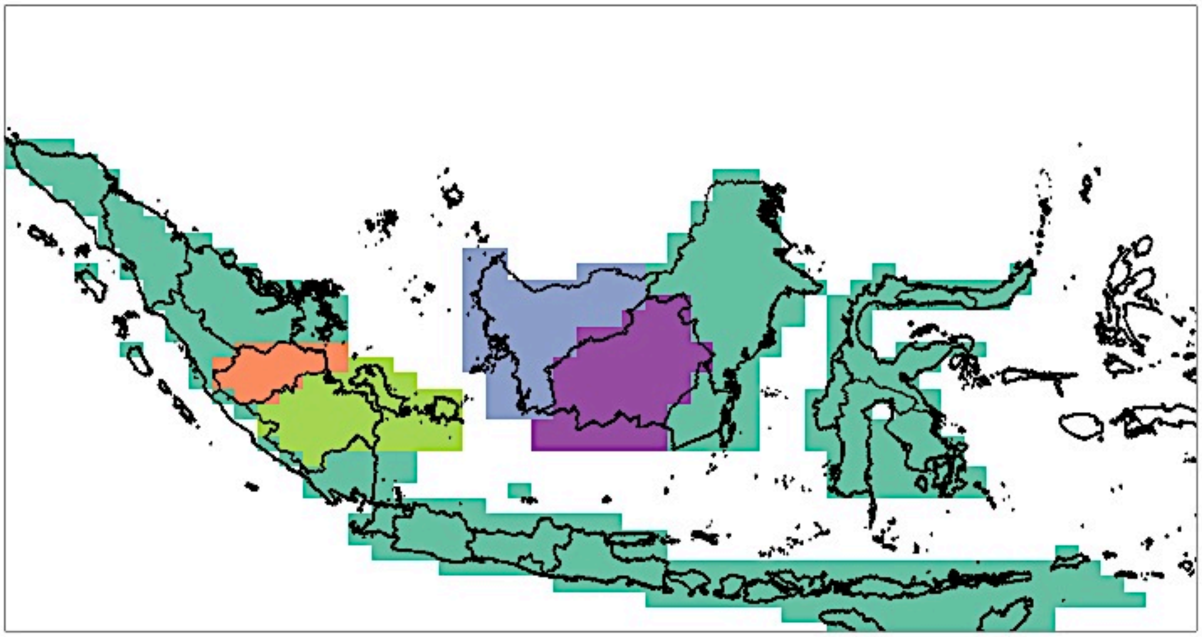

Figure S2. Province masks at 0.5 x 0.67° resolution used in this analysis. Jambi is shown in coral, West Kalimantan in blue, and Central Kalimantan in purple. South Sumatra and Bangka-Belitung are combined and shown in green. Other provinces are shown in teal.

5. Adjoint sensitivities

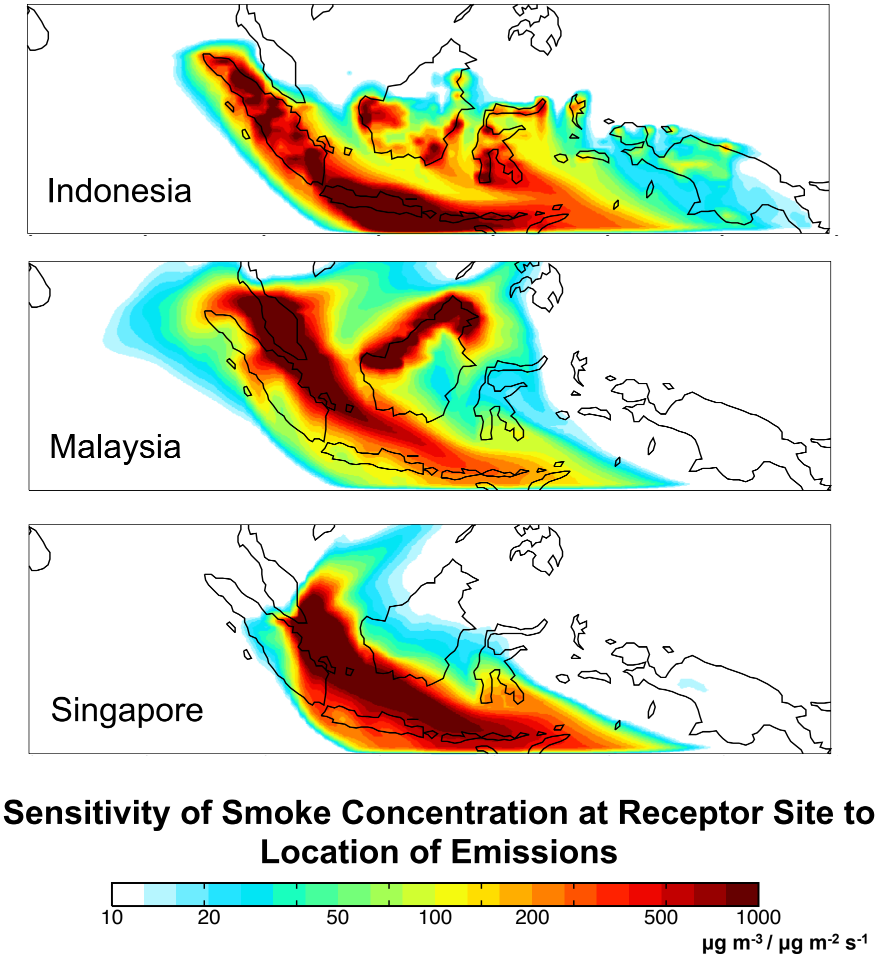

Figure S3. GEOS-Chem adjoint sensitivities simulated for September-October 2006 of population-weighted $PM_{2.5}$ in each receptor region to smoke emissions in gridboxes across the domain. The top panel shows the sensitivities for Indonesia; the middle panel, Malaysia; and the bottom panel, Singapore. These sensitivities are for hydrophobic organic carbon (OC) specifically, but spatial patterns are similar for hydrophilic OC as well as for BC.

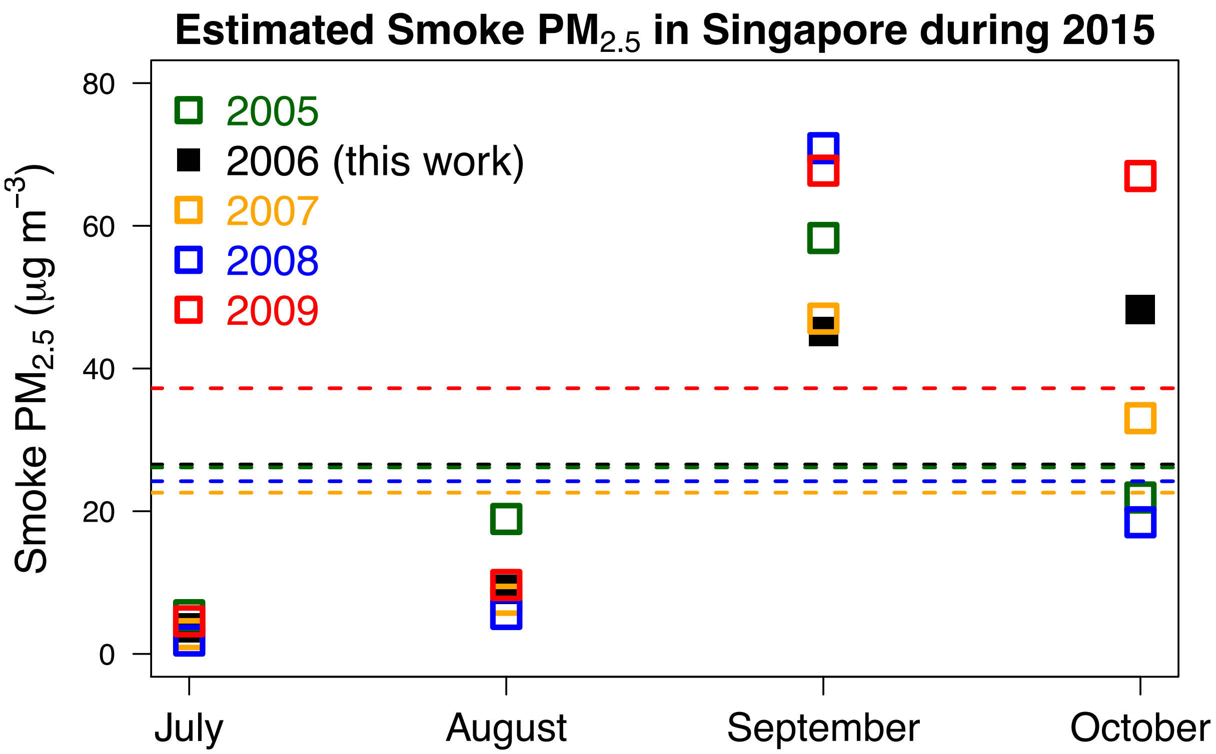

Figure S4. Monthly mean smoke exposure at Singapore estimated using 2015 GFAS emissions scaled by 50% and a suite of adjoint sensitivities for 2005-2009. The exposures used in this work, estimated with the 2006 sensitivities, are shown in black filled squares. Estimates produced using sensitivities from 2005 are shown in green, 2007 in orange, 2008 in blue, and 2009 in red. Dashed lines show corresponding July-October averages for each year. The plot shows the impact that application of different meteorological fields has on estimates of smoke exposure in Singapore. Of the five years, only 2006 is characterized by the simultaneous El Niño and positive Indian Ocean Dipole conditions similar to those in 2015.

6. Fire management strategies in Indonesia

The rapid assessment framework demonstrated in this work would allow policy makers in Indonesia to quickly identify the burning areas that are leading to the most severe air pollution in populated areas downwind during extreme haze events. This information can then be used to prioritize fire management efforts including land use management strategies to help mitigate the domestic and transboundary smoke pollution resulting from these fires. However, implementing effective fire management strategies on the ground in Indonesia is challenging. We summarize here some of the difficulties currently facing effective fire management practices in Indonesia, and, when relevant, how our adjoint approach may be implemented to help address some of these issues.

Regulating fires in smallholder farms vs. industrial plantations

One major hurdle to effectively regulating fire activity in Indonesia is the heterogeneity of the human activity landscape. For example, it is common for local communities and small farmlands to be located immediately alongside, or even within, large scale industrial concessions such as those for oil palm or timber, making the attribution of fire ignitions difficult (Cattau et al 2016, Gaveau et al 2016). Conflicting land tenure claims can even be a source of fire ignitions to reclaim land, independent of any agricultural benefit (Dennis et al 2005). Additionally, while the use of fire as a land management tool can perhaps be replaced by other alternative approaches to slash-and-burn techniques on the large plantations, fire is often the only affordable mechanism of land maintenance for small scale farmers (Tomich et al 1998, Palm et al 2004). Certain land management practices outside of the burning season have been shown to help reduce smoke emissions and the likelihood of escaped fires from small farms (Sahrajo and Munoz 2005, Sahrajo 2011), but would require widespread efforts to incentivize the use of these practices amongst local communities in order to matter for regional haze. Using the GEOS-Chem adjoint to identify the burning areas contributing most severely to downwind pollution during extreme haze events would help identify priority areas where developing economically feasible alternative land clearing practices in small scale farms and settlements would most benefit local and regional human health.

Extinguishing fires in peatlands

Another challenge to firefighting efforts in Indonesia is the difficulty involved with actually extinguishing fires in peat, even with adequate resources. Because peat fires tend to burn at low temperatures, they can smolder for many days to weeks or even months, undetected within the subsurface peat layers (Turetsky et al 2015 and references therein). Due to this smoldering tendency and to the variability in peat layer depth, which can range from inches to tens of meters in some places, it is difficult for firefighters to know if the peat fires have been completely extinguished. Subsurface peat fires can even migrate through the subsurface away from their ignition source, reigniting weeks later in a completely different location (Rein 2009). Identifying the areas contributing most to smoke downwind in near real time could help fire management officials decide quickly where best to allocate their front line fire-fighting efforts (e.g., trained personnel or helicopters for emergency water application) to better ensure that peat fires in these areas have been fully extinguished. It would also guide the development of new approaches for extinguishing peat fires when these traditional methods are ineffective (Byron and Shepard 1998).

A better approach to reducing fires in peatlands would be to counteract the effects of human degradation through peatland restoration (Jaenicke et al 2010). Peatland areas are naturally resistant to fire due to their characteristically high moisture content (Turetsky et al 2015 and references therein). Though human activity has degraded much of the peatlands in Indonesia, making these lands more fire-prone, efforts to restore peatlands to their natural fire-resistant state are ongoing (Indriatmoko et al 2014). However, these restoration efforts face many of the challenges common amongst conservation groups, such as a lack of funding and resources, and limited participation from the public. Conservation efforts also rarely provide an obvious economic benefit to the local communities, limiting their incentive to participate (Nicolas and Beebe 1999, Chokkalingam et al 2007). Identifying the areas most important for regional haze events would allow for more targeted efforts to restore degraded peatland and develop sustainable partnerships with local communities in these high priority burning areas.

Enforcing existing policies

Lastly, effectively enforcing existing regulations related to illegal burning in Indonesia has proven difficult (Jones 2006, Evers et al 2016). Insufficient enforcement of these regulations during past extreme haze events has been attributed in part to inadequate planning and resource availability arising from inefficient organization within the Indonesian government (Dennis et al 2005, Jones 2006 and references therein). In addition, many of the companies or individuals accused of burning illegally escape with minimal punishment, providing no deterrent for getting caught (Jones 2006). Complicating the issue further is the jurisdictional ambiguity surrounding the enforcement of fire regulations; in many areas, fire use is regulated by both traditional community laws and national regulations from the Indonesian government, which can be contradictory (Byron and Shepard 1998, Dennis et al 2005, Gaveau et al 2016). The adjoint method presented in this work would allow both state and local governments to prioritize the allocation of police resources to those areas where enforcing the bans against illegal burning would most effectively reduce damage to human health. Identifying the provinces where burning is most important for regional air quality degradation would also highlight areas where the need for cooperation between national and local governments on issues of fire regulation and enforcement is paramount. Additionally, many large companies have pledged not to use fire for land management to obtain certification from the Roundtable on Sustainable Palm Oil (RSPO; http://www.rspo.org/), though policing such pledges is a challenge. The adjoint approach could be used to both estimate the benefits to regional human health of no-burn pledges from companies in particular provinces, as well as provide a means of accountability for companies burning in the high priority areas most influencing regional air quality. Coupled with improved spatial maps to reduce inconsistencies in land tenure claims (http://blog.cifor.org/22534/new-tech-better-map-on-tap-to-protect-indonesian-forests?fnl=en), the adjoint would be a powerful tool for no-burning enforcement.

Extreme haze in Indonesia will likely continue to be an issue until the challenges mentioned above are more fully addressed. However, the capability to pinpoint the areas most affecting regional human health during extreme haze with our adjoint approach would help stakeholders and policymakers prioritize the areas where fire management is most important for domestic and regional air quality, increasing the precision and therefore the effectiveness with which all these fire management strategies can be implemented.

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