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Greenhouse gas and air pollutant emissions from land and forest fire in Indonesia during 2015 based on satellite data

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Abstract. Land and forest fire still become a major problem in environmental management in Indonesia. In this study, we conducted quantitatively assessment of land and forest fire emissions in Indonesia during 2015. We applied methodology of emission inventory based on burned area, biomass density, combustion factor and emission factor for each land cover type using several satellite data such as MODIS burned area, Pantropical National Level Carbon Stock Dataset, as well as Vegetation Condition Index. The greenhouse gases emissions from land and forest fire in Indonesia during 2015 were (in Gg) 806,406 CO_2, 8,002 CH_4, 96 N_2O, while pollutants emissions were (in Gg) 85,268 CO, 1,168 NOx, 340 SO_2, 3,093 NMVOC, 1,041 NH_3, 259 BC, 1,957 OC, 4,118 $PM_{2.5}$ and 5,468 PM_{10}. September was the peak of fire season that generate 58% (species average) of total emissions for this year. The largest contribution was from shrubland/savanna burning which account for 66% (species average) of the total emissions, while about 81% of the total emissions were generated from peatland fire. The results of this study emphasizethe importance of proper peatland management in Indonesia as land and forest fire countermeasures strategy.

1. Introduction

Land and forest fire is a major cause of land surface changes with impacts on the climate system, vegetation composition and the chemical composition of the atmosphere. It is the largest source of primary fine carbonaceous particles and the second largest source of trace gases in the global atmosphere [1]. Global impact of forest fire can be caused by greenhouse gases (GHGs) emissions which lead to global warming, while regional to local impact can be affected by pollutant gases and particles emissions which lead to air pollution.

Severe land and forest fire frequently occurred in Indonesia that caused negative impacts on atmospheric environment, not only in Indonesia it self but also to surrounding countries such as Malaysia and Singapore. For example, during the dry season of 1997, 2006 and 2015, severe forest fire occurred in Sumatra and Kalimantan, Indonesia, and it resulted in various types of air pollution over large area by emitting aerosol particles and photochemical precursors [2–4]. On a recently study, Huijnen revealed that with a mean emission rate of 11.3 Tg CO_2 per day during Sept-Oct 2015, emissions from Indonesia forest and peatland fires exceeded the fossil fuel CO_2 release rate of the European Union (EU28) (8.9 Tg CO_2 per day) [4].

Many studies on emission inventory from forest fire or generally biomass burning in Indonesia have been conducted by some researchers, either in global scale, regional scale, or specifically for

Indonesia region [4–7]. However, these studies investigated thefire emissions in Indonesia during the last decade, or had a relatively coarse spatial resolution. Moreover, some previous studies used land type-based aboveground biomass density[5], or measurement data in a typical study plot or statistical data as available fuel with country or province-based above ground biomass density [6,8], which means the available fuels in an area or land type were usually used to represent the whole area or land type. Such representations usually do not reflect the spatial variations and heterogeneities of biomass within the area or land type because the biomass varies significantly with the type of vegetation and geographical location.

Therefore, this study was conducted to quantify emissions of land and forest fire in Indonesia during the last year 2015, which was the largest fire year since 1997 [4]. This study assessed the generated emissions from land and forest fire, including shrubland, plantation and agricultural land fire, using the latest available data, which are expected to give more accurate results. Several important species of fire emissions were quantified, consisted of GHGs (CO_2, CH_4, N_2O) and air pollutants (CO, NOx, SO_2, NH_3, NMVOC, OC, BC, $PM_{2.5}$, PM_{10}). Updated land and forest fire emissions inventory will provide a general assessment of the potential effects of forest fire, as well as important information, which can be used for formulation of appropriate mitigation measures and evaluation of emissions reduction policy in Indonesia.

2. Methods and Data

Emissions from land and forest fire, or commonly open burning biomass, are generally calculated using the burned area, available fuels, combustion factor, and emission factor with the following equation [9]:

$$Es = \sum_{i=1}^{n}(B \times F \times CF \times EF_s)_i \quad (1)$$

where Es is emissions for each species (g), B is burned area (m^2), F is available fuels for combustion (kg/m^2), CF is combustion factor, defined as the fraction of combusted fuel to the total amount (unitless), EFs is emissions factors for species, defined as the mass of species per mass of dry matter burned (g/kg), and i is land cover types. We applied Equation 1 for land and forest fire emissions calculation on monthly basis, i.e. the calculation was performed using monthly data for the year 2015.

2.1. Burned Area

Burned area data were derived from the MODIS direct broadcast burned area product (MCD64A1), which was used to estimate the entire area that have been burned in Indonesia during 2015. MCD64A1 is a MODIS satellite-derived product that uses surface reflectance, daily active fire, and land cover products to delineate burned areas and burn cells which are tagged with approximate burn date[10]. MCD64A1 has a spatial resolution of 500 m and temporal resolution of a month, and the day of burning and a temporal uncertainty range of the burn date are noted for every pixel.

The MCD64A1 are available online at ftp://fuoco.geog.umd.edu/db/MCD64A1/, and provided in Hierarchical Data Format (HDF), 10° tile size with SIN projection. In this study, we created mosaic of the data tiles that cover the study area (Indonesia region) using Modis Reprojection Tool (MRT). Then we extracted the Julian date of burning from the data, converted the raster data to polygon and overlaid with national land cover and peatland distribution map using ArcGIS.

Figure 1 shows the spatial variation of burned area average (ha) in Indonesia during 2015. In this map, the burned area were aggregated to 0.25° resolution. However during our emissions calculation, we preserved the original resolution of the data (500 m). The area in Indonesia that have relatively large annual burned area is the southern part of Central Kalimantan, which have burned area exceeded 45,000 ha inside one pixel area (0.25°). Another area that also have large burned area is the eastern part of South Sumatera, which approximately have burned area up to 30,000 ha in one pixel area.

2.2. Fuels

In this study, we took into account both above ground biomass (AGB) and below ground biomass (BGB) as available fuels for combustion. We used satellite derived biomass density data to determine the AGB, namely the Pantropical National Level Carbon Stock Dataset, which was published by Woods Hole Research Center. This dataset was generated using three-stage data collection and modelling strategy that is specifically designed to allow measurements collected on the ground to be up-scaled to the 500m resolution of MODIS imagery using GLAS (Geoscience Laser Altimeter System) LiDAR data for the period circa 2007-2008[11].

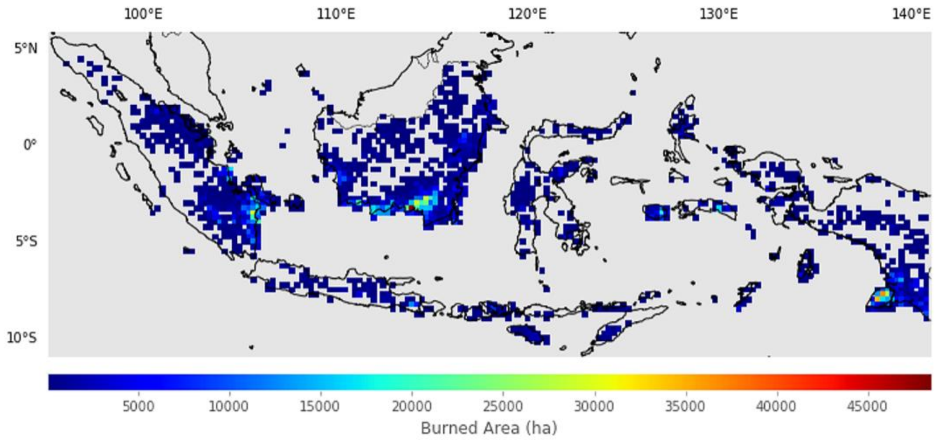

Figure 1. Burned area in Indonesia during 2015 derived from MODIS MCD64A1 (aggregated to 0.25° resolution).

The Pantropical National Level Carbon Stock Dataset are available online at http://whrc.org/publications-data/datasets/, and provided in GeoTIFF format with 500 m resolution. In this study, we converted the raster data to polygon and overlaid with burned area to obtain the biomass density in each burned area. Based on this dataset, the area that have relatively high biomass density are the western part of Sumatera, the middle part of Kalimantan and Papua Islands, where the biomass density in these area reached up to 464 Mg/ha.

Meanwhile, the below ground biomass (BGB) were derived from the Indonesia peatland distribution data, which was provided by Wetlands International. The data was distributed online at data.globalforestwatch.org, and provided in ArcGIS layer format. In this study, we converted the data to polygon and overlaid with burned area to obtain the peat availability in each burned area. This data provide peat depth distribution that classified into 6 categories, as shown on Figure 2. This figure describe that peatland area in Indonesia mostly distributed in eastern part of Sumatera, southern part of Kalimantan and southern part of Papua. The thickest layer of peat soil were located at the southern part of Central Kalimantan where the peat soil layer exceeded 10 m depth.

Previous studies did not consider peatland fire [6] or assumed constant depth of burned peat soil [12]. Here, we assumed the depth of burned peat soil based on the peat depth category. On the first category (peat depth <50 cm), we took the middle value between 0-50 cm i.e. 25 cm as the burned peat depth. While on the other category (peat depth > 50 cm), we assumed 51 cm as the burned peat depth. The peat dry bulk density was assumed 100 kg/m^3. These assumptions referred to some previous studies that reported that the burned peat depth were varied between 20-150 cm [13]and 25-85cm [14] based on Indonesian field measurements.

2.3. Combustion Factor

The combustion factor (CF) is the fraction of biomass actually consumed in a fire as determined by fuel type and moisture conditions. It varies greatly among the different biomass of different fuel types.

We determined fuel moisture conditions according to the time series of MODIS Vegetation Condition Index (VCI), which were derived from Normalized Difference Vegetation Index (NDVI) [15]. These data were available online at ftp://ftp.star.nesdis.noaa.gov/ and provided in weekly temporal resolution with 1/112° spatial resolution.

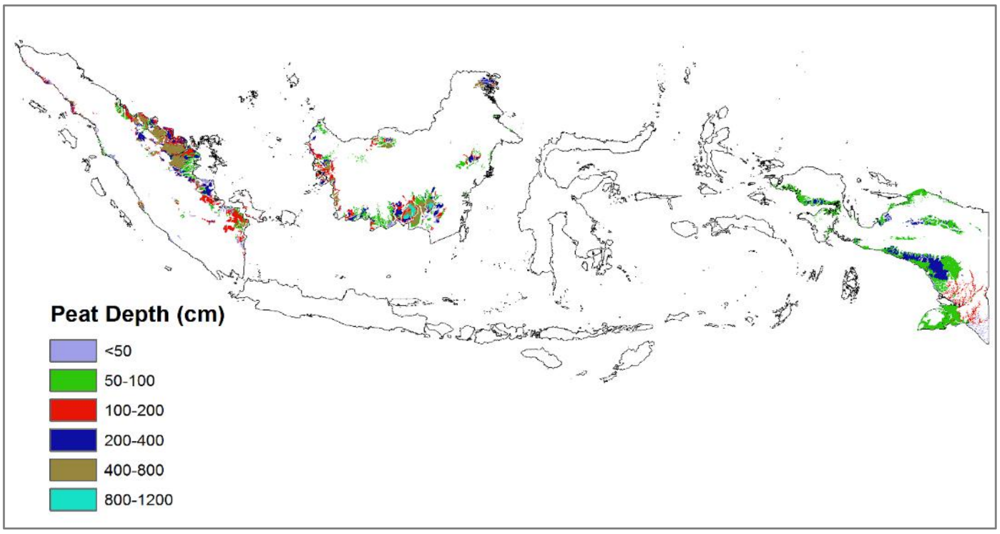

Figure 2. Peat depth distribution that represent below ground biomass in Indonesia.

In order to calculate CF, we equally divided VCI values, which range from 1 to 100, into six different categories, representing fuel moisture conditions of very dry, dry, moderate, moist, wet, and very wet, respectively[16]. The monthly variation in moisture conditions were used to associate with fuel moisture category factors (mcf), as shown on Table 1.

Table 1. Moisture category factor (mcf) (from [17]).

Moisture condition	Canopy	Shrub
Very dry	0.33	0.25
Dry	0.5	0.33
Moderate	1	0.5
Moist	2	1
Wet	4	2
Very wet	5	4

The CF is a function of fuel type and moisture category and was calculated from the following model [17]:

$$\mathrm{CF_i} = (1 - \mathrm{e}^{-1})^{\mathrm{mcf}}, \tag{2}$$

whereCFi denotes the fraction of fuel loading consumed for fuel type i, which is forest (canopy) and shrub; and mcf is the moisture category factor. The mcf value for each fuel type was determined using the fuel moisture condition derived from MODIS VCI data (Table 1), which increases from dry to wet fuel conditions.

2.4. Land Cover and Emission Factors

The land cover data was derived from the Indonesian Land Cover Map 2011 from the Ministry of Forestry, Indonesia. The land cover map were available online at http://webgis.dephut.go.id:8080/kemenhut/index.php/id/fitur/unduhan, which provided in kml format for each province. The land covers in this data were classified into 21 categories, plus 2 additional categories for cloud and no data. The dataset with the original land cover classification system were then re-classified into six broad categories of vegetation susceptible to fires in Indonesia (tropical forest, woodland, shrubland, cropland, paddy field and peatland). The re-classification was performed in order to match with the available emission factor (EF) for each land cover type.

The EFs for this study were selected from several available publications. We referred to some previous EFs compilation studies to determine EFs for tropical forest and shrubland [6,18], woodland [18,19], cropland [19,20], paddy field [12,20] and peatland [12,19]. The selected EFs for all species from different biomes used in this study are summarized in Table 2.

Table 2. Selected emission factors for each land cover (re-classified) in Indonesia.

No	Land cover (re-classified)	Emission Factors (g/kg)											
		CO_2	CH_4	N_2O	SO_2	NOx	CO	NMVOC	NH_3	BC	OC	$PM_{2.5}$	PM_{10}
1	Tropical Evergreen Forest	1601	6.44	0.2	0.43	1.44	106	8.1	1.1	0.64	6.79	14.8	18.5
2	Woodland	1636	4.4	0.21	0.54	2.19	81	5.21	1.44	0.52	3.76	7	10.2
3	Shrubland/Savanna	1685.8	2	0.21	0.9	3.9	63	3.4	0.56	0.37	2.62	5.4	8.3
4	Farmland (Combined Crops)	1130	4.56	0.1	0.216	0.7	86.3	7	1.3	0.48	0.7	3.9	8.05
5	Paddy field	1177	9.59	0.07	0.18	2.28	93	7	4.1	0.52	2.99	8.3	9.1
	Peatland	1703	20.8	0.2	0.71	2.26	210	7	2.55	0.57	4.3	9.05	11.8

3. Results and Discussion

3.1. Annual Emissions

The annual emissions of land and forest fire in Indonesia for each species (CO_2, CH_4, N_2O, CO, NO_x, SO_2, NMVOC, NH_3, BC, OC, $PM_{2.5}$, and PM_{10}) for the year 2015 are presented in Table 3. Throughout this year, emissions of the three main GHGs from land and forest fire in Indonesia were 806,406 Gg/year, 8002 Gg/year and 96 Gg/year of CO_2, CH_4 and N_2O respectively. These amounts are equal to 1004 TgCO_2-e/year based on Global Warming Potential (GWP) values of IPCC 4th Assessment Report for 100 years time horizon. As a comparison, according to Indonesia 1st Biennial Update Report (2016), GHGs emissions in Indonesia during 2000-2012 period (exclude LULUCF) was 612 Tg CO_2-e/year. This comparison could illustrate the large contribution of land and forest fire to national GHGs emissions in Indonesia, which is almost twice than GHGs emissions from all sector (excluding LULUCF) based on 2000-2012 average.

Table 3. The annual emissions of land and forest fire in Indonesia for the year 2015.

Species	Emissions (Gg)	Species	Emissions (Gg)
CO_2	806,406	NMVOC	3,093
CH_4	8,002	NH_3	1,041
N_2O	96	BC	259
CO	85,268	OC	1,957
NO_x	1,168	$PM_{2.5}$	4,118
SO_2	340	PM_{10}	5,468

3.2. Spatial Distribution

In this study, we found that the emissions of all species presented similar spatial distribution even though their magnitudes differed greatly. This is reasonable since all species would be emitted from the existed burned area with different magnitude depend on the EF of each species and the availability of burnable peat soil. Figure 3 depicts the spatial distribution of annual average of CO_2 emissions during 2015, which is also similar to the other species. This spatial pattern is also comparable to the distribution of burned area as shown on Figure 1. In general, the emissions could be observed throughout most of Indonesia area with high spatial variability. The western part of Indonesia generally generated higher emissions than the eastern area. The area that has relatively large annual emissions is the southern part of Central Kalimantan, which generate CO_2 emissions more than 25 Tgin one pixel area (0.25°).

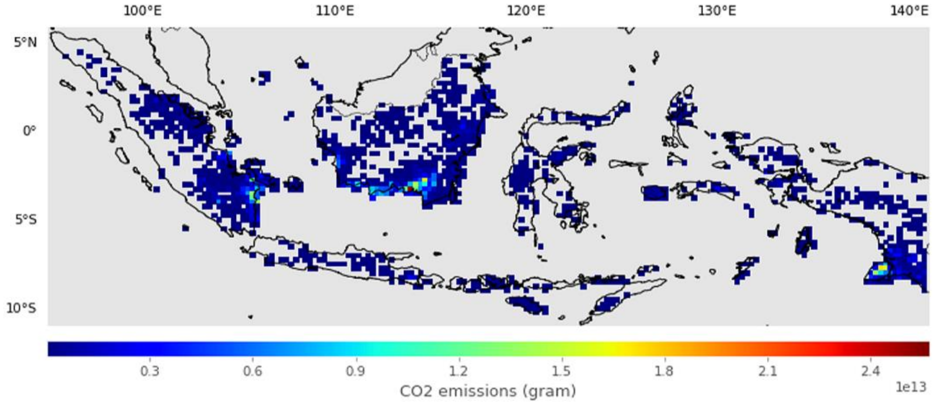

Figure 3.Spatial distribution of CO_2 emissions.

3.3. Spatio-Temporal Variation

Assessment of monthly variation in CO_2 emissions revealed that the highest emissions were generated during September-October period, which is correspond to peak of dry season in most part of Indonesia. The dry season in Indonesia generally lasts from July through October when there is relatively little precipitation. Local farmers usually prepare fields by cutting down the accessible forest and short vegetation, which they then allow to dry until immediately before the rainiest part of the year to ensure an effective burn. Consequently, values in burned area and CO_2 emissions are typically high during September-October period.

To investigate the spatio-temporal variations, we plot the peak month of CO_2 emissions for each pixel area, as shown on Figure 4. Here we can observed that the middle and northern part of Sumateraand the northern part of Kalimantan have earlier peak of fire season which are occurred during May-July period, while the other area (mostly the middle to eastern part) have peak of fire season during Sep-Nov period. This spatio-temporal variability were likely due to variability on annual rainfall pattern. Aldrian and Susanto identified that there are three rainfall regions in Indonesia which have distinct annual rainfall pattern, namely region A, B and C [21]. By referring the rainfall region map in those study, it can be seen that the monthly peak of emissions were associated with the dry season in particular region.

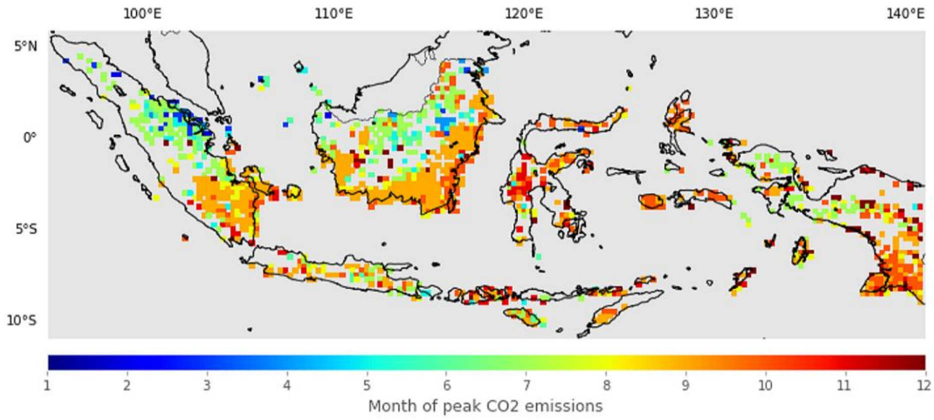

Figure 4. Spatio-temporal variation of CO_2 emissions.

3.4. Land Cover and Peatland Contributions

The contributions of each land cover type to the total emissions were graphed for all trace gases and aerosols (Figure 5). Here we also separated the emissions that originated from peatland area and non-peatland area for each land cover type. The results showed that for different emission species, the contribution of each land cover type to the total amount varied moderately.However, on average, emissions from shrublands/savanna burning are the largest contributor to the total emissions (66%; 56% on peatland + 10% on non-peatland), followed by burning of woodlands (19%; 15%+4%), farmland (9%; 8%+1%), and tropical evergreen forest (6%; 2%+4%).

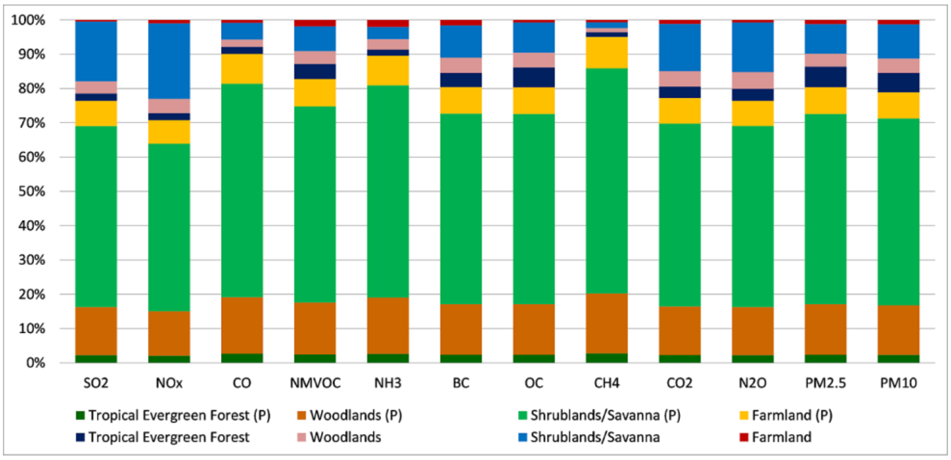

Figure 5. Contributions of each land cover type to the total emissions.

We found that peatlands fire had a very significant contribution to the total emissions. Proportion of burned area on peatlands was 69% of the total burned area during this year (1,598,756 ha of the total 2,321,141 ha). However, peatlands fire contributedas much as 81% (on species average) to the total emissions. This was due to peatlands having a relatively higher density of biomass that consist of above and below ground biomass.

4. Conclusions

Emissions of GHGs and pollutants from land and forest fire in Indonesia during 2015 have been assessed in this study. We found that the most severe forest fire event during this period was occurred on the southern part of Central Kalimantan. The peak of emissions was occurred during September which account for 58% of the total annual emissions. Peak season of land and forest fire occurred earlier in western part of Indonesia (May-Jul) than the eastern area (Sep-Nov). The largest contribution was from shrubland/savanna burning which account for 66% (on average) of the total emissions. Burned area on peatlands was 69% of the total burned area in this country, whereas peatlands fire (comprise above and below ground biomass) contributedas much as 81% (on average) to the total emissions.

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References

[1] Andreae M O and Merlet P 2001 Emission of trace gases and aerosols from biomass burning *Global Biogeochem. Cycles* **15** 955–66
[2] Tsutsumi Y, Sawa Y, Makino Y, Jensen J B, Gras J L, Ryan B F, Diharto S and Harjanto H

1999 Aircraft measurements of ozone, NOx, CO, and aerosol concentrations in biomass burning smoke over Indonesia and Australia in October 1997: Depleted ozone layer at low altitude over Indonesia *Geophys. Res. Lett.* **26** 595–8

[3] Zhang L, Li Q B, Jin J, Liu H, Livesey N, Jiang J H, Mao Y, Chen D, Luo M and Chen Y 2011 Impacts of 2006 Indonesian fires and dynamics on tropical upper tropospheric carbon monoxide and ozone *Atmos. Chem. Phys.* **11** 10929–46

[4] Huijnen V, Wooster M J, Kaiser J W, Gaveau D L A, Flemming J, Parrington M, Inness A, Murdiyarso D, Main B and van Weele M 2016 Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997 *Sci. Rep.* **6** 26886

[5] Chang D and Song Y 2010 Estimates of biomass burning emissions in tropical Asia based on satellite-derived data *Atmos. Chem. Phys.* **10** 2335–51

[6] Permadi D A and Kim Oanh N T 2013 Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact *Atmos. Environ.* **78** 250–8

[7] Gaveau D L a, Salim M A, Hergoualc'h K, Locatelli B, Sloan S, Wooster M, Marlier M E, Molidena E, Yaen H, DeFries R, Verchot L, Murdiyarso D, Nasi R, Holmgren P and Sheil D 2014 Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. *Sci. Rep.* **4** 6112

[8] Song Y, Chang D, Liu B, Miao W, Zhu L and Zhang Y 2010 A new emission inventory for non agricultural open fires in Asia from 2000 to 2009 *Environ. Res. Lett.* **5** 14014

[9] Seiler W and Crutzen P 1980 Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning *Clim. Change* **2** 207–47

[10] Giglio L, Loboda T, Roy D P, Quayle B and Justice C O 2009 An active-fire based burned area mapping algorithm for the MODIS sensor *Remote Sens. Environ.***113** 408–20

[11] Baccini A, Goetz S J, Walker W S, Laporte N T, Sun M, Sulla-Menashe D, Hackler J, Beck P S A, Dubayah R, Friedl M A, Samanta S and Houghton R A 2012 Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps *Nat. Clim. Chang.* **2** 182–5

[12] Shi Y and Yamaguchi Y 2014 A high-resolution and multi-year emissions inventory for biomass burning in Southeast Asia during 2001–2010 *Atmos. Environ.* **98** 8–16

[13] Boehm H-D V, Siegert F, Rieley J O, Page S E, Jauhiainen J, Vasander H and Jaya A 2001 Fire impacts and carbon release on tropical peatlands in Central Kalimantan, Indonesia *22nd Asian Conference on Remote Sensing* pp 5–9

[14] 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

[15] Kogan F N 1997 Global Drought Watch from Space *Bull. Am. Meteorol. Soc.***78** 621–36

[16] Zhang X, Kondragunta S, Schmidt C and Kogan F 2008 Near real time monitoring of biomass burning particulate emissions (PM2.5) across contiguous United States using multiple satellite instruments *Atmos. Environ.***42** 6959–72

[17] Anderson G K, Sandberg D V. and Norheim R A 2004 *Fire Emission Production Simulator (FEPS) User's Guide Version 1.0*

[18] Akagi S K, Yokelson R J, Wiedinmyer C, Alvarado M J, Reid J S, Karl T, Crounse J D and Wennberg P O 2011 Emission factors for open and domestic biomass burning for use in atmospheric models *Atmos. Chem. Phys.***11** 4039–72

[19] 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

[20] Kanabkaew T and Kim Oanh N 2011 Development of Spatial and Temporal Emission Inventory for Crop Residue Field Burning *Environ. Model. Assess.***16** 453–64

[21] Aldrian E and Dwi Susanto R 2003 Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature *Int. J. Climatol.* **23** 1435–52