Doubling of annual ammonia emissions from the peat fires in Indonesia during the 2015 El Niño

Simon Whitburn, Martin van Damme, Lieven Clarisse, Solène Turquety, Cathy Clerbaux, Pierre-François Coheur

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Key Points:
- NH_3 emissions in Indonesia for 2015 are 2–3 times higher than in the past 7 years
- IASI-derived ammonia emission factors for peatlands are 2.5–8 times lower than those used in GFAS
- First IASI-derived assessment of peat soil combustion

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2

Correspondence to:
S. Whitburn,
swhitbur@ulb.ac.be

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Doubling of annual ammonia emissions from the peat fires in Indonesia during the 2015 El Niño

S. Whitburn[1], M. Van Damme[1], L. Clarisse[1], S. Turquety[2], C. Clerbaux[1,3], and P.-F Coheur[1]

[1]Faculté des Sciences, Service de Chimie Quantique et Photophysique, Spectroscopie de l'Atmosphère, Université libre de Bruxelles (U.L.B.), Brussels, Belgium, [2]UMPC University Paris, Ecole Polytechnique, CNRS/INSU, LMD-IPSL, Palaiseau, France, [3]LATMOS/IPSL, UPMC University Paris, Sorbonne Universités, UVSQ, CNRS, Paris, France

Abstract In the autumn of 2015, thousands of square kilometers of forest and peatlands in Indonesia went up in flames. Among the primary species emitted by fires, ammonia (NH_3) is of special relevance for air quality. Here we derive daily and total NH_3 emission fluxes over the affected area using satellite measurements for the years 2008–2015. The 2015 fires emitted an estimated 1.4–8.2 Tg of NH_3 (with a maximum of 0.06–0.33 Tg d^{-1}). On an annual basis, the 2015 NH_3 emissions are a factor 2–3 larger than in the previous 7 years. We derive NH_3 emission factors for peat soils, which are found to be 2.5–8 times lower than those used in the GFASv1.2 emission inventory but in excellent agreement with those reported in other recent studies. Finally, we estimate that 3.28×10^9 m^3 peat soil was consumed during these 2015 fires, corresponding to an average burn depth of 39 cm.

1. Introduction

Indonesia experienced in the autumn of 2015 the most severe forest fires in almost two decades. In the region, fires are generally human induced for land clearing purposes and therefore recurrent [*Gaveau et al.*, 2014]. In 2015, the fires were amplified by the strongest El Niño–Southern Oscillation (ENSO) since 1997, which caused severe droughts throughout the western Pacific [*Chisholm et al.*, 2016]. Fires burned out of control for about 2 months between September and October, mostly on Sumatra and the Indonesian portion of Borneo. They caused the loss of about 2.6 million hectares of tropical forests and peatlands [*Glauber et al.*, 2016], below the 1997–1998 record of 4.56 million hectares [*Heil and Goldammer*, 2001], and the release of 227 ± 67 Tg of total carbon into the atmosphere [*Huijnen et al.*, 2016]. Peat fires also propagated underground, making them unpredictable and very difficult to control.

The fires greatly impacted the local and regional ecosystems, and atmospheric transport of the fire plumes over the region was responsible for the exposure of 40 million people to hazardous levels of air pollution [*Chisholm et al.*, 2016]. It is anticipated that the fires will have a small but discernible impact on the global climate as was the case in 1997 [*Heil and Goldammer*, 2001; *Page et al.*, 2002; *Harrison et al.*, 2009]. To assess these impacts, a more accurate determination of the fire emissions is needed. Several estimates have been reported recently for carbon species: *Huijnen et al.* [2016] used the modeling and assimilation framework of the Copernicus Atmosphere Monitoring Service (CAMS) combined with in situ smoke measurements to estimate carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4) emissions, while *Parker et al.* [2016] derived CH_4 and CO_2 enhancements and biomass burning emission ratios from the measurements of the Greenhouse gases Observing SATellite (GOSAT). More recently, *Stockwell et al.* [2016] calculated emission factors (EFs) for peatlands from in situ measurements for a series of trace gases. No studies on total emissions have been conducted up to now for noncarbon species such as NH_3, which is of prime importance to the environment since it is known to be responsible for eutrophication and acidification of the ecosystems. In the atmosphere, it combines with acid gases (mostly sulfuric acid (H_2SO_4), nitric acid (HNO_3), and hydrochloric acid (HCl)) resulting in the formation of secondary aerosols that in turn impact climate and human health.

In this paper, we determine and analyze the atmospheric ammonia (NH_3) emissions from the 2015 Indonesian fires based on satellite observations and we derive new EF_{NH_3} from peatlands for this event. The use of satellite observations offers the possibility to follow a particular event throughout its entire duration and spatial extent owing to the good spatial and temporal coverage compared to airborne and ground-based measurements. This is particularly true for the Infrared Atmospheric Sounding Interferometer (IASI) instrument used here,

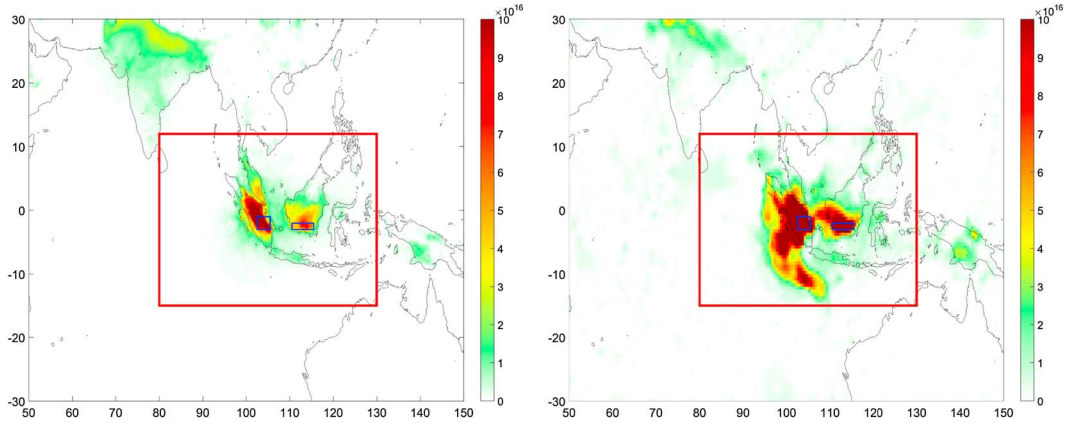

Figure 1. (left) NH_3 total columns (molec cm^{-2}) from IASI measurements (morning overpasses) between August and November 2015 on a 0.5° by 0.5° grid. The distribution is an arithmetic mean of all measurements within a cell. The red rectangle shows the studied area for fluxes calculation. The blue rectangles show the studied areas for the calculation of the NH_3 enhancement ratios relative to CO. (right) NH_3 total columns (molec cm^{-2}) measured on a single day, 25 October 2015, (MetOp A and B) distributed on a 0.5° by 0.5° grid.

which has exceptional sampling. We discuss these emissions in a multiple-year perspective using available measurements since 2008. The quantification of NH_3 emissions from fires is important to assess, on one hand, how much of the nitrogen pool in the soil was consumed and, on the other hand, the contribution of the nitrogen species on the degradation of air quality and ecosystem health. We also derive a first top-down estimation of the amount of peat soils that was consumed during the event.

2. IASI Satellite Measurements of NH_3 and CO

The 2015 fires in Indonesia provide an excellent case for the study of NH_3 wildfire emissions from satellite since (1) forests and peatlands burned with a high intensity during a long time period, (2) fires were restricted to a limited area, and (3) they occurred far away from other sources of NH_3. Most of the results in this paper are obtained using the measurements from the Infrared Atmospheric Sounding Interferometer (IASI), a hyperspectral infrared sounder on board the polar Sun-synchronous MetOp satellites. It covers the entire globe twice daily (crossing the equator at 9:30 and 21:30 local solar time) with a relatively small footprint on the ground (circular pixel of 12 km diameter at nadir), a good spectral resolution (0.5 cm^{-1} apodized) [*Clerbaux et al.*, 2009] and a dense spatial coverage (compared to other similar instruments, such as TES) [*Shephard et al.*, 2011]. Only daytime measurements were used in this work because of the generally more favorable thermal contrast prevailing during daytime in the region compared to nighttime. The retrieval of NH_3 is based on a new robust and flexible algorithm [*Whitburn et al.*, 2016]. We also used in support to our analysis CO tropospheric columns retrieved from IASI using the FORLI algorithm [*Hurtmans et al.*, 2012]. The FORLI-CO columns have been intercompared and validated [*George et al.*, 2015] and used in several previous studies in relation to fire emission and transport [e.g., *Krol et al.*, 2013].

The exceptional character of the 2015 fires is shown in Figure 1. Figure 1 (left) shows the mean NH_3 total columns (molec cm^{-2}) distribution (MetOp A and B measurements) between August and November 2015 in a 0.5° by 0.5° grid. Figure 1 (right) shows the (transported) NH_3 fire plume (molec cm^{-2}) and emission sources measured on 25 October 2015. Here and elsewhere in this study, only total columns with a relative error lower than 100% or an absolute error lower than 7.5×10^{15} molec cm^{-2} and a cloud contamination lower than 25% are retained. Doing this, low columns typical for background conditions with a large relative error but a small absolute error are also taken into account, reducing the high bias reported in other studies [*Van Damme et al.*, 2014]. High NH_3 total columns are found above Indonesia, mostly in the eastern part of Sumatra and in the Indonesian portion of Borneo in agreement with the localization of the fire hot spots. The highest mean columns reach 1.6×10^{17} molec cm^{-2} which is 3–4 times larger than those over India that usually dominate the distribution in the same time period. Transported plumes over the Indian Ocean are also clearly visible, especially on the daily NH_3 total column (molec cm^{-2}) distributions (Figure 1, right).

When quantifying trace gas emissions from fires, an important parameter is the emission factor (EF_x), which is defined as the mass of a trace gas X emitted per kilogram of biomass burned (g kg^{-1} dry matter (DM)). As it

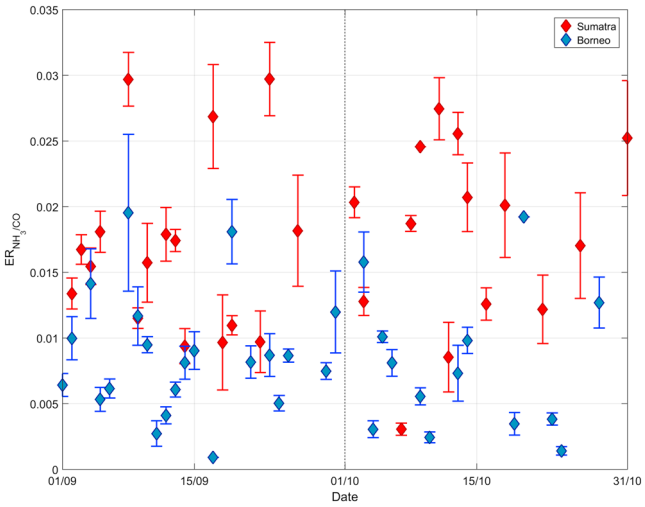

Figure 2. Daily NH_3 enhancement ratios relative to CO ($ER_{NH_3/CO}$) calculated from the slope of the linear regression of NH_3 versus CO total columns between 1 September and 31 October 2015, over Sumatra (red) and Borneo (blue). The error bars correspond to the standard errors on the regression slope. Daily $ER_{NH_3/CO}$ with a correlation coefficient <0.3 for the slope have been excluded.

cannot be derived from satellite measurements directly, a related parameter, the enhancement ratios (ERs), is frequently used. The $ER_{NH_3/CO}$ is defined as the ratio of the number of emitted molecules of NH_3 (or the NH3 total column) over the emitted molecules of CO (or the CO total column, the reference species) [*Goode et al.*, 2000; *R'Honi et al.*, 2013]:

$$ER_{NH_3/CO} = \frac{[NH_3]_{smoke} - [NH_3]_{ambient}}{[CO]_{smoke} - [CO]_{ambient}} \quad (1)$$

As enough measurements are available from IASI, daily average ERs can best be estimated from the slope of the linear regression of NH_3 versus CO total columns (by considering each IASI measurement) [*Andreae and Merlet*, 2001; *Coheur et al.*, 2009]. We have calculated the daily mean $ER_{NH_3/CO}$ separately over the two principal burning areas in the region (blue rectangles in Figure 1) between 1 September and 31 October 2015. The first is in Sumatra and extends from 3–1° S to 102.5–105.5° E and the other is in the Indonesian portion of Borneo from 3–2° S to 110.5–115.5° E. The 2 months time series of the daily mean $ER_{NH_3/CO}$ (±standard error) is shown in Figure 2. Note that the $ER_{NH_3/CO}$ with a correlation coefficient of the linear regression (between NH_3 and CO) lower than 0.3 were excluded from the analysis. While we do not find a clear trend in the evolution of the $ER_{NH_3/CO}$ during the 2 months, there are significant differences between the two areas, with $ER_{NH_3/CO}$ almost systematically higher for Sumatra ($17.3 \times 10^{-3} \pm 6.8 \times 10^{-3}$, on average) than for Borneo ($8.4 \times 10^{-3} \pm 4.9 \times 10^{-3}$). Since peat soils were found to be the dominant contribution to the emissions during the fire event (especially for reduced species) [*Huijnen et al.*, 2016], the measured $ER_{NH_3/CO}$ can be considered representative of the $ER_{NH_3/CO}$ for peatlands. In this regard, observed differences in $ER_{NH_3/CO}$ between the two regions are in agreement with the measurements of *Stockwell et al.* [2014] who found much higher EF_{NH_3} for peat soils in Sumatra than in Borneo, despite the similarities in the percent nitrogen content.

3. Fluxes, Masses and Emission Factors

3.1. NH_3 Flux Emissions and Masses

IASI total columns of NH_3 (molec.cm^{-2}) were converted to daily fluxes (Tg NH_3 d^{-1}) using a simplified box model similar to *R'Honi et al.* [2013] and *Whitburn et al.* [2015] and considering four different effective lifetimes (τ_{eff}) for NH_3 of 6 h, 12 h, 24 h and 36 h (since the effective lifetime of NH_3 is unknown and highly variable) in agreement with the NH_3 lifetime reported in *Dentener and Crutzen* [1994]; *Aneja et al.* [2001] and *R'Honi et al.* [2013]. Details of the methodology are given in Text S1 in the supporting information. The domain considered for the calculation, extending from 15° S to 12° N in latitude and from 80° to 130° E in longitude (red rectangle in Figure 1), was selected to include the majority of the transported NH_3 plumes. Note that this selected region does not show other significant sources of emissions.

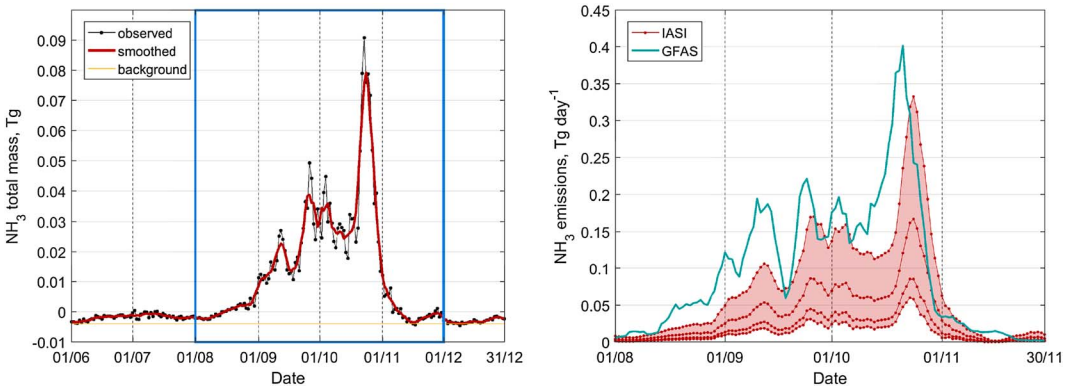

Figure 3. (left) Daily total NH_3 masses in Tg (black dots and red line) over the area 15° S–12° N, 80–130° E between June and December 2015. The red line represents the 5 day simple moving average total masses; the yellow line corresponds to the background total masses used for the calculation of the daily fluxes. (right) NH_3 emission fluxes in Tg d^{-1} between August and November 2015 (period defined by the blue rectangle on Figure 3, left) using four different effective lifetimes for NH_3: 6, 12, 24, and 36 h. The shaded area corresponds to the set of possible values of NH_3 emission fluxes within the range of values given by the different effective lifetimes (red lines). The cyan line correspond to the 5 day moving average NH_3 emissions from the GFASv1.2 inventory.

Figure 3 (left panel) shows for the period extending from June 1 to December 31 the daily total masses in Tg (in black daily values and in red 5 day simple moving average) above the studied area. We find large daily amounts of NH_3 between September 10 and the end of October with daily total masses between 0.02 and 0.04 Tg NH_3 and a peak value at 0.08 Tg around 20–25 October. For the sake of comparison, these peak emitted masses are about 1.5–2 times larger than the daily total masses reported in *R'Honi et al.* [2013] for the 2010 Russian fires, for a surface which is about 40% smaller. These observed differences can be explained by differences in the type of burned fuel, since both peatlands and boreal forest were affected during the 2010 Russian fires. After October 31, mean NH_3 columns (Figure 1) and total masses (Figure 3) quickly return to background values because of the short lifetime of NH_3 and the end of fires associated with the arrival of rain.

The right panel in Figure 3 shows the NH_3 emission fluxes (Tg d^{-1}) between August 1 and November 30, with a mean background value subtracted. The latter is taken as the minimum of the total masses observed in 6 months intervals and is represented by a yellow line on the left panel. Note that this subtraction process leads to a slight overestimation in background conditions as the total emitted masses can be negative (Figure 3, left panel). As mentioned above, NH_3 emission fluxes are calculated by considering four different effective lifetimes for NH_3 (6 h, 12 h, 24 h and 36 h) and the results are presented as a set of possible values of NH_3 fluxes (shaded area) within the range of values given by the different lifetimes (red lines). The maximum NH_3 flux is calculated for October 24 with values between 0.06 and 0.33 Tg d^{-1}. Higher values are expected for the smaller effective lifetime. By summing the daily emission fluxes over the whole period (between 1 September and 31 October), the total emissions for the event are calculated to be, respectively, 1.4, 2.1, 4.1, and 8.2 Tg and make up 76% of the total emissions for the year 2015 within the studied region.

3.2. Comparison With the GFAS Inventory and Calculation of New EF

These calculated fluxes from IASI measurements can be compared with these from the Global Fire Assimilation System (GFASv1.2) biomass burning emission inventory (cyan line on Figure 3) which rely for the estimation of the emissions fluxes on the linear relationship between the biomass burned in a fire and the radiative energy it releases [*Kaiser et al.*, 2012]. We find systematically higher fluxes for the bottom-up (GFAS) than for the top-down (IASI) estimates, even when considering an effective lifetime of 6 h for NH_3. These observed differences could point to underestimation of the IASI NH_3 columns, but it is unlikely that this is the main factor responsible as large NH_3 columns lead to larger spectral signatures and reduced measurement uncertainties. It is also possible that the assumed NH_3 lifetime is still too large, leading to an underestimation of the calculated daily fluxes. To examine this possibility, we have estimated a mean effective lifetime of NH_3 from the IASI measurements on multiple days (seven) showing a well-marked transported plume (see Text S2, Table S1, and Figure S1 in the supporting information). We find a mean lifetime of about 21 h which is well in the range used to calculate the emission fluxes. Finally, it is possible that the emissions are overestimated in GFAS through an overestimation of the EF_{NH_3}.

Table 1. EF_{NH_3} in g kg^{-1} Dry Matter Derived From the Total NH_3 Emissions (E_{NH_3}(tot)) for Different Effective Lifetimes (τ_{eff}) for NH_3

τ_{eff} (h)	12	21	24	30	36
E_{NH_3}(tot) (Tg)	4.1	2.3	2.1	1.7	1.4
EF_{NH_3} (g kg^{-1} DM)	7.7	4.2	3.7	2.9	2.4

[a]The 21 h lifetime corresponds to that determined empirically (see Text S2 in the supporting information).

To explore this last possibility, we focus on the fraction of emissions related to peat soils which dominated, by far, the total emissions [*Huijnen et al.*, 2016]. In support to this analysis, we use CO emissions estimated from the IASI CO total columns following the same method as for NH_3 (see section 3.1) and for which the EFs used in the emission inventories are thought to be more reliable. Note that a larger domain than for NH_3 was considered (30°S–30°N and 40–150°E) because of the longer lifetime of CO (of about a week to months [*Holloway et al.*, 2000; *Yurganov et al.*, 2011]). The comparison of the IASI-derived daily CO emissions fluxes (calculated for three different lifetimes: 7, 15, and 30 days) with GFAS (see Figure S2) gives a good correspondence, especially when considering a lifetime of 30 days for CO, with differences of 13% on average. Over the whole fire period (between 1 September and 31 October), we find total emissions of CO of about 122 Tg. Based on the results of *Huijnen et al.* [2016], we consider that about 90% of these (i.e., 110 Tg) are attributed to CO originating from burning peatland. The remaining 12 Tg are attributed to tropical forests. Assuming that the other EFs used in GFAS are valid, we can then derive an average EF_{NH_3} for peatlands for this specific event following

$$E_{CO}(\text{peat}) \times \frac{EF_{NH_3}}{EF_{CO}}(\text{peat}) + E_{CO}(\text{TF}) \times \frac{EF_{NH_3}}{EF_{CO}}(\text{TF}) = E_{NH_3}(\text{tot}) \quad (2)$$

with E_{CO}(peat) (= 110 Tg) and E_{CO}(TF) (= 12 Tg) the fraction of CO emissions originating from peatlands and tropical forests, and E_{NH_3}(tot) the total NH_3 emissions calculated by considering different effective lifetime for NH_3 (between 12 h and 36 h; see Table 1); EF_{CO}(peat) = 210 g kg^{-1} DM, EF_{CO}(TF) = 101 g kg^{-1} DM, EF_{NH_3}(TF) = 0.93 g kg^{-1} DM. We find this way an EF_{NH_3} for peatland between 2.4 (for the 36 h lifetime) and 7.7 (12 h lifetime) g kg^{-1} DM. It is, as expected, lower than the one used in GFAS (= 20 g kg^{-1} DM), by a factor 2.5–8 and than the one given in *Akagi et al.* [2011] (10.8 g kg^{-1} DM, derived from Indonesian and boreal peat), but is in excellent agreement with the EFs reported by *Stockwell et al.* [2014] specifically for Indonesian peat (7.57 g kg^{-1} DM) using open-path Fourier transform infrared spectroscopy. More recently, *Stockwell et al.* [2016] measured even lower EF_{NH_3} for the peat soils (2.86 ± 1.00 g kg^{-1} DM) for the 2015 fires, but their analyses were restricted to the Borneo island. Including our new estimate of EF_{NH_3}(peat) in equation (2), we conclude that 90–98% of the NH_3 emitted in 2015 originated from peatlands.

A second estimate of NH_3 emission factors, $EF^*_{NH_3}$, can be derived from $ER_{NH_3/CO}$ (estimated in section 2). Since they were measured in the immediate vicinity of the emission sources, the two quantities are related via

$$EF^*_{NH_3} = ER_{NH_3/CO} \times \frac{MM_{NH_3}}{MM_{CO}} \times EF_{CO}, \quad (3)$$

where MM_{NH_3} and MM_{CO} are the molar masses of NH_3 and CO, and EF_{CO} is taken as the one used in GFAS for peatlands (= 210 g kg^{-1} DM). This gives $EF^*_{NH_3}$ of 2.21 (±0.86) and 1.07 (±0.63) g kg^{-1} DM for Sumatra and Borneo, respectively, which is in good agreement with the EF_{NH_3} derived from equation (2) when considering the effective lifetime of 36 h for NH_3 (= 2.4 g kg^{-1} DM). The $EF^*_{NH_3}$ should be taken as a lower bound since (1) they also include the emissions from nonpeat fires with lower specific EF_{NH_3} and (2) they do not take into account the accumulation of CO in the area.

Given the above, we conclude that the average EF_{NH_3} for the Indonesian peatlands is probably in between $EF^*_{NH_3}$ and EF_{NH_3} estimated with the lower lifetime of 12 h for NH_3, i.e., between 2.21 g kg^{-1} DM and 7.7 g kg^{-1} DM. This is much lower than the factor applied to peatland emissions in GFAS and likely explains the high flux values in the inventory.

3.3. Comparison With the Previous Years and Estimation of Burned Peat Soils

The exceptional character of the 2015 emissions in the perspective of the previous years is illustrated in Figure 4 where the daily fluxes (Tg d^{-1}) calculated over the period 2008–2015 considering the IASI-derived

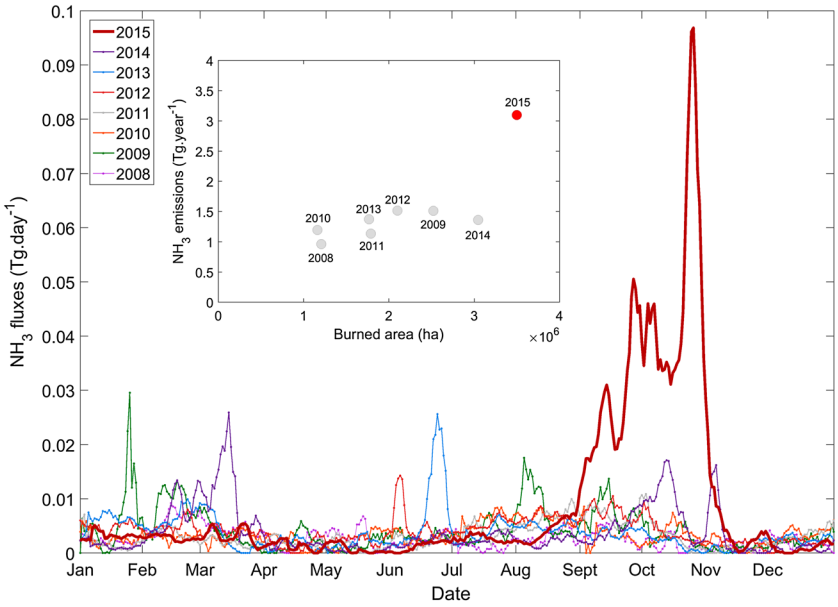

Figure 4. NH_3 emission fluxes in Tg d^{-1} (5 day simple moving average) between 2008 and 2015 by considering the empirically derived effective lifetime of 17 h for NH_3. (inset) Cumulated annual NH_3 emissions fluxes in Tg yr^{-1} calculated from the daily NH_3 emissions fluxes (Tg d^{-1}) (considering the same effective lifetime of 17 h for NH_3) relative to the total annual burned area (ha) for the region (15° S–12° N, 80–130°E).

lifetime of 21 h for NH_3 are shown, as well as the yearly fluxes (Tg yr^{-1}) relative to the Global Fire Emissions Database Version 4 (GFEDv4) burned area (ha) [*Randerson et al.*, 2015] for the same period (inset). On a daily basis (Figure 4), we find that emission fluxes at the peak in 2015 are 3 to 6 times higher than for the seven previous years, which have maximum generally between 0.015 and 0.03 Tg d^{-1}. Note also the presence of marked peaks of NH_3 emissions (although much weaker than the peak of autumn 2015) for the relative large fires of June 2013 [*Gaveau et al.*, 2014] and for the period between February and March 2014. On a yearly basis (Figure 4, inset), we find that the annual NH_3 emissions for the year 2015 (3.1 Tg yr^{-1}) are as well 2–3 times higher than the annual emissions for the period 2008–2014, but interestingly, this is not systematically the case of the burned area. This is especially true for the years 2009 and 2014 for which we calculate annual NH_3 emissions about 2 times lower than for the year 2015 while the corresponding burned areas are only 13–29% lower. We interpret this as differences in the fraction of peatland burned compared to tropical forest (since peatlands and tropical forests have very different EF_{NH_3}) but also in the burn depth of the peat soils, which is known to be highly variable from one fire event to another [*van der Werf et al.*, 2010]. Based on the GFEDv4 burned area [*Randerson et al.*, 2015], we find that close to 8.5×10^5 ha peatland burned during the 2 months period of the fires. Following the same methodology as in *Huijnen et al.* [2016] but using the IASI data (details of the procedure are given in Text S3 in the supporting information), we estimate a total loss of 3.28×10^9 m^3 of peat soils for the fire event of 2015 (considering a peat bulk density of 0.16 g cm^3), which translates to an average loss of 62 kg DM m^{-2} and an average burn depth of 39 cm. This is about 13 cm deeper than what was calculated by *Huijnen et al.* [2016] based on CO_2 emissions from bottom-up approaches but well in the range of burn depths (18–60 cm) measured by *Stockwell et al.* [2016] at different sites in Borneo. It is important to keep in mind that the derived amount of burned peat soil is directly proportional to the chosen lifetime for CO in the calculation of the emissions (here 30 days) which remains uncertain and variable. Nevertheless, it should be emphasized that it is the first time we are able to estimate how much peat soils were consumed during a fire event (and to what depth) using a top-down approach.

4. Conclusion

In this work, we have given a first top-down estimation of how much NH_3 was emitted during the 2015 Indonesia's peat and forest fires using IASI observations combined to a simple box model with first-order loss in NH_3. We found maximum daily emissions of about 3 to 6 times higher than the emissions from the seven previous years (2008–2014). From the NH_3 (and CO) emissions, we derived new EF_{NH_3} for peatlands in the range

2.4–7.7 g kg^{-1} dry matter (DM), depending on the lifetime considered for NH_3 (between 12 and 36h). These values suggest an overestimation of the EF_{NH_3} used in GFAS and given in *Akagi et al.* [2011] by a factor 4 to 8. The new EF_{NH_3} were also supported by the low $EF^{*}_{NH_3}$ (at around 1–2 g kg^{-1} DM) derived from the NH_3 enhancement ratios relative to CO ($ER_{NH_3/CO}$) over the two principal fire source areas (Sumatra and Borneo). Finally, we have also provided a top-down assessment of how much peat soils was consumed, following the same methodology as in *Huijnen et al.* [2016]. We found a total loss of 3.28×10^9 m^3 of peatlands, corresponding to an average burn depth of 39 cm, in good agreement with *Huijnen et al.* [2016] and *Stockwell et al.* [2016].

Acknowledgments

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