Title:

Characteristics of fire-generated gas emission observed during a large peatland fire in 2009 at Kalimantan, Indonesia

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Abstract

To investigate the characteristics of gas emissions from a tropical peatland fire, ground-level measurement of fire-generated gases was conducted during a large fire event in Kalimantan, Indonesia in 2009. Concentrations of CO and CH_4 showed positive linear correlations with that of CO_2. The relationship between concentrations of N_2O and CO_2 were divided into two parts, suggesting the influence of additional N_2O generation during sample storage. The CO_2-normalized emission ratio was calculated for CO, CH_4, and N_2O. The molar ratio of these fire-generated gas emissions was summarized as CO_2:CO:CH_4:N_2O = 1.00:0.382:0.0261:0.000156, whereas the emission ratio calculated on the global warming potential (GWP) basis was CO_2:CH_4:N_2O = 1.00:0.237:0.0465. The GWP emission based on this ratio was 87.8–91.2% of a simple evaluation in which all carbon was assumed to be emitted as CO_2. This is the first trial to evaluate the emission ratios of major greenhouse gases on the basis of ground-level observation during an actual tropical peatland fire.

Key words:

Biomass burning,
Emission ratio,
Fire-generated gas emission,
Global warming potential,
Indonesia,
Tropical peatland

1. Introduction

Tropical peatland in Southeast Asia is a vast reservoir of terrestrial carbon. According to the latest estimation, it covers 24.8 million hectares and stores 68.5 PgC peat that is equal to 11–14% of global peat carbon (Page et al., 2011). In recent decades, large-scale peatland fires have occurred frequently in this area. Page et al. (2002) estimated that 0.12–0.15 PgC peat (5.6–13.4% of the total peat carbon storage) was lost by a widespread fire in 1997 from a one million hectare area in Central Kalimantan, Indonesia. According to van der Werf et al. (2008), average carbon emission from fire during 2000–2006 in equatorial Asian countries (Indonesia, Malaysia, and Papua New Guinea) was 0.128 ± 0.051 PgC/yr, which was comparable to the emissions from fossil fuel combustion in these countries (0.148 PgC/yr during 2000–2004). Several studies have suggested that gas emissions from the 1997–1998 tropical peatland fires in Southeast Asia had a great impact on large-scale atmospheric concentrations of CO_2, CO, and CH_4 (e.g. Langenfelds et al., 2002; Novelli et al., 2003; van der Werf et al., 2004).

Regional gas emissions from peatland fires have been evaluated mainly on the basis of satellite images (e.g. Levine, 1999; van der Werf et al., 2008). Airborne monitoring also has been applied for direct observation of large-scale biomass burning (e.g. Cofer III et al., 1989; 1990a; 1990b; Ikegami et al., 2001). This method can determine averaged gas concentrations for large-scale distribution in the atmosphere. Ground-level monitoring is another method for direct measurement of gas emissions from biomass burning. Compared to airborne monitoring, it is a relatively low-cost method and can provide ground-truth data for the large-scale evaluation based on remote-sensing techniques. However, reports on the ground-level monitoring in tropical peatland are still fragmentary (e.g. Radojevic and Hassan, 1999; Muraleedharan et al., 2000a; Limin et al., 2007).

To investigate the characteristics of gas emission from biomass burning, emission ratio (ER) has been used. The emission ratio of gas Y to gas X ($ER_{Y/X}$) is defined as a quotient of excess mixing ratios ($\Delta Y/\Delta X$), which is the ratio of the excess amount of gas Y above the background to that of gas X above the background (Christian et al., 2007). For example, the ER of CO to CO_2 ($ER_{CO/CO2}$) is widely used as a good indicator of the relative amount of the flaming and smoldering combustion of biomass burning (Radojevic, 2003; Yokelson et al., 2007). On the basis of the "CO_2-normalized" emission ratios ($ER_{Y/CO2}$), emissions of fire-generated gases are evaluated quantitatively relative to that of CO_2, similar to the concept of global warming potential (GWP).

In this study, characteristics of gas emissions from a tropical peatland fire were investigated on the basis of the ground-level observations in Kalimantan, Indonesia in 2009. Concentrations of major greenhouse gases (GHGs; CO_2, CH_4, and N_2O) as well as CO were measured and their $ER_{Y/CO2}$ was calculated to evaluate the influence of fire-generated gas emissions on global warming.

2. Materials and Methods

2.1 Site description

The study area is located near Palangka Raya (2°S 114°E), Central Kalimantan Province, Indonesia. This area is the northern edge of Block C in the ex-Mega Rice Project, a national project that was initiated in 1996 and canceled in 1999 (Muhamad and Rieley, 2002). During the execution of this project, many canals and ditches were constructed throughout the area, which promoted overdrainage of the peatland and made the area subject to fire. Because of extremely dry conditions, peatland fires have frequently occurred in the dry season, particularly in El Niño and Southern Oscillation (ENSO) years (Hirano et al., 2007; 2012; van der Werf et al., 2008). The incomplete combustion of peat generates much smoke and causes dense haze, which has recently become a serious socio-economic problem (Limin et al., 2007).

One of the recent ENSO events occurred in 2009–2010. Hirano et al. (2012) reported considerable decrease in rainfall and groundwater level in peat swamp forest around Palangka Raya during the dry season (July-October) in 2009. Usup et al. (2004) conducted peat burning experiment to elucidate combustion and thermal characteristics of peat fire (but no gas measurement) in the Block C area in 2002, which was also an ENSO year. According to their results, the gravimetric water content of peat soil was about 100% at the ground surface. They actually succeeded in igniting peat soil at several locations to perform field experiments. Frandsen (1987) reported on the relationship between the content of moisture and minerals on ignition limit of a peat moss mixture. This relationship suggests that a peat-like material which consists of 100% organic matter can be ignited under gravimetric water content < 110%. Previous surveys conducted on peat soil in Kalimantan Island indicate that organic content of the soils are nearly 99% (Melling et al., 2005a; 2005b; 2006; 2007). Judging from these conditions, peat soil in the study area would be dry enough to support self-sustaining peat fire during the dry season in 2009.

2.2 Sample collection

There were two large fire events near the study area in 2009: the first occurred from August 8 to 30, burning 380 ha; the second occurred from September 19 to October 10, burning approximately 1300 ha. Air samples were collected on September 30 and October 4, in the middle of the second fire event. During the collection, the sampling location had many hot spots and was continually covered by smoke. To obtain wide ranges of gas concentrations, sampling was conducted as follows: some samples were collected just above a smoking hole; other samples were collected several meters leeward from major hot spots. Using a plastic syringe, 300 mL of air was collected in a 500-mL Tedlar® bag. Two samples were taken in duplicate at 12 sites. After the sampling, CO_2 and CO concentrations were determined within 2–3 h. Before that, 20 mL of each air sample was transferred to a pre-evacuated 10-mL vial capped with a butyl rubber septum using a plastic syringe equipped with a side-hole needle. These bottles were shipped to Hokkaido University, Japan to analyze CH_4 and N_2O concentrations.

2.3 Gas analysis

CO_2 and CO concentrations were determined with a non-dispersive infrared analyzer (ZFP9GC11, Fuji

Electric, Tokyo, Japan) and a controlled potential electrolysis analyzer (CO-85FL, Riken Keiki, Tokyo, Japan). CH_4 concentration was determined with a gas chromatograph (GC-8A) that consisted of a flame ionization detector maintained at 130°C and a 2-m long activated carbon column (80/100 mesh) at 70°C with pure nitrogen gas as a carrier (Shimadzu, Kyoto, Japan). N_2O concentration was determined with a gas chromatograph (GC-14B) that consisted of an electron capture detector maintained at 340°C and a 1-m long Porapak N column at 60°C with PR gas (5% CH_4 in Ar; Shimadzu, Kyoto, Japan).

2.4 Numerical analysis

According to the definition, $ER_{Y/CO2}$ can be calculated from a single pair of CO_2 and gas Y concentrations and their atmospheric background values. However, in this study, it was difficult to determine the background because more than 10 days had passed since the beginning of the second large fire in 2009 and a dense haze had covered the study area during the sample collection. Instead of using the atmospheric background, $ER_{Y/CO2}$ was determined as the slope of a linear regression for the plot of gas Y vs. CO_2. Helas et al. (1995) also adopted the linear regression method to exclude uncertainties due to a poorly defined background. Yokelson et al. (1999) confirmed that the ERs given by the ratio of averaged concentration of coupled gases were almost same as those obtained by linear regression.

3. Results and Discussion

3.1 Relationship between concentrations of CO_2 and other gases

Concentrations of CO, CH_4, and N_2O in each gas sample generally increased with that of CO_2 in the same sample (Fig. 1). The maximum concentrations of CO_2 and CO reached approximately 2500 and 1000 ppmv, respectively, and those of CH_4 and N_2O were less than 100 and 1 ppmv, respectively.

$ER_{CO/CO2}$, $ER_{CH4/CO2}$, and $ER_{N2O/CO2}$ estimated as the slope of linear regression for the whole range of observed CO_2 were 0.382, 0.0261, and 0.000156, respectively (Table 1). All correlations were high (R^2 = 0.773–0.968) and statistically significant ($P < 0.001$). In the case of N_2O, additional regression analyses were performed by dividing the CO_2 range into two parts. When CO_2 < 1500 ppmv, the correlation was not significant ($P > 0.05$). When CO_2 > 1500 ppmv, the correlation was higher (R^2 = 0.954) but less significant ($P < 0.05$) relative to the regression for the whole CO_2 range because only four samples were obtained in this CO_2 range. Such difference in the correlation of CO_2 and N_2O between the divided CO_2 ranges might be attributed to additional generation of N_2O during storage of the sample gas (discussed in 3.2).

3.2 CO_2 normalized emission ratios

The previously reported values of $ER_{CO/CO2}$ based on laboratory experiments were approximately 0.2–0.5 for peat and bog soil (0.29 ± 0.11 in average of 11 data with standard deviation; Yokelson et al., 1997;

Muraleedharan et al., 2000b; Christian et al., 2003; Chand et al., 2005; Iinuma et al., 2007), 0.1–0.2 for litter and logs (Bertschi et al., 2003), and less than 0.15 for above-ground biomass (Yokelson et al., 2008; McMeeking et al., 2009). Several airborne observations conducted in different combustion stages showed that $ER_{CO/CO2}$ obtained in the smoldering stage was higher than that obtained in the flaming stage in most cases (Cofer III et al., 1989; 1990a; 1990b). The $ER_{CO/CO2}$ of 0.382 in this study clearly reflected characteristic peat burning; it was highly incomplete and dominated by smoldering combustion.

The previously reported $ER_{CH4/CO2}$ based on laboratory experiments were approximately 0.008–0.070 for peat (0.033 ± 0.027, four data; Yokelson et al., 1997; Muraleedharan et al., 2000b; Christian et al., 2003), 0.004–0.044 for litter and logs (Bertschi et al., 2003), and 0.0003–0.0156 for above-ground biomass (Yokelson et al., 2008; McMeeking et al., 2009). The $ER_{CH4/CO2}$ of 0.0261 in this study was similar to the averaged value for peat burning in a laboratory.

Previously reported data on $ER_{N2O/CO2}$ obtained for individual fuel types are limited. A series of airborne observations for several vegetation types in North America showed 0.00014–0.00025 in flaming combustion and 0.00017–0.00041 in smoldering combustion (Cofer III et al., 1989; 1990a; 1990b). From ground-level measurements, Griffith et al. (1991) evaluated the $ER_{N2O/CO2}$ up to 0.00008 for the burning of scrub land and coniferous forest, while Delmas et al. (1995) reported 0.000145 in African savanna. In this study, the $ER_{N2O/CO2}$ obtained for the whole range of observed CO_2 was 0.000156, which was similar to the results reported in previous studies.

However, it has revealed that N_2O concentration is subject to increase in a grab-sampled container in which nitric oxide (NO) and sulfur dioxide (SO_2) coexist (e.g. Muzio and Kramlich, 1988; Cofer III et al., 1990b; Linak et al., 1990). de Soete (1988) proposed the following mechanism for N_2O production in dry gas mixtures:

$$2\ NO + SO_2 = N_2O + SO_3$$

Wang et al. (2003) formulated a series of potential chemical reactions that produced N_2O from NO and SO_2, and Preto et al. (2004) experimentally investigated this process and its time dependence. According to their results, detectable N_2O increase in proportion to the initial concentration of NO and SO_2 as well as O_2 and water vapor was found within an hour after sample collection at 25°C. In general, NO is the single most abundant species among detectable fire-generated nitrogen compounds, whereas most of the plant sulfur emitted in gaseous form is SO_2 (Andreae, 1991). Cofer III et al. (1990b) observed N_2O concentration in grab sample containers that had initial N_2O concentrations (0.3–0.9 ppmv) similar to those in this study. According to their results, grab samples with high initial N_2O (> 0.4 ppmv) showed considerable N_2O increase during storage, whereas almost no increase was shown in low initial N_2O samples (≤ 0.4 ppmv). Therefore, the inflection point in the CO_2-N_2O relationship (Fig. 1) may be attributed to the dependence of additional N_2O generation on its initial concentration. For CO_2 and CH_4, there has been no report on a major changing process in gaseous composition of smoke sample during storage.

3.3 Effect of fire-generated gases on global warming

On the basis of the $ER_{Y/CO2}$ for the whole range of observed CO_2 (Table 1), the molar ratio of all gas emissions was simply given as CO_2:CO:CH_4:N_2O = 1.00:0.382:0.0261:0.000156, although the value of $ER_{N2O/CO2}$ is disputable. According to the 4th Assessment Report from the Intergovernmental Panel on Climate Change, the GWP of CH_4 and N_2O are 25 and 298, respectively (for 100 yr time horizon). Then, the ER of major GHGs on the GWP basis was given as CO_2:CH_4:N_2O = 1.00:0.237:0.0465. This evaluation of GWP emission (= 1.28) was equivalent to 91.2% of a simpler evaluation in which (1) only the total amount of gaseous carbon emissions (CO_2, CO, and CH_4) was considered, and (2) all carbon was assumed to be emitted as CO_2 (= 1.41). If N_2O emission was assumed to be zero (= 1.24), the GWP evaluation was 87.8% of the same simple evaluation. These differences result in uncertainties in the evaluation of the effect of biomass burning on the global warming. Therefore, evaluation of peat carbon loss only is not sufficient and it should be coupled with the $ER_{Y/CO2}$ of major GHGs.

CO is not a GHG; however, it affects the lifetime of CH_4 because both gases are consumed through photochemical reactions with OH radicals in the atmosphere that are produced from tropospheric O_3 (WMO 2011). This "surface ozone", the third most important anthropogenic GHG after CO_2 and CH_4 (Denman et al. 2007), is then produced through the oxidation of CO and CH_4 in the presence of NO_x (WMO 2011). Because biomass burning is one of the major sources of atmospheric CO, its emission from peatland fires indirectly affects the global warming effect and should be considered for the projection of global climate change.

4. Conclusions

Characteristics of gas emissions from a tropical peatland fire were investigated on the basis of ground-level observations in Kalimantan, Indonesia in 2009. Concentrations of CO and CH_4 in air samples linearly increased with that of CO_2 with high correlations, whereas the relationship between N_2O and CO_2 showed an inflection point, suggesting the influence of additional N_2O generation during sample storage. Calculated values of $ER_{CO/CO2}$ reflected smoldering combustion in the peatland fire. Evaluation of total GWP emission based on $ER_{Y/CO2}$ was 87.8–91.2% of a simple evaluation in which all carbon was assumed to be emitted as CO_2. Although it was still a snapshot of gas emission characteristics for a prolonged peat fire, this study is the first trial to evaluate the ERs of major GHGs on the basis of ground-level observation during an actual tropical peatland fire.

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Figure and Table Captions

Fig. 1

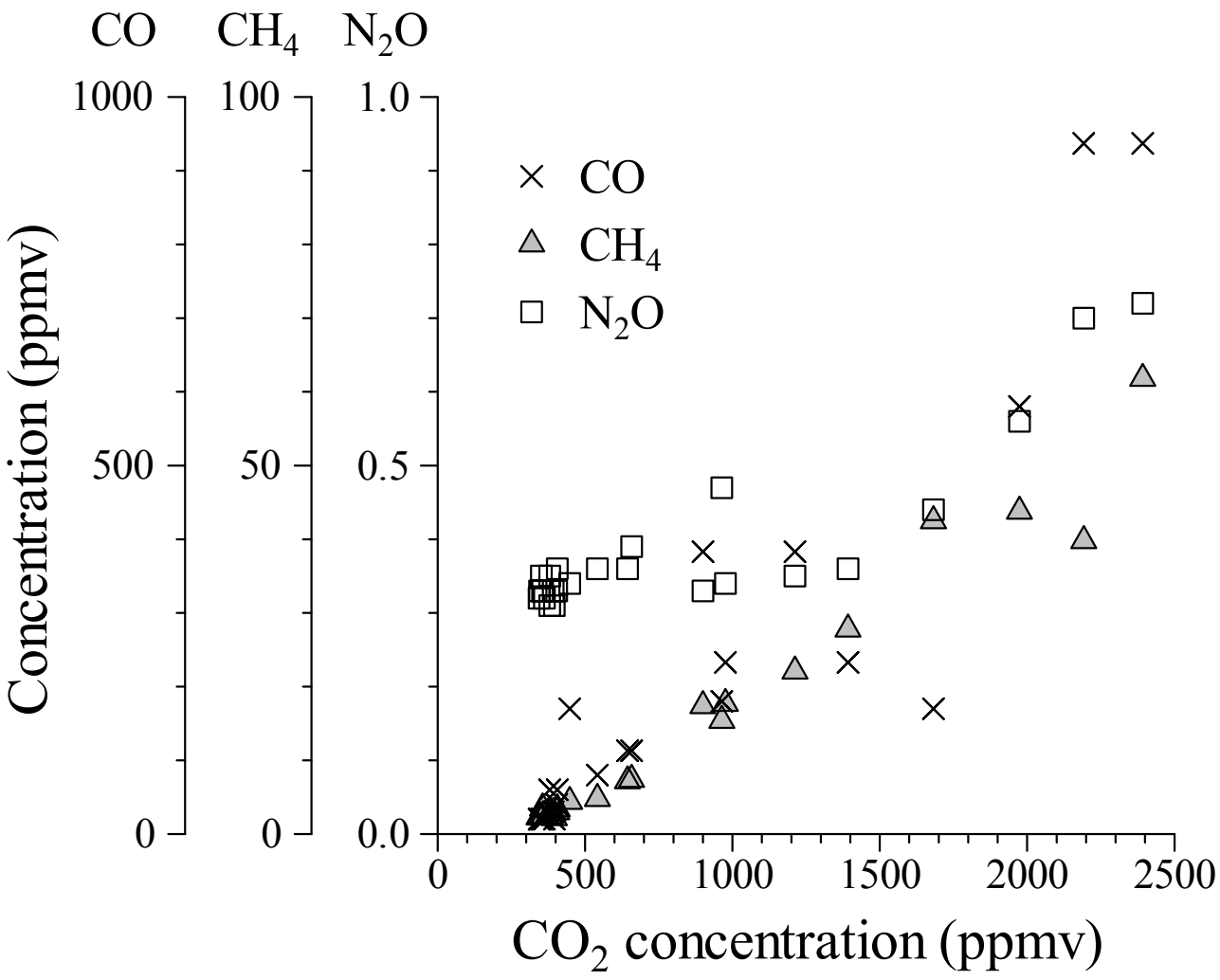
Concentrations of CO, CH_4, and N_2O in each gas sample vs. that of CO_2 in the same sample obtained from ground-level measurement during a tropical peatland fire.

Table 1

Results of linear regression analysis on each gas concentration pair to obtain the emission ratio of gas Y to gas X ($ER_{Y/X}$).

1 **Fig. 1**

2


CO
CH4
N2O
1000
100
1.0
500
50
0.5
0
0
0.0
Concentration (ppmv)
CO
CH4
N2O
0
500
1000
1500
2000
2500
CO2 concentration (ppmv)

3

4

5

1 **Table 1**

2

Gas X	Gas Y	*n*	Slope ($ER_{Y/X}$)	Intercept (ppmv)	R^2
CO_2	CO	23	3.82×10^{-1}	−118	0.829 ***
CO_2	CH_4	24	2.61×10^{-2}	−7.58	0.968 ***
CO_2	N_2O				
Range of CO_2					
All		24	1.56×10^{-4}	0.259	0.773 ***
< 1500 ppmv		20	4.82×10^{-5}	0.319	0.191 †
1500 ppmv <		4	4.27×10^{-4}	−0.275	0.954 *

*** Significant at the 0.001 probability level.

* Significant at the 0.05 probability level.

† Not significant at the 0.05 probability level.

3

4