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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\textsubscript{4} showed positive linear correlations with that of CO\textsubscript{2}. The relationship between concentrations of N\textsubscript{2}O and CO\textsubscript{2} were divided into two parts, suggesting the influence of additional N\textsubscript{2}O generation during sample storage. The CO\textsubscript{2}-normalized emission ratio was calculated for CO, CH\textsubscript{4}, and N\textsubscript{2}O. The molar ratio of these fire-generated gas emissions was summarized as CO\textsubscript{2}:CO:CH\textsubscript{4}:N\textsubscript{2}O = 1.00:0.382:0.0261:0.000156, whereas the emission ratio calculated on the global warming potential (GWP) basis was CO\textsubscript{2}:CH\textsubscript{4}:N\textsubscript{2}O = 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\textsubscript{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 (ΔY/ΔX), 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$_{CO/CO_2}$) 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$_{Y/CO_2}$), 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$_2$O) as well as CO were measured and their ER$_{Y/CO_2}$ 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, CO₂ 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 CH₄ and N₂O concentrations.

### 2.3 Gas analysis

CO₂ 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$_2$O 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, ERY/CO$_2$ 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, ERY/CO$_2$ 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$_2$O 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$_2$O were less than 100 and 1 ppmv, respectively.

ER$_{CO/CO_2}$, ER$_{CH_4/CO_2}$, and ER$_{N_2O/CO_2}$ 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$_2$O, 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$_2$O between the divided CO$_2$ ranges might be attributed to additional generation of N$_2$O during storage of the sample gas (discussed in 3.2).

#### 3.2 CO$_2$ normalized emission ratios

The previously reported values of ER$_{CO/CO_2}$ based on laboratory experiments were approximately 0.2–0.5 for peat and bog soil ($0.29 \pm 0.11$ in average of 11 data with standard deviation; Yokelson et al., 1997;
Muraleedharan et al., 2000b; Christian et al., 2003; Chand et al., 2005; Inuma 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\textsubscript{CO\textsubscript{2}} 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\textsubscript{CO\textsubscript{2}} of 0.382 in this study clearly reflected characteristic peat burning; it was highly incomplete and dominated by smoldering combustion.

The previously reported ER\textsubscript{CH\textsubscript{4}/CO\textsubscript{2}} 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\textsubscript{CH\textsubscript{4}/CO\textsubscript{2}} of 0.0261 in this study was similar to the averaged value for peat burning in a laboratory.

Previously reported data on ER\textsubscript{N\textsubscript{2}O/CO\textsubscript{2}} 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\textsubscript{N\textsubscript{2}O/CO\textsubscript{2}} 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\textsubscript{N\textsubscript{2}O/CO\textsubscript{2}} obtained for the whole range of observed CO\textsubscript{2} was 0.000156, which was similar to the results reported in previous studies.

However, it has revealed that N\textsubscript{2}O concentration is subject to increase in a grab-sampled container in which nitric oxide (NO) and sulfur dioxide (SO\textsubscript{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\textsubscript{2}O production in dry gas mixtures:

\[
2 \text{NO} + \text{SO}_2 = \text{N}_2\text{O} + \text{SO}_3
\]

Wang et al. (2003) formulated a series of potential chemical reactions that produced N\textsubscript{2}O from NO and SO\textsubscript{2}, and Preto et al. (2004) experimentally investigated this process and its time dependence. According to their results, detectable N\textsubscript{2}O increase in proportion to the initial concentration of NO and SO\textsubscript{2} as well as O\textsubscript{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\textsubscript{2} (Andreae, 1991). Cofer III et al. (1990b) observed N\textsubscript{2}O concentration in grab sample containers that had initial N\textsubscript{2}O concentrations (0.3–0.9 ppmv) similar to those in this study. According to their results, grab samples with high initial N\textsubscript{2}O (> 0.4 ppmv) showed considerable N\textsubscript{2}O increase during storage, whereas almost no increase was shown in low initial N\textsubscript{2}O samples (≤ 0.4 ppmv). Therefore, the inflection point in the CO\textsubscript{2}-N\textsubscript{2}O relationship (Fig. 1) may be attributed to the dependence of additional N\textsubscript{2}O generation on its initial concentration. For CO\textsubscript{2} and CH\textsubscript{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$_2$O = 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$_2$O 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$_2$O = 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$_2$O 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$_2$O and CO$_2$ showed an inflection point, suggesting the influence of additional N$_2$O 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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References


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Concentrations of CO, CH₄, and N₂O in each gas sample vs. that of CO₂ in the same sample obtained from ground-level measurement during a tropical peatland fire.

Results of linear regression analysis on each gas concentration pair to obtain the emission ratio of gas Y to gas X (ERₓᵧ).
Table 1

<table>
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<th>Gas X</th>
<th>Gas Y</th>
<th>n</th>
<th>Slope (ERY/X)</th>
<th>Intercept (ppmv)</th>
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<td>CO2</td>
<td>CO</td>
<td>23</td>
<td>$3.82 \times 10^{-1}$</td>
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<td>0.829 ***</td>
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<tr>
<td>CO2</td>
<td>CH4</td>
<td>24</td>
<td>$2.61 \times 10^{-2}$</td>
<td>-7.58</td>
<td>0.968 ***</td>
</tr>
<tr>
<td>CO2</td>
<td>N2O</td>
<td></td>
<td></td>
<td></td>
<td></td>
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Range of CO2

- **All**
  - 24
  - $1.56 \times 10^{-4}$
  - 0.259
  - 0.773 ***
- < 1500 ppmv
  - 20
  - $4.82 \times 10^{-5}$
  - 0.319
  - 0.191 †
- $1500 \text{ ppmv} <$
  - 4
  - $4.27 \times 10^{-4}$
  - -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.