Ground-based measurements of column-averaged carbon dioxide molar mixing ratios in a peatland fire-prone area of Central Kalimantan, Indonesia

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Tropical peatlands in Indonesia have been disturbed over decades and are a source of carbon dioxide (CO₂) into the atmosphere by peat respiration and peatland fire. With a portable solar spectrometer, we have performed measurements of column-averaged CO₂ dry-air molar mixing ratios, XCO₂, in Palangka Raya, Indonesia, and quantify the emission dynamics of the peatland with use of the data for weather, fire hotspot, ground water table, local airport operation visibility and weather radar images. Total emission of CO₂ from surface and underground peat fires as well as from peatland ecosystem is evaluated by day-to-day variability of XCO₂. We found that the peatland fire and the net ecosystem CO₂ exchange contributed with the same order of magnitude to the CO₂ emission during the non-El Niño Southern Oscillation year of July 2014-August 2015.

Tropical peatland is one of the ecosystems, which stores a large amount of terrestrial carbon over millennia. Indonesian peatlands store 57 Gt C, about 10% of the global peat carbon pool¹. Since the 1970’s, tropical peatlands have been disturbed by logging, anthropogenic land-use change including deforestation and drainage, leading to release of carbon and reduction of carbon storage²³⁴. Peatland fires and oxidative peat decomposition by peat respiration are two main processes that release carbon from peat soil to the atmosphere³⁴⁻¹⁰. Tropical peatland is characterized by waterlogged conditions and low rates of decomposition. Drainage construction lowering the ground water level (GWL) enhances aerobic peat oxidation, resulting in steady releases of CO₂⁶⁻⁷¹¹⁻¹³. The estimated amount of carbon emitted from peatlands in Indonesia is 0.1–0.5 Gt C/y, using measured annual flux data of carbon emission. In recent decades, frequency of forest fires across the tropics has been increasing¹⁴. Forest fires in Indonesia tend to occur annually in the dry season even in non-El Niño Southern Oscillation years primarily by anthropogenic activities for the development of agriculture and plantations¹⁵⁻¹⁸.

As for assessment of the current status of Indonesian peatland and quantification of its disturbance, the CO₂ emissions from fires is quantitatively estimated from satellite imagery data by a bottom-up method³⁹⁻¹⁰⁻¹⁹. This method is robust but has a difficulty in estimating the contribution of smoldering low-intensity underground peatland fires. An alternative top-down method monitors the increments of atmospheric CO₂ concentrations by satellite observation, e.g., Greenhouse gases Observing SATellite (GOSAT)²⁰.

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In this article, we report monitoring of column-averaged dry-air molar mixing ratios, $X_{CO_2}$, in an Indonesian fire-prone area over the dry and wet seasons in Palangka Raya, Central Kalimantan, using a portable solar photometer for field measurements. The location of our observation station is shown in Fig. 1. We used a Fiber-Etalon Sun-photometer for column Carbon dioxide (FES-C), which is attached with a fiber Fabry-Perot optical device. It probes larger sample volumes than in situ and smaller scales than sensors onboard satellites, and is suitable for measurement of CO2 emission from local peatlands.

We discuss variabilities of $X_{CO_2}$ with use of weather data and peatland-specific parameters including airport visibility records, hotspot counts, GWL data and weather radar images. The MODerate resolution Imaging Spectroradiometer (MODIS) hotspot data are used to estimate the contribution of surface and underground fires to $X_{CO_2}$, from which CO2 and particulate matter are produced. Peatland fires characterized by low intensity burning spread slowly into peat deposits below the surface for long periods of time, contributing to emissions.

**Results**

**Background levels of $X_{CO_2}$**. A time series of $X_{CO_2}$ data at Palangka Raya is shown in Fig. 2A along with environmental parameters. Increments in $X_{CO_2}$ above the background levels, $\Delta X_{CO_2}$, are due to peatland fires and the net ecosystem CO2 exchange. Data missing in $X_{CO_2}$ from mid-September to October 2014 was due to thick haze and dense smoke coverage that weakened the solar spectral intensity.

In estimation of the $X_{CO_2}$ background levels, we use the annual trend obtained by fitting the GOSAT data on sea between the Kalimantan and Java Islands between 21st July, 2009–30th May, 2015 as described Supplementary S1. The GOSAT annual trend is $2.00 \pm 0.10$ (1σ) ppm/y. Hereafter, the uncertainty represents one standard deviation. The mean background level of FES-C is 395.8 ppm between 1st December, 2014–6th January, 2015 and 19th May–2nd July, 2015 in non-fire wet seasons that are characterized by high GWL, low temperature and high visibility. At Bukit Kototabang, Sumatra, Indonesia, a meteorological station (0.165°S, 100.295°E) has been performing surface measurement of CO2 concentrations that irregularly varied with $\pm 5$ ppm due to peat fire and respiration, the mean value of which is 393.4 ppm for the non-fire season between July – November 2014. Combination of the FES-C non-fire wet season data with the annual trend coefficient of 2.00 ppm/y gives the best-fit background level in units of ppm:

$$\text{Background (n)} = (394.3 \pm 1.2) + (2.00 \pm 0.10) \times \frac{n}{365.25},$$  

where $n$ is day after 1st July, 2014.
Increments in \( \Delta \text{XCO}_2 \) by peat respiration. The \( \text{CO}_2 \) emission from peat respiration or aerobic peat oxidation has a strong correlation with lowering GWL\(^7\). As marked by the two blue double arrows in Fig. 2A between July–August 2014 and mid–March–mid–May 2015, \( \Delta \text{XCO}_2 \) increase while mean GWL and precipitation are reduced to −0.12 m and 0.22 mm/h, respectively. The mean temperature goes up by 0.2 °C. During these observation periods, visibility in Fig. 2C is high and no hotspots appear in Fig. 2B. GWL and rain precipitation at the other station, Taruna Jaya (2.23°S, 114.07°E), behaved similarly to those of Fig. 2E\(^{24}\). The increments in \( \Delta \text{XCO}_2 \) are due to peat respiration enhancement in peatland and not to fire enhancement.

Increments in \( \Delta \text{XCO}_2 \) by peatland fires. Figure 2 shows that the fire season in the beginning–to–middle of September 2014 is characterized by high \( \Delta \text{XCO}_2 \) large hotspot counts, low visibility, low GWL and low precipitation. \( \Delta \text{XCO}_2 \) increased up to 10.0 ppm (mean 6.0 ppm). The increments are caused mostly by peatland fires because the surface peat that is fresh and less decomposed is destroyed by fire and the peat respiration activities are reduced\(^7\).

Discussion

Increments in \( \Delta \text{XCO}_2 \) corrected for airmass transport. Our tethered balloon observation for vertical distribution of the \( \text{CO}_2 \) concentrations as described in Supplementary S2 suggests that \( \text{CO}_2 \) emitted from the ground into the atmosphere is homogeneously mixed at altitude up to ~700 m and is dispersed by prevailing south-easterly to southerly wind with an average wind reach distances of 160 km/day. (See Supplementary S3) Palangka Raya is located 136 km away from the southerly coastal area and surrounded by lowland peat swamp forest ecosystems\(^{25}\). Wind flow that travels over those surroundings reaches daily over Palangka Raya. Using the land-use map and the results of 24-hr backward trajectory calculations, we obtain fractional coverages, \( P_{\text{daily}} \), of the trajectories at 1500 m height travelling over the peatland and lowland from sea area as shown in Supplementary S3. If we assume that the whole peatland area in the southern vicinity of Palangka Raya is
homogeneously contaminated by emitted CO2, then, the daily emission from peatland may be obtained by
\[ F = \sum \left( \frac{\Delta XCO_2}{P_{daily}} \right) \sigma_{air}, \]
where \( F \) is the total carbon emission as described in Supplementary S3.

**Total carbon emission by net ecosystem exchange.** The total carbon emission is \( F \times m_c = 3,000 \pm 140 \ gC/m^2 \) for two non-fire periods of Fig. 2A in July 2014–May 2015, where \( m_c \) is the molecular weight of carbon (12 g/mol). The yearly net ecosystem CO2 exchange controlled chiefly by oxidative peat decomposition, NEE, is 1,500±70 gC/(m^2y) averaged for two non-fire seasons in 2014–2015. NEE is the difference between the ecosystem respiration and the gross primary production due to photosynthesis. Since this NEE excludes the contributions of emission from lowland and other sources during wind travelling, it should be an upper limit value.

When the contribution of CO2 emission from the lowland area is included, \( P_{daily} \) is defined as the ratio of peatland + lowland trajectory distance/whole trajectory distance: \( Sum = 475 \pm 29 \ ppm \) and \( F \times m_c = 1,990 \pm 120 gC/m^2 \), then, NEE is 1,000±60 gC/(m^2y) averaged for 2014–2015. Hirano et al.7 measured NEE per year using the eddy covariance technique on the two locations at both a drained swamp forest (2.35°S, 114.14°E) and a drained burnt swamp forest (2.34°S, 114.04°E) in the former Mega Rice Project area of Palangka Raya. Two stations are located within our observation area. Their NEE values show a clear seasonal variation as a function of GWL and range from 105 to 532 (1 standard distribution) and from 427 to 571 gC/(m^2y) over the year of 2004–2008, respectively.

There is a large discrepancy between our estimated NEE and Hirano's reported values. This is partly due to difference in hydrological environments. The average temperature during our observation period in Fig. 2D is higher by ~1.5°C than during Hirano’s period. According to Luo and Zhou24, there are some factors controlling the soil respiration, e.g., temperature, soil moisture and soil oxygen. In wetlands, oxygen is usually the limiting substrate for respiration, soil drying due to increased temperature could stimulate soil respiration. The discrepancy would also be due to the fact that our measurement is only for one particular observation area during a particular term.

**Correlation between fire-origin XCO2 and airport operation visibility records to evaluate missing data due to thick haze that weaken the solar spectral intensity.** During the dry season, the area is covered by haze when peatland fires occur, reducing airport visibility. Kusumaningtyas et al.27 attributed high values of scattering albedo or low visibility to surface and smoldering combustion in the peatland. Using the fire-origin \( \Delta XCO_2 \) for 35 days of FES-C measurement, a linear relationship between \( \Delta XCO_2 \) and visibility is empirically obtained with a correlation coefficient \( R = -0.79 \) in Fig. 3:

\[ \Delta XCO_2 = (9.6 \pm 0.8) - (1.20 \pm 0.16) \times \Delta \text{vis} \]

where \( \Delta \text{vis} \) is the average visibility in units of km at UTC = 20–0 h as described in Supplementary S4. Several XCO2 data in September–November are not available because of weak solar intensity due to thick haze conditions, which can be estimated by Eq. (3). Thus obtained XCO2 are plotted by the yellow diamonds in Fig. 2A. Using both the measured and calculated values, we estimated the mean \( <\Delta XCO_2> \) to be 7.8 ppm during the fire season from 3rd September, 2014 to 11th November, 2014, total 70 days.

**Haze area size of air contaminated with emitted species.** We use the data of Fig. 2 in evaluating peatland dynamics caused by fire in combination with the data from satellite observation. Comparing Fig. 2B,C, one notices that visibility is low about two more weeks after surface fire ceases. Aerosol optical depth (AOD)
images from the Terra-MODIS AOD data base\textsuperscript{28} show dense aerosol plumes over Palangka Raya with a size of 30–100 km, an example of which is shown in Supplementary S5. To estimate quantitatively the sizes of hazy areas over Palangka Raya, we inspect our radar images measured with a C-band Doppler weather radar at the station during the fire period between 15\textsuperscript{th} September – 11\textsuperscript{th} October, 2014. During the period, precipitation is below 10 mm/month and the AODs reported by the AERONET are over three\textsuperscript{29}, suggesting that the radar images are due to fire-origin aerosols. A typical haze area image over Palangka Raya is shown in Fig. 4(left). The average radius of 48 images is 44 ± 14 km with height below 1.6 km. We assume that the air is homogeneously mixed and flows from the fire clusters all around the vicinity of Palangka Raya in Fig. 1. According to the NASA multi-angle imaging spectroradiometer analysis of fire plumes in the Borneo Island by Zender et al., fire plumes travel with the mean length of 41.4 ± 26.7 km and the average plume width-to-length ratios of 0.268 ± 0.147\textsuperscript{30}.

Estimation of active duration of underground fires from correlation between hotspot count and increment in $\Delta XCO_2$. Burning of peat soil occurs under smoldering condition characterized by low heat and long duration that can last up to four months\textsuperscript{3,9,31,32}. Hence, it is essential to estimate an active duration of the underground fire. For quantitative analysis, the hotspot data between September – November 2014 are chosen. Supplementary S6 shows that the hotspot count density over peatland is evenly distributed where hotspot counts 506–4186 are selected to analyze with high confidence. Since prevailing southerly wind travels with an average reach distance of 160 km/day during the fire season, daily $\Delta XCO_2$ is corrected by the daily trajectory fraction $P_{\text{daily}}$ over peatland. Below we evaluate correlation coefficients, $R$, between $\Delta XCO_2/P_{\text{daily}}$ and hotspot count accumulated for active durations of underground fires as described in Supplementary S6. In this data analysis, the contribution of a hotspot to $\Delta XCO_2/P_{\text{daily}}$ is distance-normalized by $1/r^2$ where $r$ is the distance between the hotspot and the observation station. To simplify the analysis, we assume the following conditions: 1) surface fire with high temperature is detected by the MODIS satellite sensor and lasts for one day as a hotspot, 2) underground fire lasts longer but undetectable by the MODIS sensor as described in Method, and 3) hotspots emit the same amount of CO\textsubscript{2} until emission ceases.

The results of correlation analysis are shown in Fig. 4(right), in which $R$ depend on the active underground fire duration of 1–30 days (including one day of surface fire) but does not on the observing fire field ranges of $r = 30–100$ km radii. The correlation coefficients are independent of $r$ because hotspots distribute evenly over the peatland area. We found $R \sim 0.5$ with an active fire duration centered ~17 days (including one day of surface fire) for all $r$. Within the range of one-standard deviations shown in Fig. 4, the active fire duration is estimated to be in a range of 10–25 days centered around 17 days.

The fire image sensor on board the TET-1 satellite has detection capabilities in monitoring low-intensity peatland fire fronts through smoke. Fire front edges observed in the TET-1 images may be indicative that the fire is slowly spreading through the deeper peat layer for two weeks in the peatland of Central Kalimantan\textsuperscript{33}.

Total emission of $CO_2$ per MODIS hotspot. During the fire season, \textit{Sum}(\$\Delta XCO_2/P_{\text{daily}}$) is 886 ± 33 ppm. In this calculation, we include $\Delta XCO_2$ values estimated from Eq. (3) for the thick haze period. The uncertainty includes uncertainties of instrumental and estimation of $\Delta XCO_2$ in Eq. (3) as well as that of $P_{\text{daily}}$. We obtain the conversion factor $CF$ for emission per hotspot by;

$$CF = \text{Sum}(\Delta XCO_2/P_{\text{daily}}) \cdot \sigma_{\text{em}} \cdot S(r)/N(r).$$
where \( S(r) = \pi r^2 \) is the observing fire area, and \( N(r) \) is the total hotspot count during the fire season. According to the haze images, we estimate the active observation area for XCO\(_2\) to be \( r = 44 \pm 14 \) km. In the range of 30–60 km, the hotspot density, \( N(r)/S(r) \), is almost constant \( 0.16 \pm 0.02 \) count/km\(^2\), due to homogeneous distribution of the hotspots over the peatland. Thus calculated conversion factor during the fire season of 2014 in Palangka Raya is \( CF = (8.5 \pm 1.4) \times 10^7 \) kgCO\(_2\)/hotspot.

Summary and Conclusion
We have demonstrated the approach of using solar absorption spectra recorded with a small Fabry-Perot solar photometer at a site in a source region for an estimation of the CO\(_2\) source strength of the surrounding fires. This methodology is applied to observation of the variability of the column averaged dry-air molar mixing ratios of CO\(_2\) in Palangka Raya, Central Kalimantan, Indonesia in July 2014–August 2015, an non-ENSO year. Our methodology is not a general one but a specific one to peatland field measurements. Assuming the conditions described in the text, the CO\(_2\) data are analyzed in combination with the peatland-specific parameters such as hotspot counts, water levels, airport visibility records and radar images as well as weather data. We found that the increments are due to the underground smouldering fires in the fire season and the aerobic peat oxidation in the beginning of the dry season. Both sources contribute with the same order of magnitude to the enhancement in the atmospheric CO\(_2\) concentration.

Methods
Location of the observation station and its surroundings. Monitoring of XCO\(_2\) was performed at the Tjilik Riwut Palangka Raya BMKG Station, Palangka Raya, Central Kalimantan, Indonesia (2.224°S, 113.946°E, 10 m a.s.l.) from June 2014 to August 2015 with a portable Fiber-Etalon Sun-photometer for CO\(_2\), instrumental details of which are described in Supplementary S7. Visibility records and weather data were provided by the BMKG station. The station for measurement of precipitation and ground water level is located at 2.31°S and 114.06°E as shown in Fig. 1st. The C-band Doppler weather radar (Gematronik/Selex SI, Meteor 600 C, single / linear horizontal polarization) was located at the Palangka Raya BMKG station.

Satellite product 1: hotspot counts. We use daily active fire detection data derived from the MODIS observation as a peatland fire index, extracting the data collection 6 from the Fire Information for Resources Management System\(^{42}\). The MODIS active fire product includes the hotspot counts with high-confidence detection in a range larger than 60%. In MODIS active fire algorithm, temperature thresholds of detection potential fire pixel is 300–314 K\(^{44}\). Although the temperature of underground fire reaches above them, the spatial resolution and thick haze hamper the ability of the MODIS sensor to detect some of active smouldering fires.

Satellite product 2: carbon dioxide mixing ratios of GOSAT. The GOSAT satellite data set is a product of measurements on the Java Sea between the Kalimantan and Java Islands as shown in Fig. 1(left). GOSAT data (V02.40) from 15th June, 2009 to 23rd April, 2014, (V02.31) from 25th June, 2014 to 29th October, 2014, (V02.40) from 6th May, 2015 to 29th July, 2015.

Data Availability. Datasets during the current study are available in http://www.tonokura-lab.k.u-tokyo.ac.jp/pub/SR.html.

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Author Contributions

W.I., K.T., G.I. and M.K. designed the experiment. W.I., K.T., M.K. and M.O. wrote paper. K.F. and M.O. performed instrument data analyses. O.K., M.A.R. and D.G. performed instrument maintenance and provided meteorological data. Y.S. and R.I. evaluated the data quality. I.M. provided the TCCON data at Tsukuba.

Additional Information

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