CO2 emissions from the 2010 Russian wildfires using GOSAT data

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In the summer of 2010, more than 6 hundred wildfires broke out in western Russia because of an unprecedented intense heat wave that resulted from strong atmospheric blocking. The present study evaluated the CO2 emissions using GOSAT (Greenhouse gases Observing SATellite) data from July 23 to August 18, 2010 for western Russia. The results demonstrated that the GOSAT CAI (Cloud and Aerosol Imager) was well-suited for the identification of smoke plumes and that the GOSAT FTS (Fourier-Transform Spectrometer) TIR (Thermal InfraRed) could be used to calculate the height of the plumes at approximately 800 hPa (1.58 km). Using GOSAT data, we estimated that the 2010 fires in western Russia emitted 255.76 Tg CO2. We also calculated the CO2 emissions by employing the Biomass Burning Model (BBM) for the same study site and obtained a similar result of 261.82–302.48 Tg CO2. The present study proposes a new method for the evaluation of CO2 emissions from a wildfire using remote sensing data, which could be used to improve the knowledge of the burning of biomass at a regional or a continental scale, to reduce the uncertainties in modeling greenhouse gases emissions, and to further understand how wildfires impact the atmospheric carbon cycle and global warming.

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1. Introduction

Wildfire emissions are among the most important factors that affect the global atmospheric composition, climate and local environmental pollution (Crutzen and Andreae, 1990). The burning of biomass is a major source of atmospheric particulates and some types of greenhouse gases in the global troposphere (Garbaras et al., 2015), and it has a strong effect on the atmospheric environment on a regional scale near the source. Forest fires destroy plants and release CO2, CO and other trace gases to the atmosphere while burning, thus playing a key role in global warming and the carbon cycle (Goto and Suzuki, 2013; Levine, 1999; Witte et al., 2011).

The effect of wildfires on the accumulation of CO2 is obvious because the smoke plumes released from the burning biomass contain large amounts of CO2 (Mei et al., 2012). Wildfires have been considered an important reason of the interannual variability of CO2, but an accurate assessment of global CO2 emissions from wildfires is necessary to confirm this hypothesis (Simmonds et al., 2005). At present, the amount of CO2 released from the burning of biomass, especially from forest fires, is still uncertain because CO2 emissions depend not only on the fuel type and combustion phase but also on the season, the wind speed and other factors. These uncertainties make it a challenge to accurately quantify the CO2 released from forest fires. An accurate estimate of CO2 emissions is critical to identify CO2 emission reduction targets and understand climate/carbon cycle feedbacks (Goto and Suzuki, 2013; Lu et al., 2006; Narayan et al., 2007).

Studies of CO2 emissions from wildfires started in the late 1970s. Many researchers argued that the CO2 released from wildfires alters the atmospheric constituents and indirectly affects climate change (Adams et al., 1977; Crutzen et al., 1979; Wong, 1978). Seiler and Crutzen (1980) proposed the Biomass Burning Model (BBM) to calculate GHG emissions from forest fires for the first time. The above-ground fuel load, combustion efficiency and emission factors
are the major parameters in the BBM. All of these parameters change with species and vegetation type, which makes it difficult to accurately estimate CO2 emissions (Rosa et al., 2011). Many workers improved the model and obtained satisfactory results at different study sites (Amiro et al., 2010; Dixon and Krankina, 1993; Goto and Suzuki, 2013; Robinson, 1989). However, the accuracy depends on the location because of variations in emission factors, the fuel load and combustion factors. Cofer et al. (1998) used a helicopter to collect smoke samples during a crown fire in Canada to analyze CO2 and four other trace gases. They calculated the CO2-normalized mean emission ratios and emission factors. Their results have implications for further studies, but they did not estimate the amount of CO2 emissions. Pereira et al. (2009) employed a linear regression model between fire radiative power (FRP), the amount of biomass burned and the smoke aerosol emission factor during a wildfire event to assess the total amount of aerosol and trace gas emissions. However, the FRP satellite products required validation, which was not performed, and the study encountered several technical problems. Rosa et al. (2011) argued that they could use an empirical model to obtain CO2 emissions from burned areas because of the strong relationship between them. However, the empirical model must be known, and it may vary in different regions. Simpson et al. (2011) used the CO2 from NASA Langley Atmospheric Vertical Observations studies and concluded that CO2 emissions from global boreal forest fires were 588 ± 66 Tg yr⁻¹.

Optical remote sensing data have been widely used for many years to monitor fire scars and interannual vegetation recovery and have provided a large amount of useful information (Labonne et al., 2007; Witte et al., 2011). Space-based sensors that were specially designed for GHG concentration provide measurements at remote places or for vigorous burns or heavy smoke plumes and have great potential to improve the precision of CO2 emission estimates from forest fires. Currently, the Thermal And Near-infrared Sensor for carbon Observation (TANSO) onboard the Greenhouse gases Observing SATellite (GOSAT) provides accurate measurements of GHG concentrations from space with the potential to meet this requirement (Oguma et al., 2011; Reuter et al., 2010). Ross et al. (2013) reported CH4 to CO2 emission ratios from 3 types of wildfire plume samples using GOSAT data and obtained satisfactory results. However, they did not determine CO2 emissions from forest fires. Despite recent advances in quantifying the global distribution of CO2 emissions from space, challenges remain for quantifying CO2 emissions from wildfires because of the difficulties in identifying CO2 enhancement in smoke plumes. The difficulties usually come from the satellite data, such as coarse resolution or the inability to simultaneously obtain CO2 concentrations from wildfires and from clear skies.

The present study selected wildfires that occurred in Russia during 2010 as a case study to evaluate CO2 emissions using GOSAT data. As far as we know, this report describes for the first time that calculating CO2 emissions from wildfire using satellite data alone. In this paper, we (1) retrieve ΔXCO2 from wildfires smoke plumes by comparison with the clear sky values, (2) identified smoke plume areas using GOSAT Cloud and Aerosol Imager (CAI) images, (3) determined smoke plume heights from GOSAT Fourier-Transform Spectrometer (FTS) Thermal InfraRed (TIR) data, (4) quantified the CO2 emissions, and (5) verified our results with the BBM and emission ratio methods.

2. Materials and methods

2.1. Study region and time scale

It is estimated that Russia contains approximately 6.2 × 10⁸ ha of boreal forest, which is 66.7% of the global total area, and approximately 83.9% of that area is stocked boreal forest (Conard and A. Ivanova, 1997). Because of the wide distribution and the large carbon reserves, Russia’s boreal forests play a key role in the global carbon cycle. Wildfires have been considered as a major disturbance in Russian forests because approximately 95% of Russian forests are boreal forests, and 71% of them are dominated by coniferous forests with a high fire risk. In the summer of 2010, intense wildfires occurred in western Russia near Moscow due to high temperatures and the absence of precipitation (Chubarova et al., 2012; Witte et al., 2011).

The 2010 Russian wildfires, which developed dramatically in late July, could be clearly identified using satellite data. Based on the identification of forest fire smoke plumes using GOSAT CAI and other researchers’ study regions, we restricted our study region to 45°–63° N and 32°–70° E. Further, we focused only on the time that serious fires occurred, from July 22 to August 18, 2010, which was the same as Witte et al. (2011), although Krol et al. (2013) argued that the most intense burning period was from July 16 to August 17.

2.2. GOSAT data

GOSAT was launched on January 23, 2009, from Tanegashima Island, Japan, carrying two main instruments: the Thermal And Near-infrared Sensor for carbon Observation (TANSO) Fourier Transform Spectrometer (FTS) and Cloud and Aerosol Imager (CAI). TANSO-FTS has four bands: three of SWIR (approximately 0.76, 1.6, and 2.0 μm) that are used to estimate the columnar concentrations of CO2 and one TIR band (5.5–14.3 μm), which is used to describe the vertical profile of CO2 concentration in the upper troposphere. TANSO-CAI imagery has four bands (0.380, 0.675, 0.870, and 1.600 μm) with a spatial resolution of 500-m and has been mainly used to map the characteristics of clouds and aerosols from space (Guerelet et al., 2013; Ross et al., 2013).

The main purpose of the GOSAT project is to accurately assess the emission and absorption of GHGs on a regional and global scale. Therefore, it contributes to the assessment of carbon cycle of an ecosystem by environmental administrations and researchers. GOSAT is the world’s first satellite that was designed to estimate CO2 and CH4 concentrations (XCO2 and XCH4, in ppm, XCO2 and XCH4 indicate the mole fraction of CO2 and CH4 in the dry air) from SWIR bands, with a return cycle of three days (Guo et al., 2012; Oguma et al., 2011).

In the present study, TANSO-FTS SWIR L2 data were used to obtain XCO2 changes (ΔXCO2) due to forest fire emissions. CAI L1B + images were used to identify smoke plumes, and TANSO-FTS TIR L2 data were used to calculate the height of the smoke plumes.

2.3. Methods and data processing

As noted above, the GOSAT XCO2 data have units of concentration in ppm, and it was necessary to convert these numbers to density values (mg m⁻³) using

\[
mg \text{ m}^{-3} = M/22.4 \times \text{ppm} \times (273/(273+T)) \times (Ba/1013.25),
\]

where M is the molecular weight of CO2, and ppm is the concentration of CO2, T is the temperature (°C), and Ba is the atmospheric pressure (hPa).

Next, we calculated the height of a smoke plume (H) using the isotherm pressure equation proposed by Wu (1990):

\[ H = \frac{273}{T_1} - \frac{273}{T_2} - \frac{273}{T_3}, \]

where \( T_1, T_2, \) and \( T_3 \) are the temperatures at the ground, middle, and top of the smoke plume, respectively.
\[ H = (R \cdot T / g \cdot M) \cdot \ln(P_0 / P) - h. \]  

(2)

where \( R \) is the universal gas constant (8.31 J mol\(^{-1}\) K\(^{-1}\)), \( T \) is the thermodynamic temperature (K), \( g \) is the gravitational acceleration (9.8 m s\(^{-2}\)), \( P_0 \) is the standard atmospheric pressure (1013.25 hPa), \( P \) is the desired atmospheric pressure (hPa), and \( h \) (km) is the height of land surface.

The CO\(_2\) emissions (\( E_{\text{CO}_2} \)) for a smoke plume were calculated by:

\[ E_{\text{CO}_2} = \rho \cdot V = mg \cdot m^{-3} \cdot S \cdot H, \]  

(3)

where \( S \) is the area of a wildfire smoke plume.

2.4. Biomass Burning Model

The BBM (Andreae and Merlet, 2001; Cinnirella and Pirrone, 2006; Goto and Suzuki, 2013; Levine, 1999; Rosa et al., 2011; Seiler and Crutzen, 1980) is the most commonly used method to evaluate trace gas emissions, and it was used to validate the CO\(_2\) emissions from Russia’s summer forest fires in 2010 using GOSAT data. The BBM can be described as

\[ E_s = A \cdot B \cdot \beta \cdot \text{EF}, \]  

(4)

where \( E_s \) represents the CO\(_2\) emissions, \( A \) indicates the burned area (ha), \( B \) is biomass fuel load (Mg ha\(^{-1}\)), \( \beta \) is the combustion factor (%), and \( \text{EF} \) is the CO\(_2\) emission factor (g kg\(^{-1}\)).

In this study, we did not consider CO\(_2\) released from soil because this is a very slow process. The biomass fuel load and combustion factors are crucial and difficult to estimate accurately. Biomass fuel load estimates are complex because of the high spatial heterogeneity of different vegetation covers. The combustion factor, which indicates the ratio of the burnt biomass during a fire, is also difficult to estimate because of different vegetation characteristics (i.e., plant age, growth cycle and water content) and also because of the behavior of fire (Rosa et al., 2011).

2.5. Emission ratio (ER)

Trace gas release from the burning of biomass could be explained by the emission ratio. ERs are calculated from the excess concentration of a reference gas, usually CO (\( \Delta \text{XCO} \)) or CO\(_2\) (\( \Delta \text{XCO}_2 \)), divided by the excess concentration of a specific trace gas (\( \Delta X \)) in a smoke plume. To obtain \( \Delta X \), the trace gas concentration in a fire plume must minus the background values (Andreae and Merlet, 2001; Iii et al., 1989; Simpson et al., 2011).

Forest fires release CO\(_2\), CO, CH\(_4\) and other trace gases, and all the gases released have relatively consistent emission ratios for a special forest type. Cofer et al. (1998) and Simpson et al. (2011) obtained similar emission ratios of CO (using CO\(_2\) as reference gas) by analyzing smoke plume samples in Canada. In the present study, we use CO as reference gas and CO\(_2\) as the target gas to measure CO\(_2\) emissions from boreal forest fire (equation (5)).

\[ ER_{\text{XCO}_2/\text{XCO}} = \frac{\Delta \text{XCO}_2}{\Delta \text{XCO}} = \frac{P_{\text{XCO}_2} - B_{\text{XCO}_2}}{P_{\text{XCO}} - B_{\text{XCO}}}. \]  

(5)

\( P_{\text{XCO}_2} \) and \( B_{\text{XCO}_2} \) indicate the CO\(_2\) concentration of smoke plumes and background, respectively.

2.6. Data processing

GOSAT CAI L1B + data were used to identify the smoke plumes that were released from Russian forest fires in 2010. First, we downloaded all the CAI data that covered the study area from July 23 to August 18, 2010. In total, 159 scenes of HDF (Hierarchical Data Format) images were downloaded from the GOSAT homepage (https://data.gosat.nies.go.jp). The next step was to artificially identify whether the CAI images contained wildfire smoke. To do this, the CAI band 1 (0.380 \( \mu m \)) and true color composition of RGB = 431 were selected. Fig. 1 shows the example of how to identify smoke plumes on August 8, 2010. From Fig. 1 (a and b), we can see that smoke plumes could be identified easily. The radiance value of the clouds is quite high and that of the clear sky is very low, while the smoke plumes are in the middle. We defined a threshold for band 1 to obtain the approximate smoke plume areas (Fig. 1c). Next, based on a visual inspection, a Region of Interest (ROI) was built to restrict the smoke plumes to obtain the final forest fire smoke plumes (Fig. 1d). Using the same method, we identified smoke plumes for each forest fire day. Elevated radiance values of the CAI band 1 indicated a higher concentration of smoke plumes and more CO\(_2\) emissions. Finally, because of the 3-day revisit interval, we had to examine a mosaic 3 days of smoke plumes to obtain the plume areas of the entire region. Since we knew that the satellite images had overlapping areas with the neighboring orbits, and the study area, we eliminated that overlap.

A three day revisit interval combined with three exposures at each location with a footprint of 86.6 km\(^2\) resulted in the observation of approximately 0.2% of the Earth’s surface in each revisit period by TANSO-FTS. It was challenging to find FTS SWIR L1B observations containing wildfire smoke plumes. To accomplish this, we downloaded all the FTS SWIR L1B point data in the study region and then overlaid them with the forest fire smoke plumes obtained in the previous step. Referring to the intermediate results of Ross et al. (2013), we found the FTS L1B points that contained wildfire smoke plumes as shown in Table 1. \( S_{\text{XCO}_2} \) is the \( X_{\text{CO}_2} \) values that were exposed to smoke plumes, and \( B_{\text{XCO}_2} \) is the background values. The background points must be on the same day and not far from the points exposed to smoke plumes, and sometimes, \( B_{\text{XCO}_2} \) is the mean value of more than one point. We assumed that an increase in the CO\(_2\) concentration was the result of wildfire emissions alone. In total, 25 FTS L1B point data were observed during the study duration. Based on artificial identification, we classified the smoke plumes as light smoke, smoke and thick smoke, and we found that thick smoke usually corresponded to higher \( \Delta X_{\text{CO}_2} \) values.

3. Results

3.1. Identification of forest fire smoke plume areas

Fig. 2 shows the 3-day summed smoke plume distribution and areas. The smoke plume areas increased from July 23 to August 9 because of the dramatic growth of the fire points and the burned areas, and then as the wildfires came under control, the smoke plume areas decreased. In total, the smoke plume areas reached 1780.67 million ha for the study region in 2010.

3.2. \( \Delta X_{\text{CO}_2} \) retrieval and simulation

Table 1 shows the different smoke classifications that corresponded to different \( \Delta X_{\text{CO}_2} \) values. We used a linear regression model to calculate the \( X_{\text{CO}_2} \) value of the smoke plumes that were not covered by the FTS L1B points. A scatter plot of \( \Delta X_{\text{CO}_2} \) against the CAI band 1 radiance values is shown in Fig. 3. This graph illustrates that higher radiance values usually corresponded to higher CO\(_2\) emissions (\( R^2 = 0.44, P < 0.001 \)). We could calculate the CO\(_2\) emissions from wildfires for each smoke plume pixel with this regression equation.
3.3. Height of wildfire smoke plumes from the GOSAT TIR data

The GOSAT-FTS TIR L2 data provided CO2 profiles at 28 levels of atmospheric pressure. We selected 10 GOSAT TIR L2 data points from July 29 to August 18 that covered the smoke plumes and 10 data points in clear sky conditions, and then we analyzed the CO2 concentration changes against atmospheric pressure (Fig. 4). Compared with the profile of CO2 concentrations when the skies were clear, we found that the elevation of 800 hPa was the break point when the FTS TIR points were exposed to smoke plumes. We assumed that the increase in the CO2 concentration from ground level to 800 hPa was the result of forest fire emissions and that the smoke was distributed evenly up to this height. Based on equation (2), we obtained the height of a smoke plume as 1.58 km. Fig. 4a also indicates that on August 13 and 16, the break point of CO2 concentration appeared at approximately 700 hPa, and in Fig. 4b, the effect on August 09 was quite different from that of other days at 800 hPa. On the one hand, because of the limited CO2 points in the clear sky on August 09, we had to choose only one point near the smoke plumes, and the discrepancy may be affected by the smoke plumes. On the other hand, this discrepancy occurred possibly because of the different smoke concentrations or the bias of the smoke plume identification process.

3.4. Quantifying the CO2 released from wildfires

We put the previously determined smoke plume areas and height into equation (3) to calculate the weight of the CO2 emissions for each smoke plume pixel and later summed the values to obtain the amount of CO2 released in 3 days (Fig. 5). In total, 255.76 Tg CO2 were released from Russian forest fires in 2010. On August 04–06, wildfires in Russia emitted the highest amount of CO2 at 54.51 Tg. At the beginning of the study time, on July 23–25, wildfires released only 0.44 Tg CO2, and the CO2 emissions subsequently increased with the increase of fire points and burned areas. After August 6, the CO2 released decreased to 14.72 Tg by August 16–18. Although the wildfires in Russia in 2010 started at the end of July and lasted to the start of September, we considered only the
active period in the present study.

4. Discussion

4.1. Height of forest fire smoke plumes in other studies

The wildfire smoke injected height has a strong influence on the smoke transport distance and is also an important parameter in CO₂ emission models. In the present study, the wildfire smoke plume heights were determined to be a key factor for calculating the CO₂ emissions from the forest fires.

Many researchers have used different methods to identify the height of forest fire smoke plumes and found various results. Yurganov et al. (2011) estimated the polluted layer height in Moscow after the forest fire of 2010. They compared the CO volume mixing ratios from a TV tower with the ground surface value and obtained a height of approximately 360 m. Ross (2012) and Mielenz et al. (2012) used the MISR (Multi-angle Imaging Spectroradiometer) instrument on the Earth Observing System’s (EOS) Terra satellite and CALIOP (Cloud–Aerosol Lidar with Orthogonal Polarization) data, respectively, to calculate the height of smoke plumes in the Russian wildfires of 2010 and obtained similar results. Ross (2012) found a smoke plume simultaneously observed by GOSAT CAI and MISR on August 7, 2010, and after calculation, the author determined that most of the smoke plumes extended higher than 1.5 km. Mielenz et al. (2012) found a clear CALIOP image of a smoke plume by using the changes in the CO₂ concentration with atmospheric pressure. Using TIR L2 data, we found that the height of a smoke plume was approximately 800 hPa (1.58 km), which was quite similar to the results from most other studies.

4.2. CO₂ emissions using BBM

Using the GOSAT SWIR L2 data, we calculated that 255.76 Tg of CO₂ were released from wildfires in Russia in the summer of 2010. This result was compared to the BBM results, the most commonly used method of studying the burning of biomass. For BBM, we must know the fuel load (C), emission factors (EF), combustion factor (β) and the burned area (A) of the study region. The accuracy of these parameters directly determines the CO₂ emission results. Estimating all of these parameters is complex because of their high spatial heterogeneity and the dynamic character of vegetation and fire behavior.

Akagi et al. (2010) summarized the results of former studies from controlled laboratory experiments and field-based measurements of EF for the soil, peat and litter layers and then converted the EF to a standard form based on the method of carbon balance for 14 vegetation types. They determined that the EF of CO₂ for a boreal forest is 1485 ± 107 g kg⁻¹, which means that 1485 ± 107 g CO₂ is emitted from the burning 1 kg of dry biomass. Akagi et al. (2010) also measured the biomass consumption per unit area, i.e., the estimated biomass fuel load (B) multiplied by the combustion factor (β) for many types of open burning, and the value for a boreal forest was 38 Mg ha⁻¹ (in the present study, we considered only the study region of Siberia).

Using remote sensing data such as the Moderate Resolution Imaging Spectroradiometer (MODIS), GOSAT CAI, Landsat TM or other sensors, it is not difficult to identify fire scarred areas. However, it was challenging to map hundreds to thousands of burned areas (Konovalov et al., 2011; Matsueda, 2011) in western Russia from the wildfires in 2010. Based on the satellite data received by the Forest Institute and Academy of Sciences in Russia, the Global Fire Monitoring Center reported that by early August 2010, the

### Table 1

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<th>ID</th>
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<th>Lat</th>
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Fig. 2. 3-day smoke plume areas in the study region. The preceding 9 figures show the distribution of 3-day smoke plumes and the last figure shows the smoke plume area in million ha (23–25 of X-axis means July 23–25 and 01–03 means August 01–03). Here, the 3-day description means the sum of 3 days but without overlapping regions.
burned area in western Russia had reached about five million ha. The Global Fire Emissions Database (GFED 4.1) provides global burned areas at 0.25° resolution from 1995 to 2015 on a monthly scale. GFED 4.1 was produced by combining the MODIS burned area map and active fire data from other satellite sensors. It provides monthly burned areas by the fraction of each 0.25° pixel (Giglio et al., 2013). Using the GFED 4.1, we calculated the burned area in the study region and obtained results of 8.48 and 8.39 million ha for July and August, respectively, which were much higher than 5 million ha. In the present study, we assumed a burned area of five million ha because it was confirmed by two Russian Institutes (EMERCOM and the Irkutsk Institute of Solar and Terrestrial Physics) for the same time (GFMC State DUMA Report on the Fires in Western Russia, 2010).

Using the BBM discussed in section 2.4, we obtained CO2 emissions of 261.82–302.48 Tg, which were slightly higher than those calculated from the GOSAT data but were within the tolerance range. Differences in the burned areas, the time scale and the study regions may be the reasons for the different results. In any case, this was an excellent result for us, which means that it was achieved by using remote sensing data to estimate the CO2 emissions without considering the wildfire process and parameters.

4.3. GOSAT observation results vs. other studies

As far as we know, no one has evaluated the amount of CO2 emissions from a forest fire for a particular fire event. However, studies of CO emissions from the Russian forest fires of 2010 exist, and the results are quite different. Three satellite data sets (MOPITT V4, AIRS L3 V5 and IASI products) and two ground-based spectrometers (one in Moscow and the other 53 km away in western Moscow) were used during the wildfires to evaluate the total column of CO in and around Moscow, and the authors estimated that the total CO released from Russian wildfires was 34–40 Tg during July and August 2010 (Yurganov et al., 2011). Konovalov et al. (2011) used chemistry transport models and modified them for the primary pollutants from wildfire emissions. They estimated that the 2010 western Russia forest fires emitted ~9.7 Tg CO, and approximately 30% of this amount was identified as emissions from peat fires. Using the Infrared Atmospheric Sounding Interferometer (IASI), an excellent sensor for monitoring trace gas emissions from forest fires, R’Honi et al. (2013) estimated that the total CO emitted from July and August 2010 in the west of Russia was between 19 and 33 Tg.

Emission ratios have been calculated by many researchers and similar results have been obtained for the same forest type. Lii et al. (1989) determined the CO2-normalized emission ratios for many types of trace gases under different combustion conditions in boreal forest fires in northern Ontario, Canada. They found that the emission ratio of CO (ΔXCO2/ΔXCO2) was 0.069 ± 0.004. Simpson et al. (2011) analyzed smoke plume samples from Canadian boreal forest fires and found that the ER of CO was 0.11 ± 0.07. Cofer et al. (1998) obtained an average value of 0.190 ± 0.017. Because the forest types in Canada and Russia are similar, we used Simpson’s CO emission ratio to calculate the CO2 emissions from the Russian forest fires of 2010, not only because the value of 0.11 ± 0.07 was in the middle of the results from the 3 studies but also because that study collected the most air samples (947 samples). Finally, it was found that CO2 emissions were 485.71 ± 571.43 Tg (by Yurganov et al.), ~138.57 Tg (by Konovalov et al.) and 271.43–471.42 Tg (by R’Honi et al.). One could see that CO2 emissions determined from the GOSAT data (255.76 Tg) were closest to those calculated by using R’Honi’s CO emissions, although somewhat lower. The different results of various researchers might have been caused by different data sources or dissimilar study regions. Our study also indicated that GOSAT data could be used to evaluate CO2 emissions from wildfires and could yield satisfactory results.

The transitional methods of estimating trace gases from the burning of biomass generally used land or ground-based EF measurements. EFs are unstable and usually change according to the fuel load, water content, wind speed and other factors. However, EFs vary depending not only on the forest stand burning but also on factors such as the season, water content, and even the time from the last burning (Ross, 2012). Laboratory combustion chamber experiments were mostly used for the existing EFs calculations, but this method just produces the fire characteristics from natural behaviors or many ground-based measurements that do not represent a forest stand very well (Van Leeuwen and Van Der Werf, 2011). The previous analysis indicates that GOSAT has the potential to measure more strongly lofted emissions and those over a wide extent, high intensity and for different types of wildfires.

Fig. 3. Scatter plots of ΔXCO2 against CAI band 1 radiance values.
4.4. Limitations of GOSAT data for evaluating CO2 emissions

GOSAT data can be used to determine CO2 emissions more easily than BBM. As previously noted, GOSAT has two sensors — TANSO FTS and CAI. FTS SWIR could be used to monitor XCO2 changes before and after forest fires, and FTS TIR could retrieve the vertical profile of the CO2 concentrations in the upper troposphere. CAI is well suited to distinguish smoke plumes from clear sky or clouds. All these observations indicate that the GOSAT satellite could be conveniently used to evaluate CO2 emissions from forest fires without considering the burned area, fuel load, emission factors, the degree of combustion and the combustion factor. However, limitations also exist.

On the one hand, a forest fire must be large enough and release a huge amount of smoke plumes. TANSO-FTS is a relatively high spatial resolution sensor with a 10.5-km instantaneous field of view (FOV) diameter, but observes only approximately 0.2% of the Earth’s surface in a review period. It is challenging to obtain enough FTS points that were exposed to wildfire plumes. This means that if the smoke plumes were not large enough, it would be difficult to obtain accurate values of $\Delta X_{CO2}$, which could further affect the CO2 emissions results.

On the other hand, GOSAT CAI has a limitation for obtaining smoke plumes at the same time. The observation swath of CAI is 1000 km (750 km for band 4), which means that if the smoke plume area is large enough or crosses two or more CAI orbits, we could not identify them at the same time. To determine the smoke plume area, as in the present study, image mosaics were necessary. With the development of wildfires, the mosaicked smoke plume areas must have biases in representing the mean value of the 3 days of smoke plume areas. This may also lead to bias in the CO2 emissions result. Because of the similar overpass time of Aqua (13:30) and GOSAT (13:00), we could consider using MODIS Aqua images to identify smoke plume areas. However, the relationships between the smoke plume density and $\Delta X_{CO2}$ might have a bias when using MODIS Aqua instead of GOSAT CAI.

Finally, the identifications of smoke plume areas were based on artificial visual interpretations, and the accuracy of the results is dependent on the knowledge reserve and our understanding of smoke plumes.

5. Conclusions

In this study, we used GOSAT as a data source to evaluate CO2 emissions from forest fires in Russia in the summer of 2010 when historically severe forest fires occurred. Based on previous studies and GOSAT CAI monitoring of forest fire smoke plumes, we selected a time range for this study from July 23 to August 18 in the region of 45–63°N and 32–70°E. Following are the main conclusions drawn from the results:

(1) GOSAT CAI provided data well suited for distinguishing smoke plumes from clear or cloudy skies.

(2) GOSAT FTS L1B data could be used to calculate the $\Delta X_{CO2}$ by comparing the $X_{CO2}$ values that were exposed to smoke plumes from those that represented clear sky.

(3) GOSAT FTS TIR data, which provided the CO2 profiles, could be used to monitor the height of the smoke plumes. The smoke plume height was approximately 800 hPa, or 1.58 km above the ground level, in the Russian 2010 wildfires. These results were quite similar to those of other researchers

(4) The present study proposed a new way to calculate CO2 emissions from wildfires by using remote sensing data. With this method, we determined that the 2010 Russian wildfires

![Fig. 4. CO2 concentration changes against atmospheric pressure. FTS TIR points were covered by smoke plumes (a) and in clear sky (b).](image)

![Fig. 5. 3-day CO2 emissions from Russian forest fires in 2010. 23–25 means the sum of values on July 23, 24 and 25.](image)
emitted 255.76 Tg CO₂, and this result was verified by the BBM and indirectly by several the previous studies.

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References


