



Title	CO ₂ emissions from the 2010 Russian wildfires using GOSAT data
Author(s)	Guo, Meng; Li, Jing; Xu, Jiawei et al.
Citation	Environmental pollution, 226, 60-68 https://doi.org/10.1016/j.envpol.2017.04.014
Issue Date	2017-07
Doc URL	https://hdl.handle.net/2115/74838
Rights	© 2017, Elsevier. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/
Rights(URL)	https://creativecommons.org/licenses/by-nc-nd/4.0/
Type	journal article
File Information	Guo Meng.pdf



CO₂ emissions from the 2010 Russian wildfires using GOSAT data

Meng Guo^{a, *}, Jing Li^b, Jiawei Xu^a, Xiufeng Wang^c, Hongshi He^{a, d} and Li Wu^e

^a School of Geographical Sciences, Northeast Normal University, Changchun 130024, Jilin Province, China; guom521@nenu.edu.cn (M G); xujw643@nenu.edu.cn (J X)

^b Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Science, Changchun 130102, China; lijingsara@iga.ac.cn

^c Research Faculty of Agriculture, Hokkaido University, Sapporo 060-8589, Japan; wang@env.agr.hokudai.ac.jp

^d School of Natural Resources, University of Missouri-Columbia, Columbia 65211, USA; hehs100@nenu.edu.cn

^e Remote Sensing Technique Centre, Heilongjiang Academy of Agricultural Science, Harbin 150086, China; aromawu@163.com

* Correspondence: guom521@nenu.edu.cn; Tel.: +86-431-85099550

CO₂ emissions from the 2010 Russian wildfires using GOSAT data

Abstract: 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.

Keywords: Wildfire; CO₂ Emissions; GOSAT Data; Biomass Burning Model (BBM)

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 has 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 ΔX_{CO2} 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 CO_2 and one TIR band (5.5 ~ 14.3 μm), which is used to describe the vertical profile of CO_2 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 (Guerlet 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 CO_2 and CH_4 concentrations (X_{CO_2} and X_{CH_4} , in ppm, X_{CO_2} and X_{CH_4} indicate the mole fraction of CO_2 and CH_4 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 X_{CO_2} changes (ΔX_{CO_2}) 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 X_{CO_2} data have units of concentration in ppm, and it was necessary to convert these numbers to density values ($\text{mg}\cdot\text{m}^{-3}$) using

$$\text{mg}\cdot\text{m}^{-3} = M/22.4 \times \text{ppm} \times [273/(273+T)] \times (Ba/1013.25), \quad (1)$$

where M is the molecular weight of CO_2 , and ppm is the concentration of CO_2 , T is the temperature ($^{\circ}\text{C}$), 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):

$$H = (R \cdot T / g \cdot M) \cdot \ln(P_0/P) - h, \quad (2)$$

where R is the universal gas constant ($8.31 \text{ J mole}^{-1} \text{ K}^{-1}$), 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_{CO_2}) for a smoke plume were calculated by:

$$E_{\text{CO}_2} = Q \cdot V = \text{mg}\cdot\text{m}^{-3} \cdot S \cdot H, \quad (3)$$

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 CO₂ emissions from Russia's summer forest fires in 2010 using GOSAT data. The BBM can be described as

$$E_s = A \cdot B \cdot \beta \cdot EF, \quad (4)$$

where E_s represents the CO₂ emissions, A indicates the burned area (ha), B is biomass fuel load (Mg ha⁻¹), β is the combustion factor (%) and EF is the CO₂ emission factor (g kg⁻¹).

In this study, we did not consider CO₂ 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 (ΔX_{CO}) or CO₂ (ΔX_{CO_2}), divided by the excess concentration of a specific trace gas (ΔX) in a smoke plume. To obtain ΔX , 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 CO₂, CO, CH₄ 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 CO₂ as reference gas) by analyzing smoke plume samples in Canada. In the present study, we use CO as reference gas and CO₂ as the target gas to measure CO₂ emissions from boreal forest fire (equation 5).

$$ER_{X_{CO_2}/X_{CO}} = \frac{\Delta X_{CO_2}}{\Delta X_{CO}} = \frac{PX_{CO_2} - BX_{CO_2}}{PX_{CO} - BX_{CO}}, \quad (5)$$

PX_{CO_2} and BX_{CO_2} indicate the CO₂ 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 μ m) and true color composition of RGB=431 were selected. Figure 1 shows the example of how to identify smoke plumes on August 8, 2010. From Figure 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 (Figure 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 (Figure 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 CO₂ 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 km² 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. SX_{CO2} is the X_{CO2} values that were exposed to smoke plumes, and BX_{CO2} 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, BX_{CO2} is the mean value of more than one point. We assumed that an increase in the CO₂ 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 ΔX_{CO2} values.

3. Results

3.1. Identification of forest fire smoke plume areas

Figure 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. ΔX_{CO2} retrieval and simulation

Table 1 shows the different smoke classifications that corresponded to different ΔX_{CO2} values. We used a linear regression model to calculate the X_{CO2} value of the smoke plumes that were not covered by the FTS L1B points. A scatter plot of ΔX_{CO2} against the CAI band 1 radiance values is shown in Figure 3. This graph illustrates that higher radiance values usually corresponded to higher CO₂ emissions ($R^2 = 0.44$, $P < 0.001$). We could calculate the CO₂ 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 (Figure 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. Figure 4(a) also indicates that on

August 13 and 16, the break point of CO₂ concentration appeared at approximately 700 hPa, and in Figure 4(b), 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 (Figure 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 [Mielonen 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. [Mielonen et al. \(2012\)](#) found a clear CALIOP image of a vertical profile on July 29, 2010 over Russia and argued that the heights of smoke plumes were lower than 2.0 km. [Kahn et al. \(2007\)](#) used stereo-derived smoke plume heights from the MISR instrument to analyze the forest fire smoke height around the fire points and reported that the smoke released from the major fire sources reached the relative stability layers. An evaluation of smoke height from Alaska's Yukon region in the summer of 2004 found that most of the wildfire smoke plumes reached a height of 2 km ([Kahn et al., 2008](#)). [Labonne et al. \(2007\)](#) used 178 forest fires in eastern Europe from July and August 2006 to monitor the range of maximum heights of the aerosol layer and found that it was between 1.5 and 6 km. In the present study, we found that GOSAT-FTS TIR L2 was a suitable tool to identify the boundary 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 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. Iii *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 ($\Delta X_{CO}/\Delta X_{CO_2}$) 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.* (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.

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 X_{CO2} 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 ΔX_{CO_2} , 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 1,000 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 ΔX_{CO_2} 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 ΔX_{CO_2} by comparing the X_{CO_2} 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 emitted 255.76 Tg CO₂, and this result was verified by the BBM and indirectly by several the previous studies.

Acknowledgments: This study was supported by the National Natural Science Foundation of China (41401478), the National Key Research and Development Project (2016YFA0602301) and Science & Technology Development Project of Jilin Province (No. 20140520142JH). We would like to thank the GOSAT Project of Japan for the use of their data in this study.

References

- Adams, J.A.S., Mantovani, M.S.M., Lundell, L.L., 1977. Wood Versus Fossil-Fuel as a Source of Excess Carbon-Dioxide in Atmosphere - Preliminary-Report. *Science* 196, 54-56.
- Akagi, S.K., Yokelson, R.J., Wiedinmyer, C., Alvarado, M.J., 2010. Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmospheric Chemistry & Physics* 11, 27523-27602.
- Amiro, B.D., Barr, A.G., Barr, J.G., Black, T.A., Bracho, R., Brown, M., Chen, J., Clark, K.L., Davis, K.J., Desai, A.R., Dore, S., Engel, V., Fuentes, J.D., Goldstein, A.H., Goulden, M.L., Kolb, T.E., Lavigne, M.B., Law, B.E., Margolis, H.A., Martin, T., McCaughey, J.H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J.T., Starr, G., Xiao, J., 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *Journal of Geophysical Research-Biogeosciences* 115, 4869-4890.
- Andreae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. *Global Biogeochem. Cycles* 15, 955-966.

- Chubarova, N., Nezval', Y., Sviridenkov, I., Smirnov, A., Slutsker, I., 2012. Smoke aerosol and its radiative effects during extreme fire event over Central Russia in summer 2010. *Atmospheric Measurement Techniques* 5, 557-568.
- Cinnirella, S., Pirrone, N., 2006. Spatial and temporal distributions of mercury emissions from forest fires in Mediterranean region and Russian federation. *Atmospheric Environment* 40, 7346-7361.
- Cofer, W.R., Winstead, E.L., Stocks, B.J., Goldammer, J.G., Cahoon, D.R., 1998. Crown fire emissions of CO₂, CO, H₂, CH₄, and TNMHC from a dense jack pine boreal forest fire. *Geophysical Research Letters* 25, 3919-3922.
- Conard, S.G., A. Ivanova, G., 1997. Wildfire in Russian Boreal Forests—Potential Impacts of Fire Regime Characteristics on Emissions and Global Carbon Balance Estimates. *Environmental Pollution* 98, 305-313.
- Crutzen, P.J., Andreae, M.O., 1990. Biomass Burning in the Tropics - Impact on Atmospheric Chemistry and Biogeochemical Cycles. *Science* 250, 1669-1678.
- Crutzen, P.J., Heidt, L.E., Krasnec, J.P., Pollock, W.H., Seiler, W., 1979. Biomass Burning as a Source of Atmospheric Gases CO, H₂, N₂O, NO, CH₃CL and COS. *Nature* 282, 253-256.
- Dixon, R.K., Krankina, O.N., 1993. Forest fires in Russia: carbon dioxide emissions to the atmosphere. *Canadian Journal of Forest Research* 23, 700-705.
- Garbaras, A., Masalaite, A., Garbariene, I., Ceburnis, D., Krugly, E., Remeikis, V., Puida, E., Kvietkus, K., Martuzevicius, D., 2015. Stable carbon fractionation in size-segregated aerosol particles produced by controlled biomass burning. *Journal of Aerosol Science* 79, 86-96.
- Giglio, L., Randerson, J.T., Werf, G.R.V.D., 2013. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). *Journal of Geophysical Research Biogeosciences* 118, 317-328.
- Goto, Y., Suzuki, S., 2013. Estimates of carbon emissions from forest fires in Japan, 1979-2008. *International Journal of Wildland Fire* 22, 721-729.
- Guerlet, S., Basu, S., Butz, A., Krol, M., Hahne, P., Houweling, S., Hasekamp, O.P., Aben, I., 2013. Reduced carbon uptake during the 2010 Northern Hemisphere summer from GOSAT. *Geophysical Research Letters* 40, 2378-2383.
- Guo, M., Wang, X., Liu, Y., Li, J., Wang, H., Matsuoka, N., Tani, H., 2012. The effects of sand dust storms on greenhouse gases. *International Journal of Remote Sensing* 33, 6838-6853.
- Iii, W.R.C., Levine, J.S., Sebacher, D.I., Winstead, E.L., Riggan, P.J., Stocks, B.J., Brass, J.A., Ambrosia, V.G., Boston, P.J., 1989. Trace gas emissions from chaparral and boreal forest fires. *Journal of Geophysical Research Atmospheres* 94, 2255-2259.
- Kahn, R.A., Chen, Y., Nelson, D.L., Leung, F.-Y., Li, Q., Diner, D.J., Logan, J.A., 2008. Wildfire smoke injection heights: Two perspectives from space. *Geophysical Research Letters* 35, 228-236.
- Kahn, R.A., Li, W.H., Moroney, C., Diner, D.J., Martonchik, J.V., Fishbein, E., 2007. Aerosol source plume physical characteristics from space-based multiangle imaging. *Journal of Geophysical Research-Atmospheres* 112, 236-242.
- Konovalov, I.B., Beekmann, M., Kuznetsova, I.N., Yurova, A., Zvyagintsev, A.M., 2011. Atmospheric impacts of the 2010 Russian wildfires: integrating modelling and measurements of the extreme air pollution episode in the Moscow megacity region. *Atmos. Chem. Phys. Discuss.* 11, 12141-12205.
- Krol, M., Peters, W., Hooghiemstra, P., George, M., Clerbaux, C., Hurtmans, D., McInerney, D., Sedano, F., Bergamaschi, P., El Hajj, M., Kaiser, J.W., Fisher, D., Yershov, V., Muller, J.P., 2013. How much CO

was emitted by the 2010 fires around Moscow? *Atmos. Chem. Phys.* 13, 4737-4747.

Labonne, M., Breon, F.M., Chevallier, F., 2007. Injection height of biomass burning aerosols as seen from a spaceborne lidar. *Geophysical Research Letters* 34, L11806 , doi:10.1029/2007GL029311.

Levine, J.S., 1999. The 1997 fires in Kalimantan and Sumatra, Indonesia: Gaseous and particulate emissions. *Geophysical Research Letters* 26, 815-818.

Lu, A.F., Tian, H.Q., Liu, M.L., Liu, J.Y., Melillo, J.M., 2006. Spatial and temporal patterns of carbon emissions from forest fires in China from 1950 to 2000. *Journal of Geophysical Research-Atmospheres* 111, 811-830.

Matsueda, M., 2011. Predictability of Euro - Russian blocking in summer of 2010. *Geophysical Research Letters* 38, 122-133.

Mei, L., Xue, Y., Leeuw, G.D., Guang, J., 2012. Integration of remote sensing data and surface observations to estimate the impact of the Russian wildfires over Europe and Asia during August 2010. *Biogeosciences Discussions* 9, 3771-3791.

Mielonen, T., Portin, H., Komppula, M., Leskinen, A., Tamminen, J., Ialongo, I., Hakkarainen, J., Lehtinen, K.E.J., Arola, A., 2012. Biomass burning aerosols observed in Eastern Finland during the Russian wildfires in summer 2010 - Part 2: Remote sensing. *Atmospheric Environment* 47, 279-287.

Narayan, C., Fernandes, P.M., van Brusselen, J., Schuck, A., 2007. Potential for CO₂ emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol. *Forest Ecology and Management* 251, 164-173.

Oguma, H., Morino, I., Suto, H., Yoshida, Y., Eguchi, N., Kuze, A., Yokota, T., 2011. First observations of CO₂ absorption spectra recorded in 2005 using an airship-borne FTS (GOSAT TANSO-FTS BBM) in the SWIR spectral region. *International Journal of Remote Sensing* 32, 9033-9049.

Pereira, G., Freitas, S.R., Moraes, E.C., Ferreira, N.J., Shimabukuro, Y.E., Rao, V.B., Longo, K.M., 2009. Estimating trace gas and aerosol emissions over South America: Relationship between fire radiative energy released and aerosol optical depth observations. *Atmospheric Environment* 43, 6388-6397.

R'Honi, Y., Clarisse, L., Clerbaux, C., Hurtmans, D., 2013. Exceptional emissions of NH₃ and HCOOH in the 2010 Russian wildfires. *Atmospheric Chemistry & Physics* 13, 4171-4181.

Reuter, M., Buchwitz, M., Schneising, O., Heymann, J., Bovensmann, H., Burrows, J.P., 2010. A method for improved SCIAMACHY CO₂ retrieval in the presence of optically thin clouds. *Atmospheric Measurement Techniques* 3, 209-232.

Robinson, J.M., 1989. On Uncertainty in the Computation of Global Emissions from Biomass Burning. *Climatic Change* 14, 243-262.

Rosa, I.M.D., Pereira, J.M.C., Tarantola, S., 2011. Atmospheric emissions from vegetation fires in Portugal (1990-2008): estimates, uncertainty analysis, and sensitivity analysis. *Atmos. Chem. Phys.* 11, 2625-2640.

Ross, A., 2012. GOSAT Measurements of Wildfire Emissions. UNIVERSITY OF LONDON, p. 95.

Ross, A.N., Wooster, M.J., Boesch, H., Parker, R., 2013. First satellite measurements of carbon dioxide and methane emission ratios in wildfire plumes. *Geophysical Research Letters* 40, 4098-4102.

Seiler, W., Crutzen, P.J., 1980. Estimates of Gross and Net Fluxes of Carbon between the Biosphere and the Atmosphere from Biomass Burning. *Climatic Change* 2, 207-247.

Simmonds, P.G., Manning, A.J., Derwent, R.G., Ciais, P., Ramonet, M., Kazan, V., Ryall, D., 2005. A burning question. Can recent growth rate anomalies in the greenhouse gases be attributed to

500 large-scale biomass burning events? Atmospheric Environment 39, 2513-2517.

501 Simpson, I.J., Akagi, S.K., Barletta, B., Blake, N.J., Choi, Y., Diskin, G.S., Fried, A., Fuelberg, H.E.,
502 Meinardi, S., Rowland, F.S., Vay, S.A., Weinheimer, A.J., Wennberg, P.O., Wiebring, P., Wisthaler, A.,
503 Yang, M., Yokelson, R.J., Blake, D.R., 2011. Boreal forest fire emissions in fresh Canadian smoke
504 plumes: C-1-C-10 volatile organic compounds (VOCs), CO₂, CO, NO₂, NO, HCN and CH₃CN.
505 Atmospheric Chemistry and Physics 11, 6445-6463.

506 Van Leeuwen, T., Van Der Werf, G., 2011. Spatial and temporal variability in the ratio of trace gases
507 emitted from biomass burning. Atmospheric Chemistry and Physics 11, 3611-3629.

508 Witte, J.C., Douglass, A.R., da Silva, A., Torres, O., Levy, R., Duncan, B.N., 2011. NASA A-Train and Terra
509 observations of the 2010 Russian wildfires. Atmos. Chem. Phys. 11, 9287-9301.

510 Wong, C.S., 1978. Atmospheric Input of Carbon-Dioxide from Burning Wood. Science 200, 197-200.

511 Wu, J., 1990. The change of the atmospheric pressure with elevation, Tianjin Education, p. 46.

512 Yurganov, L.N., Rakitin, V., Dzhola, A., August, T., Fokeeva, E., George, M., Gorchakov, G., Grechko, E.,
513 Hannon, S., Karpov, A., Ott, L., Semutnikova, E., Shumsky, R., Strow, L., 2011. Satellite- and
514 ground-based CO total column observations over 2010 Russian fires: accuracy of top-down
515 estimates based on thermal IR satellite data. Atmos. Chem. Phys. 11, 7925-7942.

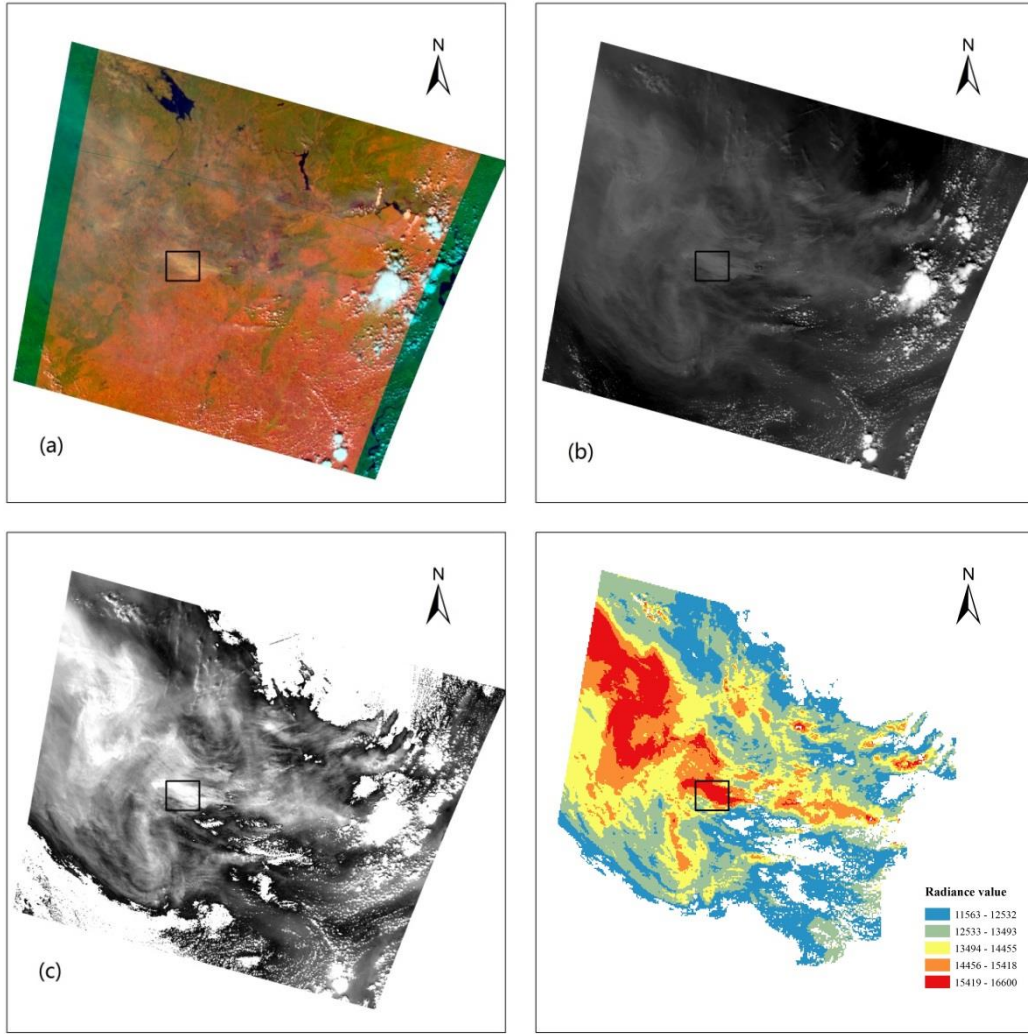
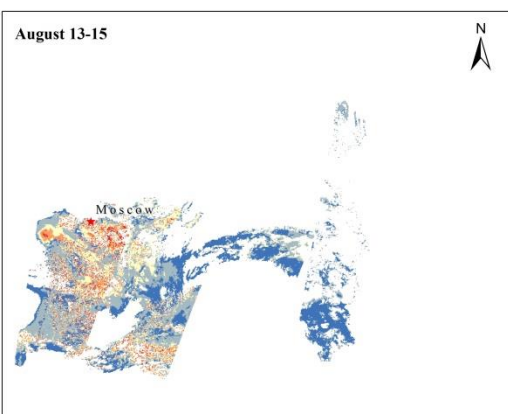
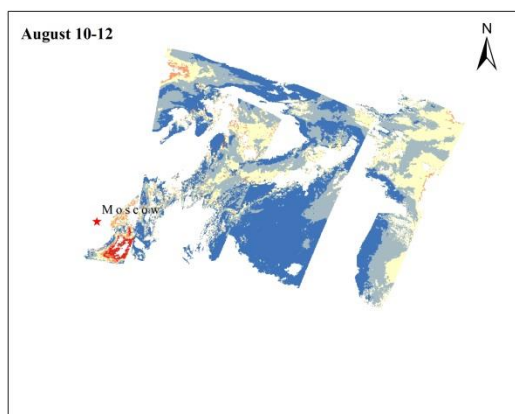
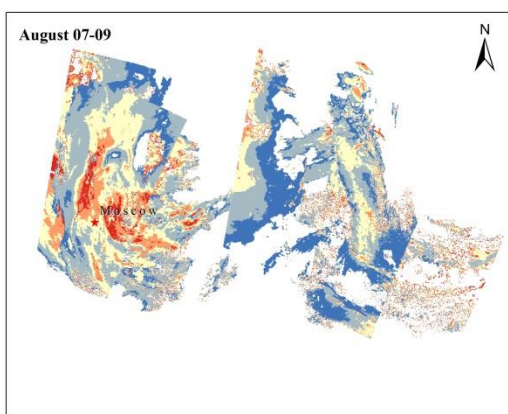
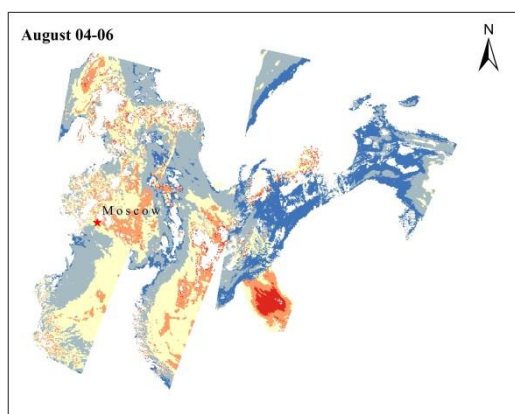
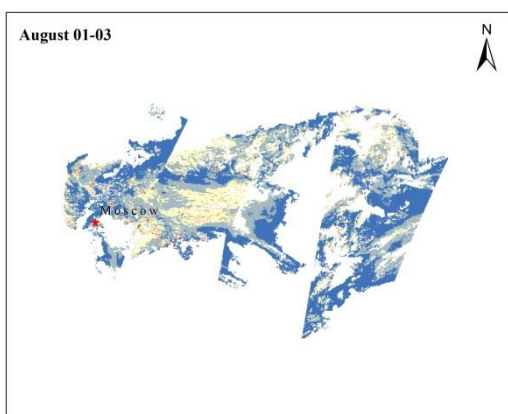
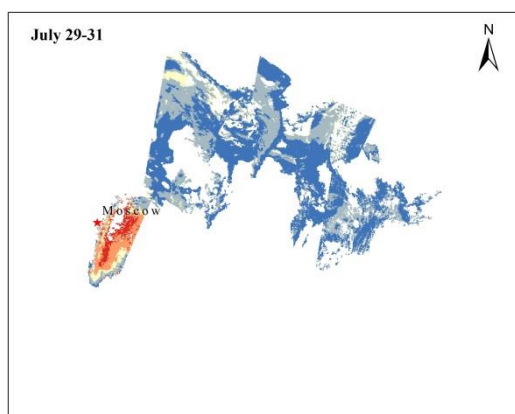
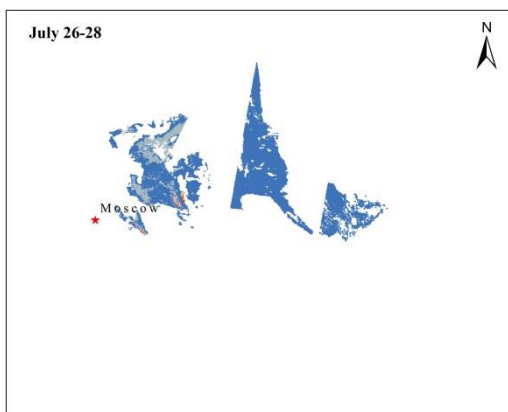
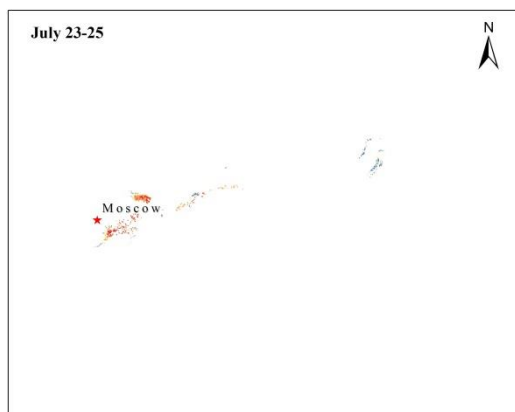


Figure 1. Example to identify smoke plumes on August 8, 2010. CAI image with band 431 (a); CAI image with band 1 (b), smoke plume areas identified by using thresholds of band 1 (c), and a subset of smoke plumes using ROI (d). The spatial resolution of (a), (b) and (c) is 500-m.



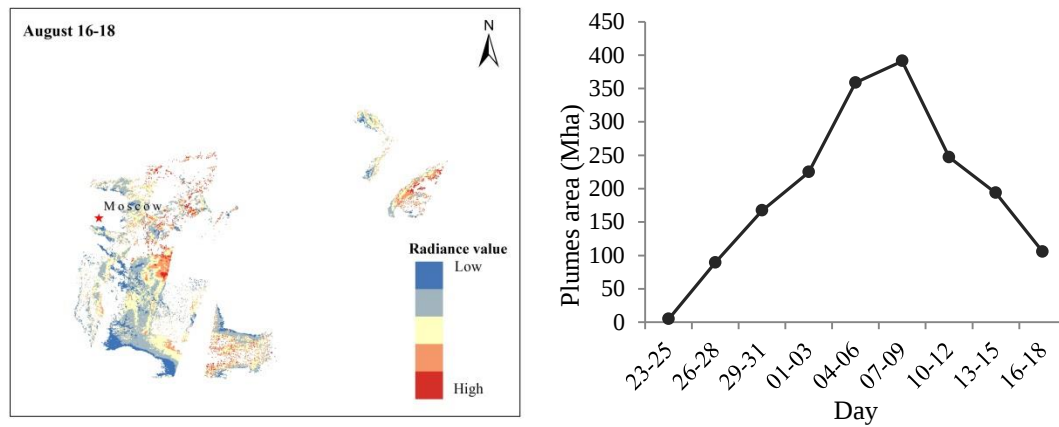


Figure 2. 3-day smoke plume areas in the study region. The preceding 9 figures show the distribution of 3-day smoke plumes and the last figure shows the smoke plume area in million ha (23-25 of X-axis means July 23-25 and 01-03 means August 01-03). Here, the 3-day description means the sum of 3 days but without overlapping regions.

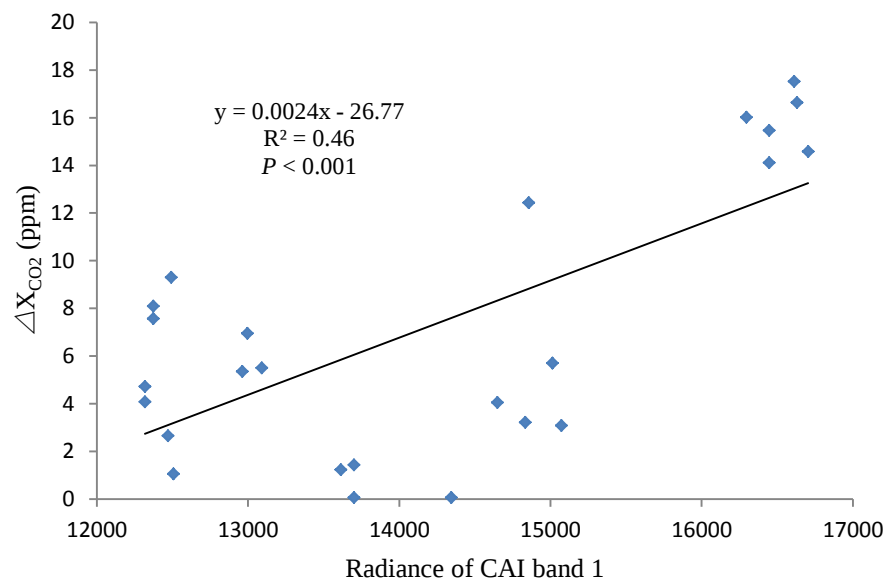


Figure 3. Scatter plots of ΔX_{CO_2} against CAI band 1 radiance values.

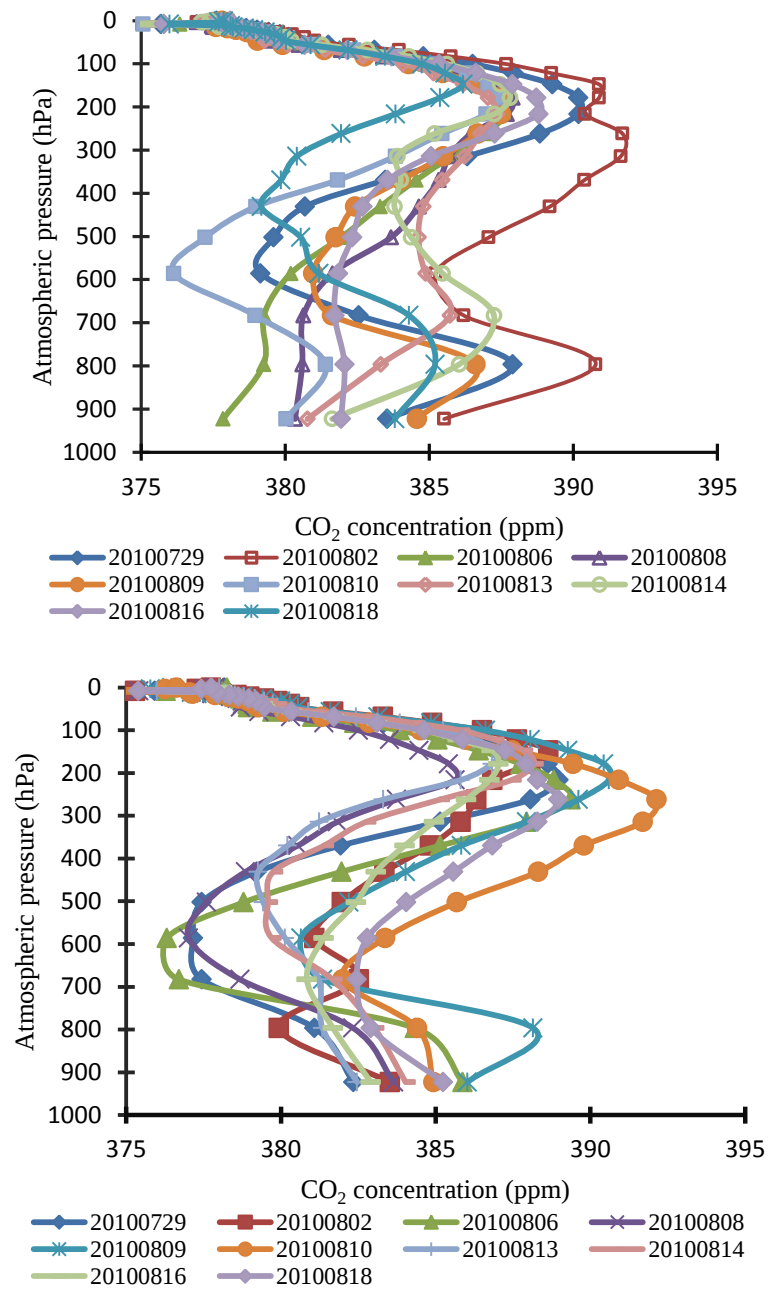


Figure 4. CO₂ concentration changes against atmospheric pressure. FTS TIR points were covered by smoke plumes (a) and in clear sky (b).

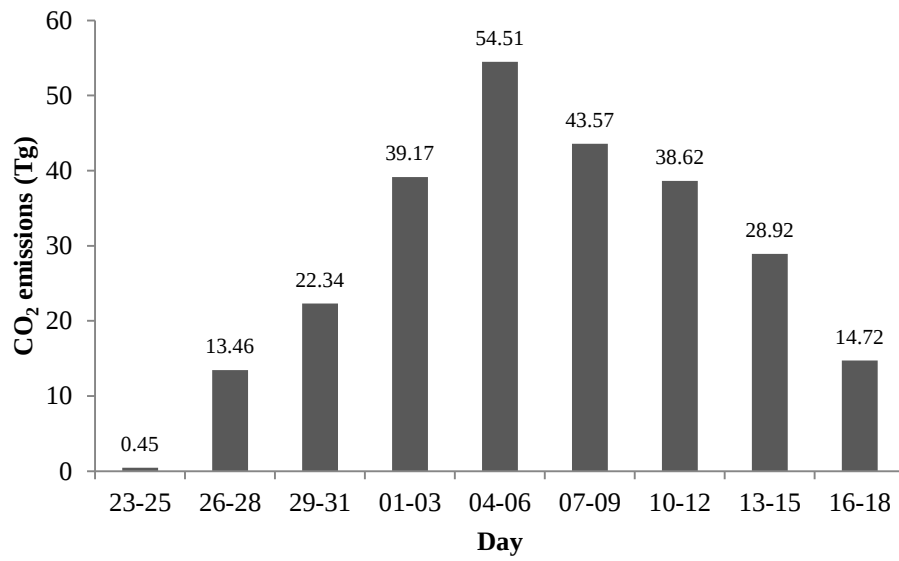


Figure 5. 3-day CO₂ emissions from Russian forest fires in 2010. 23-25 means the sum of values on July 23, 24 and 25.

Table 1. FTS L1B point data for exposures to smoke from Russian forest fires in 2010.

ID	Time	Lat	Lon	Smoke classification	PX_{CO2} (ppm)	BX_{CO2} (ppm)	ΔX_{CO2} (ppm)
1	20100801101735	56.2002	45.1421	Smoke	389.112	389.055	0.056
2	20100805105011	55.4093	41.0231	Thick smoke	402.024	386.006	16.017
3	20100805105015	55.4095	41.0207	Thick smoke	400.112	386.006	14.105
4	20100805105020	55.4088	41.0185	Thick smoke	401.468	386.006	15.462
5	20100807101741	55.9293	45.0298	Smoke	388.500	383.000	5.500
6	20100807101746	55.9326	45.0297	Smoke	389.946	383.000	6.946
7	20100807101751	55.9358	45.0304	Smoke	388.348	383.000	5.348
8	20100808104944	55.7508	37.6287	Smoke	388.736	385.655	3.081
9	20100809104948	55.7134	37.6118	Smoke	389.709	385.655	4.054
10	20100810104953	55.4384	37.4946	Smoke	398.088	385.655	12.433
11	20100811104958	55.1632	37.3787	Smoke	391.350	385.655	5.695
12	20100812105012	55.4476	41.0439	Light smoke	386.878	385.655	1.224
13	20100813105016	55.4473	41.0413	Light smoke	385.720	385.655	0.065
14	20100814105021	55.4472	41.0396	Light smoke	387.079	385.655	1.425
15	20100815105025	55.9688	36.8649	Smoke	388.874	385.655	3.219
16	20100816105044	53.4402	35.8906	Light smoke	386.710	385.655	1.055
17	20100817105048	53.4415	35.8874	Light smoke	388.309	385.655	2.655
18	20100813101743	55.9331	45.0332	Thick smoke	398.309	383.730	14.579
19	20100813101748	55.9356	45.0328	Thick smoke	401.248	383.730	17.518
20	20100813101753	55.9396	45.0338	Thick smoke	400.359	383.730	16.629
21	2010081410509	55.9958	41.3305	Light smoke	383.685	378.960	4.725
22	20100814105013	55.9964	41.329	Light smoke	383.031	378.960	4.070
23	20100814105032	53.9962	36.1053	Light smoke	388.255	378.960	9.295
24	20100814105036	53.9956	36.1008	Light smoke	387.056	378.960	8.096
25	20100814105041	53.9973	36.0976	Light smoke	386.535	378.960	7.574