Atmospheric Environment 79 (2013) 853–860

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Effect of continental sources and sinks on the seasonal and latitudinal gradient of atmospheric carbon dioxide over East Asia

Changsub Shim [a],*, Jeongsoon Lee [b], Yuxuan Wang [c]

[a] *Korea Environment Institute, 215 Jinheung-ro, Eunpyeong-gu, Seoul, South Korea*
[b] *Korea Research Institute of Standards and Science, 267 Gajeong-ro, Yuseong-gu, Daejeon, South Korea*
[c] *Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing, China*

HIGHLIGHTS

- Examination of regional scale atmospheric CO_2 column concentration over East Asia.
- The latest regional scale CO_2 simulation was conducted and evaluated.
- The recent ACOS-GOSAT, satellite CO_2 retrieval data was applied for the region.
- The characteristics of atmospheric CO_2 spatiotemporal variability over the East Asia.
- Identification of the main driving forces (sources/sinks) for the variabilities.

ARTICLE INFO

Article history:
Received 26 February 2013
Received in revised form
19 July 2013
Accepted 25 July 2013

Keywords:
Atmospheric CO_2
East Asia
GOSAT
ACOS/OCO-2
GEOS-Chem

ABSTRACT

Here we demonstrate the sharp seasonal and latitudinal gradient of atmospheric CO_2 over East Asia, where there are relatively few ground-based observations. The Greenhouse gases Observing SATellite (GOSAT) column-averaged dry air CO_2 mole fraction (xCO_2) retrieved by NASA's Atmospheric CO_2 Observations from Space (ACOS) (2009–2011) program and GEOS-Chem nested-grid CO_2 results are used. The strong anthropogenic emissions mainly from China and intensive vegetation uptake from northeastern Asia lead to a clear seasonal change of the xCO_2 between spring maximum and summer minimum (>10 ppm). In particular, the steep latitudinal gradient of summer time xCO_2 by 3–5 ppm in the vicinity of the Korean Peninsula (32°N-44°N) is likely attributed to the large difference in CO_2 fluxes among industry/cities, northeastern forests and the northwest Pacific region. This study represents the current progress to understand sub-continental scale atmospheric CO_2 variabilities with recent satellite retrievals and nested-grid modeling.

1. Introduction

Quantitative understanding of the atmospheric carbon budget including biospheric carbon exchanges is crucial for climate mitigation policy in 21st century. In this aspect, there have been efforts to monitor global atmospheric carbon dioxide from space to overcome the spatial limits of ground-based observations (Buchwitz et al., 2007; Chahine et al., 2008; Crevoisier et al., 2009; Yokota et al., 2009; Kulawik et al., 2010). The Greenhouse gases Observing Satellite (GOSAT) has observed carbon dioxide (CO_2) and methane (CH_4) column distributions since April 2009 (Maksyutov et al., 2008; Kuze et al., 2009; Yokota et al., 2009) and there have been continuous efforts to reduce the retrieval bias (Butz et al., 2011; Wunch et al., 2011; Yoshida et al., 2011; O'Dell et al., 2012). The GOSAT column CO_2 data has been recently applied to map the global CO_2 distributions with finer spatial and temporal resolution over land, but mapping CO_2 distribution solely by satellite measurements could not fully cover regional CO_2 variability mainly due to the limitation of the retrieval stems from cloud and aerosols (Hammerling et al., 2012). Here we focused on spatiotemporal variabilities of atmospheric CO_2 on a sub-continental scale. East Asia is the most human-dominated CO_2 emission region in the world, but there are relatively few monitoring sites, which restricts our understanding of spatial and seasonal CO_2 variability and relevant regional climate impacts. Under limited conditions,

---

* Corresponding author.
E-mail address: marchell@gmail.com (C. Shim).

1352-2310 © 2013 The Authors. Published by Elsevier Ltd. Open access under CC BY license.
http://dx.doi.org/10.1016/j.atmosenv.2013.07.055

satellite observations such as Atmospheric CO_2 Observations from Space retrievals of the Greenhouse Gases Observing Satellite (ACOS-GOSAT) column averaged dry air mole fraction (xCO_2) and a 3-D chemical transport model simulation with nesting capability can be useful to determine the seasonal and spatial characteristics of the regional scale CO_2 variability over East Asia. In this study, we examined the seasonal and spatial characteristics of atmospheric CO_2 and tried to identify the main fluxes contributing the characteristics over East Asia (the region of 100°E–150°E, 20°N-50°N). The methods are explained in Section2 and the spatiotemporal characteristics of regional CO_2 are explained in Section 3, followed by the model evaluation.

2. Methods

2.1. GOSAT CO_2 retrievals

GOSAT measures the concentrations of atmospheric carbon dioxide and methane with good sensitivity near the surface with the Thermal And Near-infrared Spectrometer for Carbon Observations (TANSO) Fourier Transform Spectrometer (FTS) observing in the Short Wave InfraRed (SWIR) region (0.76, 1.6, and 2.0 μm) and a wide Thermal Infrared (TIR) band (5.5–14.3 μm)) with a circular 10.5 km FOV (Kuze et al., 2006, 2009). The satellite (also known as Ibuki) moves in the 666 km sun-synchronous orbit and completes one orbit in ~100 min providing global coverage in approximately 3 days (Kadygrov et al., 2009; Yokota et al., 2009). Recently, the bias of ACOS-GOSAT product v2.9 against the Total Carbon Column Observing Network (TCCON) observations has been greatly reduced mostly by correcting the bias stemming from the O_2 A-band (0.13 ± 1.97 ppm, Wunch et al. (2011); O'Dell et al (2012)). We used ACOS-GOSAT column-averaged dry air mole CO_2 fraction products (xCO_2) (v2.9) from the NASA Goddard Earth Science Data and Information Services Center (http://disc.sci.gsfc.nasa.gov/acdisc/data-holdings/acos-data-holdings) from April 2009 to December 2011. We screened out the low-quality data with the master quality flag which defines retrieval success affected by cloud screening and retrieval algorithm diagnostics. The details of the retrieval method and data products are described elsewhere (Wunch et al., 2011; Crisp et al., 2012; O'Dell et al., 2012).

2.2. GEOS-Chem nested-grid CO_2 simulation for East Asia

We used GEOS-Chem, a global chemical transport model (v9-01-03, www.geos-chem.org) driven by GEOS-5 assimilated meteorology with nesting capability for East Asia. The GEOS-Chem CO_2 module was developed by Nassar et al. (2010), which updated the work by Suntharalingam et al. (2004). The GEOS-Chem model includes atmospheric CO_2 fluxes from biomass burning (year-specific Global Fire Emission Database version 3 (GFEDv3) (van der Werf et al., 2010)), biofuel burning (Yevich and Logan (2003)), fossil fuel combustion and cement production (from Carbon Dioxide Information and Analysis Centre (CDIAC) (Andres et al., 2011), ocean exchange (Takahashi et al. (2009)), international shipping (International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (Corbett and Koehler, 2003, 2004), and aviation (Kim et al., 2007). The fluxes from terrestrial biospheric exchange considered diurnal and seasonal variability by the Carnegie-Ames-Stanford-Approach (CASA) model (Potter et al., 1993) and residual annual exchange by inversion result from Baker et al. (2006). The CO_2 model also accounts for the chemical production of CO_2 from CO oxidation throughout the troposphere (Nassar et al., 2010). The main sources/sinks inventories such as fossil fuel emissions, biomass burning, and ocean exchanges are on a monthly basis. Further details of the model with sources/sinks are illustrated at Nassar et al. (2010).

The GEOS-Chem nested model uses native GEOS-5 meteorological fields with a horizontal resolution of 0.5° × 0.667° over Asia (70°E–150°E, 11°S-55°N, Chen et al., 2009). The lateral boundary conditions of CO_2 were archived from a GEOS-Chem global model run (2° × 2.5°) and used for every 3 h, consistent with the temporal resolution of the meteorological data. The details of the nested GEOS-Chem model are illustrated in Chen et al. (2009) and Wang et al. (2004). We initialized the model with a uniform global CO_2 concentration on January 1st in 2004 as 375 ppm, approximately equal to the global mean based on the measurements of marine surface mean CO_2 concentration (NOAA-ESRL-GMD sites) as previously set by Nassar et al. (2010), which was followed by a multi-year spin-up.

3. Results

3.1. The sharp seasonal and latitudinal CO_2 gradient over Korean Peninsula

The region for this study covers Eastern China, Korea, and Japan, the most populated region (110°E–150°E, 20°N-46°N) with the largest anthropogenic emissions in the world (Fig. 1). We find that the model simulation shows a steep latitudinal gradient of column-averaged CO_2 concentration around 40°N-45°N (will be shown in Fig. 3). In order to investigate that feature, we defined two zones, denoted "N" and "S", which represent the northern zone (124°E–132°E, 40°N-44°N) and southern zone (124°E–132°E, 32°N-36°N) over the Korean Peninsula (Fig. 1). The ACOS-GOSAT xCO_2 time series of those zones from April 2009 to December 2011 is shown to demonstrate the seasonal and latitudinal gradient in Fig. 2. The red diamonds and black crosses represent xCO_2 of "N" and "S" zone respectively. In general, the xCO_2 reaches a maximum in April when vegetation is yet to start growing and reaches a minimum in July–August when photosynthesis is strongest over the region. In particular, the summer minimum of xCO_2 at "N" zone is as low as 385 ppm whereas that of southern zone is over 390 ppm in 2010 (Fig. 2). Even though highly cloudy condition during the Asian monsoon seriously restricts the availability of xCO_2, the clear difference of xCO_2 by 3–5 ppm between two zones is found in summer (June–August) (Fig. 2). The difference is larger than the level of standard deviation of the monthly mean (~2 ppm). The differences of GEOS-Chem column-averaged CO_2 results between two zones estimated from in July 2009 and 2010 are 3.6 and 3.5, respectively. That summertime latitudinal xCO_2 gradient over East Asia is substantially steep considering that the global model-simulated inter-hemispheric gradient of column CO_2 (45°N–45°S) by Olsen and Randerson (2004) is approximately 2.2 ppm. In addition, the latitudinal gradient of surface CO_2 over East Asia could be more significant since the north–south gradient of column CO_2 is about a half of the surface CO_2 based on the global analysis by Olsen and Randerson (2004).

The GEOS-Chem monthly mean column-averaged CO_2 in April (upper left in Fig. 3) and July (lower left) in 2009 can explain the significant seasonal difference. In April, there is higher column-averaged CO_2 (>391 ppm) moving through westerly transport from China (Sichuan province and Eastern China) through Korea and Japan, which is also evident from GEOS-Chem tagged CO_2 simulation for long-term contribution from fossil fuel and cement production (aggregated estimation since 2004, the panels at the second column). In order to estimate the seasonal contributions from fossil fuel emissions and biogenic exchange, we calculated the changes of contributions between January and April in 2009 (a part of non-growing months) and between April and July in 2009 (a part of growing months)) from fossil fuel emissions (panels at the third column in Fig. 3) and biospheric exchange (panels at the fourth