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CMAQ simulation of atmospheric CO_2 concentration in East Asia: Comparison with GOSAT observations and ground measurements

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HIGHLIGHTS

- Comparison of CMAQ CO_2 with GOSAT and ground observations over East Asia.
- ACOS-GOSAT V3.3 slightly overestimated XCO_2 over East Asia.
- Large difference between CO_2 vertical profiles of CMAQ and GOSAT.

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ABSTRACT

Satellite observations are widely used in global CO_2 assimilations, but their quality for use in regional assimilation systems has not yet been thoroughly determined. Validation of satellite observations and model simulations of CO_2 is crucial for carbon flux inversions. In this study, we focus on evaluating the uncertainties of model simulations and satellite observations. The atmospheric CO_2 distribution in East Asia during 2012 was simulated using a regional chemical transport model (RAMS-CMAQ) and compared with both CO_2 column density (XCO_2) from the Gases Observing SATellite (GOSAT) and CO_2 concentrations from the World Data Centre for Greenhouse Gases (WDCGG). The results indicate that simulated XCO_2 is generally lower than GOSAT XCO_2 by 1.19 ppm on average, and their monthly differences vary from 0.05 to 2.84 ppm, with the corresponding correlation coefficients ranging between 0.1 and 0.67. CMAQ simulations are good to capture the CO2 variation as ground-based observations, and their correlation coefficients are from 0.62 to 0.93, but the average value of CMAQ simulation is 2.4 ppm higher than ground-based observation. Thus, we inferred that the GOSAT retrievals may overestimate XCO_2, which is consistent with the validation of GOSAT XCO_2 using Total Carbon Column Observing Network measurements. The near-surface CO_2 concentration was obviously overestimated in GOSAT XCO_2. Compared with the relatively small difference between CMAQ and GOSAT XCO_2, the large difference in CO2 near surface or their vertical profiles indicates more improvements are needed to reduce the uncertainties in both satellite observations and model simulations.

1. Introduction

The atmospheric concentration of the long-lived greenhouse gas CO_2 has increased from a pre-industrial level of 280 ppm to a present-day value of approximately 390 ppm due to the accumulation of anthropogenic CO_2 emissions from deforestation and burning fossil fuels (IPCC, 2007). As the dominant anthropogenic greenhouse gas, CO_2 is the primary driver of climate changes involving surface temperature, the hydrological cycle, and extreme weather events, with a global mean radiative forcing of 1.82 W m^{-2} (IPCC, 2013). Considering the global and accumulated influence of

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long-lived greenhouse gases (Xiong et al., 2008), there is a global consensus to reduce and control CO_2 emissions. Thus, understanding the sources and sinks of CO_2, as well as the global carbon cycle, is crucial for research examining climate changes.

Several studies have focused on the global carbon budget, but there are large uncertainties surrounding regional terrestrial carbon sources and sinks (Schimel, 2007; Kou et al., 2015; Zhao et al., 2012; Zhang et al., 2013). Data assimilation using atmospheric transport models and observations is a common method to improve the accuracy of CO_2 fluxes and concentrations (Chevallier et al., 2005; Peters et al., 2007; Bruhwiler et al., 2005). However, the relatively small number of atmospheric CO_2 observation sites limits the precision of data assimilation and does not capture regional changes in CO_2 emissions.

Satellite-based CO_2 column density (XCO_2) observations offer a new way to constrain CO_2 fluxes in atmospheric inversions because of their global coverage (Chevallier et al., 2007; Hungershoefer et al., 2010; Peylin et al., 2013; Saeki et al., 2013). In several studies, data from satellites, such as the Greenhouse gases Observing SATellite (GOSAT), have been used to reduce the uncertainties associated with estimated CO_2 sources and sinks in atmospheric inversion models (Houweling et al., 2004; Maksyutov et al., 2008; Chevallier et al., 2007; Peng et al., 2015; Tian et al., 2014). However, it should be noted that errors in satellite retrievals and model simulations could lead to additional uncertainties in CO_2 concentrations and fluxes when they are assimilated into an atmospheric inversion model. Therefore, it is important to evaluate the applicability of satellite data in CO_2 assimilations. Several studies have assessed the difference in XCO_2 between GOSAT observations and GEOS-Chem simulations (Shim et al., 2011; Lei et al., 2014; Zhang et al., 2015). However, the performance of regional chemical models and their differences compared with satellite observations remains unclear, especially in East Asia, one of the regions with the highest CO_2 emissions.

In this study, a comprehensive regional air-quality modeling system was used to simulate hourly CO_2 concentrations in East Asia during 2012. The performance of the modeling system was evaluated using ground-based measurements from six sites. The uncertainties of the model simulations, as well as their differences compared with satellite results, were analyzed. The primary purpose of our study was to investigate the uncertainties and differences between simulated CO_2 and GOSAT-observed CO_2 at a regional scale and to assess the value of GOSAT data in regional CO_2 source and sink inversions in East Asia.

2. Data and methods

2.1. GOSAT XCO_2

GOSAT is the first successful satellite designed specifically to measure the concentrations of greenhouse gases (e.g. CO_2, CH_4). It was launched to Sun-synchronous orbit in 2009, covers the globe in three days, and passes the Equator at approximately 13:00 local time. Its footprint diameter at nadir is about 10.5 km. The main instrument aboard GOSAT, the Thermal and Near infrared Sensor–Fourier Transform Spectrometer (TANSO-FTS), can provide measurements at shortwave infrared CO_2 absorption bands with high accuracy and sensitivity to the CO_2 flux in the planetary boundary layer (PBL).

GOSAT XCO_2 L2 data products (Version 3.3) (O'Dell et al., 2012; Crisp et al., 2012; Wunch et al., 2011) retrieved by NASA's Atmospheric CO_2 Observations From Space project (ACOS3.3) were used in this study. The monthly XCO_2 of ACOS3.3 is approximately 1.34 ppm higher than the data from the Total Carbon Column Observing Network (TCCON) (GES DISC, 2013). Details of the products, including the retrieval algorithm and user's guide, are available at http://disc.sci.gsfc.nasa.gov/OCO-2/documentation/gosat-acos. The data extend from January 2012 to December 2012 and were downloaded from NASA Goddard Earth Sciences Data (http://disc.sci.gsfc.nasa.gov/acdisc/documentation/ACOS.shtml).

2.2. Model description

The RAMS-CMAQ modeling system was designed to simulate atmospheric CO_2. The major part of this modeling system is CMAQ (version 4.7.1), which was developed by the US Environmental Protection Agency. RAMS provides three-dimensional meteorological fields (Zhang et al., 2002; Kou et al., 2013). The study domain was 6 654 × 5 440 km^2 with a grid resolution of 64 × 64 km^2. This modeling system can describe the boundary layer and underlying surface effects. There are 15 vertical layers of space from the ground to approximately 21 km, and nearly half are distributed in the lowest 2 km of the atmosphere near Earth's surface.

The CMAQ modeling system is a multi-scale and multi-pollutant air quality model that does not contain CO_2. However, it can simulate tracer species, which can provide the modeler with insights into how the model is simulating various physical processes. We added CO_2 to the model as a tracer gas because of its stability. To model CO_2, we created special table entries appropriate to the application. CO_2 concentration was determined by atmospheric transport and input fluxes. The following surface fluxes were collected as inputs: (1) anthropogenic CO_2 emissions were obtained from the Multi-resolution Emission Inventory for China (MEIC) model, which was developed using a technology-based approach (Li et al., 2015); (2) monthly biomass-burning emissions from forest wildfires, savanna burning, and a slash-and-burn agriculture inventory with a spatial resolution of 0.5° × 0.5° were taken from the Global Fire Emissions Database provided (GFED v3; Van der Werf et al., 2010); (3) the biosphere–atmosphere exchange and ocean flux were collected from CT2013B (3° × 2°) provided by the National Oceanic and Atmospheric Administration (NOAA) CarbonTracker (Peters et al., 2007). The boundary and initial CO_2 concentrations were both obtained by interpolation of CarbonTracker results. Hourly atmospheric CO_2 concentrations were simulated in East Asia between January and December 2012 using the RAMS-CMAQ modeling system.

Fig. 1 shows the seasonal mean distribution of anthropogenic emissions, and biospheric and ocean fluxes in the model domain for 2012. The horizontal distribution of anthropogenic emissions shows large spatial heterogeneity, but lower seasonal variation. Anthropogenic emissions peak in winter in most areas, particularly in the north of China. This finding may be attributable to increased energy consumption for heating and air-conditioning in winter (Wang et al., 2012). The seasonal distribution of biospheric fluxes (Fig. 1e–h), which are strongly influenced by vegetation growth in terrestrial ecosystems, differs from the seasonal distribution of anthropogenic emissions. Biospheric fluxes in China are negative in summer, which means that the biosphere absorbs CO_2 because of strong photosynthesis. In other seasons, the biosphere acts as a source owing to relatively weak photosynthesis and strong respiration.

2.3. Ground-based observations

Ground-based measurements from six sites were used to evaluate the performance of the modeling system. Monthly observations at all stations were obtained from the World Data Centre for Greenhouse Gases (WDCGG, 2011, http://ds.data.jma.go.jp/gmd/wdcgg/).

The locations and types of sites are as follows.