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Column-averaged CO_2 concentrations in the subarctic from GOSAT retrievals and NIES transport model simulations

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Abstract

The distribution of atmospheric carbon dioxide (CO_2) in the subarctic was investigated using the National Institute for Environmental Studies (NIES) three-dimensional transport model (TM) and retrievals from the Greenhouse gases Observing SATellite (GOSAT). Column-averaged dry air mole fractions of subarctic atmospheric CO_2 (XCO_2) from the NIES TM for four flux combinations were analyzed. Two flux datasets were optimized using only surface observations and two others were optimized using both surface and GOSAT Level 2 data. Two inverse modeling approaches using GOSAT data were compared. In the basic approach adopted in the GOSAT Level 4 product, the GOSAT observations are aggregated into monthly means over $5° \times 5°$ grids. In the alternative method, the model–observation misfit is estimated for each observation separately. The XCO_2 values simulated with optimized fluxes were validated against Total Carbon Column Observing Network (TCCON) ground-based high-resolution Fourier Transform Spectrometer (FTS) measurements. Optimized fluxes were applied to study XCO_2 seasonal variability over the period 2009–2010 in the Arctic and subarctic regions. The impact on CO_2 levels of emissions from enhancement of biospheric respiration induced by the high temperature and strong wildfires occurring in the summer of 2010 was analyzed. Use of GOSAT data has a substantial impact on estimates of the level of CO_2 interanual variability.

Keywords: Carbon cycle; Atmospheric transport; Inverse modeling; GOSAT

1. Introduction

Arctic and subarctic regions are large carbon reservoirs. Permafrost soils covering about 25% of the land surface in the Northern Hemisphere store nearly twice as much carbon as is currently present in the atmosphere (Brown et al., 1997; Schuur et al., 2009).

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Schuur et al. (2009) found that areas which have thawed over the last 15 years show annual losses of old carbon that are 40% greater than those observed in minimally thawed areas, while areas that thawed decades earlier show annual old carbon losses 78% greater than those observed in minimally thawed areas. Organic carbon in permafrost soils may act as a positive feedback to global climate change due to enhanced biospheric respiration rates with warming (Koven et al., 2011).

A comparison of observations performed in 1958–1961 and 2009–2011 reveals a strikingly large (~50%) increase of atmospheric CO_2 seasonal amplitude north of 45°N, which must be attributed almost entirely to the terrestrial biosphere activity (Graven et al., 2013). None of the terrestrial ecosystem models currently participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) can account for the increase in CO_2 amplitude. However, there is a high degree of uncertainty regarding the rate of carbon release due to permafrost thaw, microbial decomposition of previously frozen organic carbon, and terrestrial biosphere activity. Moreover, the scarcity of observations in subarctic regions means that the carbon cycle there is not well monitored.

Inverse modeling of carbon exchange at the Earth's surface allows quantification of the spatial distribution of terrestrial carbon sources and sinks, and their seasonal to interannual variability, as shown by Bousquet et al. (2000) and Peters et al. (2007), among others. However, at global scales, many gaps in atmospheric CO_2 measurements remain in remote areas that are geographically distant from CO_2 observation networks, especially at high latitudes in the Northern Hemisphere, thus giving rise to large uncertainties in the estimated fluxes (Gloor et al., 2000). These gaps can be filled using satellite observations of atmospheric CO_2 concentrations (Rayner and O'Brien, 2001). The Thermal And Near-infrared Sensor for carbon Observation–Fourier Transform Spectrometer (TANSO–FTS) onboard the Greenhouse gases Observing SATellite (GOSAT) has been designed to fill gaps in ground-based observation networks through space-based monitoring of the global distribution of greenhouse gases (CO_2 and CH_4) (Kuze et al., 2009; Yokota et al., 2009). The GOSAT column-averaged dry air mole fractions of atmospheric CO_2 (XCO_2) data are expected to contribute to accurate estimates of the global carbon budget because of wide spatial coverage and high temporal resolution of the data. Although retrieval algorithms are still under development (Oshchepkov et al., 2012), the first CO_2 inverse modeling studies using GOSAT data have been completed (Takagi et al., 2011; Basu et al., 2013; Maksyutov et al., 2013; Saeki et al., 2013). The combined use of GOSAT data and surface measurements leads to a reduction in CO_2 flux uncertainties in some tropical and remote land regions, as compared with data based on surface measurements alone (Takagi et al., 2011; Maksyutov et al., 2012; Saeki et al., 2013).

Guerlet et al. (2013) used XCO_2 measured by GOSAT to reveal significant interannual variations (IAV) in CO_2 uptake during the Northern Hemisphere summer during 2009 and 2010. The reduced carbon uptake in the summer of 2010 is most likely due to the heat wave in Eurasia and fire emissions in the Northern Hemisphere, especially in central western Russia. Although wildfires occurred mainly in the forest zone (52°–58°N, 33°–43°E; Witte et al., 2011), the persistent southerly flow transported air into central and northern Europe (Grumm, 2011). During this period, huge amounts of aerosols, CO, CO_2, and other substances were released into the atmosphere as a result of biomass burning (Konovalov et al., 2011; Sitnov, 2011; Muskett, 2013). The smoke drifted long distances with air masses, and on several occasions it could be observed in Eastern Finland (Portin et al., 2012).

The transport of enhanced CO_2 should be accompanied by large amounts of other combustion products, including CO and aerosols. Smoke particles have a significant impact on the earth's radiation balance, especially in the Arctic. When present in the atmosphere, smoke particles may contribute as much as 20% to the aerosol optical thickness during summertime due to dispersion and absorption of solar radiation (Reid et al., 2005; Barnaba et al., 2011). On the ground, when deposited on snow, they have a considerable effect on surface albedo (Stohl et al., 2006, 2007). Thus, the impact of forest fires in central western Russia to the Arctic and subarctic regions are many-faceted and require further study.

In this work, we use forward simulation employing the National Institute for Environmental Studies (NIES) three-dimensional transport model (TM) and GOSAT retrieval data to analyze the distribution of XCO_2 in the subarctic. We study XCO_2 seasonal variability for the period 2009–2010 and discuss the impact of emissions from strong wildfires occurring in the summer of 2010 in central western Russia, the USA, and Canada on enhanced CO_2 concentrations in the Arctic and subarctic