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Impacts of geostationary satellite measurements on CO forecasting: An observing system simulation experiment with GEOS-Chem/LETKF data assimilation system

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ABSTRACT

We developed a chemical data assimilation system based on the GEOS-Chem global chemical transport model (CTM) and an ensemble-based data assimilation method, and performed an observing system simulation experiment (OSSE) to evaluate the impact of geostationary (GEO) satellite data obtained with a multi-spectral (thermal infrared (TIR) and near infrared (NIR)) sensor on air quality forecasting in East Asia.

Initial conditions determined by assimilation of the three observation sets improved the forecasting of trans-boundary CO outflow. The performance of GEO satellite with TIR sensor (GEO-TIR) was better than that of LEO satellite with TIR sensor (LEO-TIR). However, in Seoul district (the Korean Peninsula) and Northern Kyushu (western Japan), the positive impact of the wider coverage and higher frequency of GEO disappeared when the forecast time was longer than 48 h. GEO satellite with NIR and TIR sensor (GEO-NIR + TIR) improved the forecast most, reducing the root mean square difference (RMSD), normalized mean bias, and normalized mean difference by more than 20% even for a forecast time longer than 48 h.

Using the LEO-TIR result as a benchmark, we evaluated the ability of GEO-NIR + TIR to improve the forecast. The 60-h CO forecasting performances of GEO-TIR and GEO-NIR + TIR were about 30% and 120% better, respectively, than that of LEO-TIR. The wider coverage and higher frequency of GEO therefore improved the RMSD by 30%, and the higher sensitivity in the lower troposphere of NIR + TIR improved it by an additional 90%. Thus, the higher sensitivity in the lower troposphere of NIR + TIR as well as the wider coverage and higher frequency of GEO had a notably positive impact on the forecasting of trans-boundary pollutants over East Asia.

1. Introduction

Air quality forecasting has recently become increasingly important for human welfare and social activities. China's rapid economic growth has greatly accelerated anthropogenic emissions in East Asia (Ohara et al., 2007), which have affected air quality during the springtime in downwind regions, a phenomenon known as trans-boundary pollution (Kurokawa et al., 2009a). Yamaji et al. (2012) conducted a sensitivity analysis with a chemical transport model (CTM) and reported that approximately 40% of the increase in O_3 observed at remote Japanese sites could be attributed to increases in NO_x emissions in China. In fact, during 8–9 May 2007, trans-boundary pollution caused unprecedented high levels of photochemical ozone pollution, exceeding the Japanese advisory level of 120 ppbv over a wide area, and the Japanese government issued a photochemical smog advisory in 22 of 47 prefectures (Ohara et al., 2008; Hayasaki et al., 2008). This was the first advisory issued in Oita (Kyushu Island) and Niigata (central Japan adjacent to the Sea of Japan) prefectures since 1987.

To protect human health, it is crucial to be able to predict such heavy pollution events. Some air quality forecasts made with the use of a CTM are available on the web. The U.S. National Air Quality Forecast System (http://www.airnow.gov) provides 48-h forecasts of the Air Quality Index over North America based on the CMAQ (Community Multi-scale Air Quality modeling system; Byun and Schere, 2006) regional CTM. The Meteorological Research Institute (MRI) and the Japan Meteorological Agency (JMA) use the MRI-CCM2 (Deushi and Shibata, 2011) CTM to deliver 48-h forecasts of the surface O_3 concentration in East Asia at http://ds.data.jma.go.jp/pco/mri_ccm2/index.html. The Research Institute for Applied

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Mechanics, Kyushu University, provides forecasts of soil dust and aerosol pollutants made by using the CFORS regional (Chemical Forecasting System: Uno et al., 2003, http://www-cfors.nies.go.jp/~cfors/index-j.html) and SPRINTARS global (Spectral Radiation-Transport Model for Aerosol Species: Takemura et al., 2005, http://sprintars.riam.kyushu-u.ac.jp/forecast.html) models. Although there have been notable improvements in the modeling of atmospheric chemistry and of transport and deposition processes by CTMs over the past decade, many challenging problems remain to be solved (Carmichael et al., 2008). For example, CTMs have large uncertainties associated with incomplete emissions data and inaccurate initial and boundary conditions.

The use of data assimilation with an observational constraint has contributed substantially to the development of numerical weather prediction (NWP) and is a promising approach to better predictive capability (Kalnay, 2003). Recently, data assimilation methods have also been applied to CTM to improve the initial conditions and emission inventories (Sandu and Chai, 2011, and references therein). By using variational methods, various pollutant emissions were inversely estimated with satellite, aircraft and in-situ measurements (e.g., Hakami et al., 2005, for black carbon; Yumimoto and Uno, 2006, for CO; Yumimoto et al., 2008, for dust aerosol; Kurokawa et al., 2009b, for NO_x). Chai et al. (2007) assimilated ICARTT/INTEX-A data with the STEM 4D-Var system and showed that assimilation results provided a much better representation of O_3. With ensemble-based methods, Yumimoto and Takemura (2011) applied a local ensemble transform Kalman filter (LETKF) to SPRINTARS global aerosol climate model, and estimated direct aerosol direct effect with assimilated aerosol field. Tang et al. (2011) integrated regional CTM and air quality monitoring via ensemble Kalman filter (EnKF) to improve the surface ozone forecast. Recently, Miyazaki et al. (2012) developed a chemical data assimilation system based on LETKF (CHASER-DAS), assimilated NO_2, O_3, CO, and HNO_3 from multiple satellites simultaneously, and showed bias reductions in NO_x column, CO and O_3. However, although data assimilation is frequently applied in NWP, its use with CTMs is still in a developmental stage.

In parallel with the development of CTMs, remote sensing of tropospheric pollutants from space has become a powerful tool for investigating atmospheric pollution (Martin, 2008; Fishman et al., 2008). Considerable success has been achieved with satellites in sun-synchronous low Earth orbits (LEOs), and advances in remote sensing techniques make multi-spectral remote sensing from geostationary earth orbits (GEOs) a feasible alternative. Whereas a satellite in LEO passes over a region at given times with limited temporal frequency and horizontal coverage, a satellite in GEO can provide continental scale snapshots of air pollution with a temporal frequency of 1 h or less. In addition, multi-spectral measurement is expected to improve observational sensitivity in the lower troposphere (e.g., for ozone, O_3, Natraj et al., 2011; for carbon monoxide, CO, Deeter et al., 2009). The higher sensitivity and improved temporal and horizontal coverage should substantially improve our understanding of the emission and transport of pollutants and the accuracy of air quality forecasting. The U.S. National Aeronautics and Space Administration (NASA) is planning a GEO-CAPE (Geostationary Coastal And Pollution Events) mission (National Research Council, 2007), and Korea is planning to launch the GEO KOMPSAT geostationary satellite with a Geostationary Environment Monitoring Spectrometer (Lee et al., 2010). These satellite missions are at present in an early planning stage, and detailed requirement and estimates of their expected impacts on air quality forecasting are necessary. In this case, observing system simulation experiments (OSSEs) can become powerful tools used to evaluate the potential impact of the future observing system (Masutani et al., 2010a).

OSSEs are typically constituted by the nature run (NR), the simulated observation, and a data assimilation system, and have the following steps (Fig. 1). At first, a proxy of the "true" state commonly called as the nature run (NR) is defined. In usual, a standard model simulation with no data assimilation is used as the NR. Secondly, the simulated observations measured by the observing system, which we want to examine through the OSSE, are derived from the NR. Next, the simulated observations are assimilated into the control run (CR) to form the assimilation run (AR). The CR is an "alternative" state usually generated by a model simulation with different parameter settings, meteorological field and emissions from the NR. If we want to evaluate the impact on forecasting, we can perform the forecast run (FR) with the AR. Finally, by comparing the AR and FR with the CR, we can make a quantitative estimate of how well the simulated observation is able to bring the AR and FR closer to the NR. Through OSSEs, that we know the "true" state as the NR allows us to generate simulate observations of various observing system (e.g., satellite, field experiment, and in-situ observation network) and test them. OSSEs are also useful for assessing of the performance of a data assimilation system. In fact, OSSEs have been applied to various observing systems in NWP systems (e.g., Masutani et al., 2010b, for Doppler wind lidar; Chen et al., 2011, for a field experiment; Riishojgaard et al., 2012, for Global Wind Observing Sounder). With CTM, Edwards et al. (2009) and Zoogman et al. (2011) have carried out OSSEs for the GEO-CAPE mission to assess how it will impact forecasts of surface CO and O_3, respectively. Recently, Sekiyama et al. (2012) conducted OSSEs for a space-borne lidar with a global aerosol model. However, an OSSE for a new GEO satellite over East Asia, where trans-boundary pollution is a serious problem, is still needed.

In this study, we developed a chemical data assimilation system based on the GEOS-Chem global CTM (http://acmg.seas.harvard.edu/geos/) and an ensemble-based data assimilation method, and performed an OSSE experiment for CO observation measured by the GEO satellite in May when trans-boundary CO outflows often cover in the downwind region (Uno et al., in press). Our purposes were (1) to demonstrate the feasibility of the chemical data assimilation system, and (2) to evaluate the impact of the proposed multi-spectral sensor onboard the GEO satellite on CO forecasting in East Asia. In Section 2, we describe the chemical data assimilation system, and in Section 3, the OSSE framework and experimental setup. We present our results and discussion in Section 4 and our conclusions in Section 5.

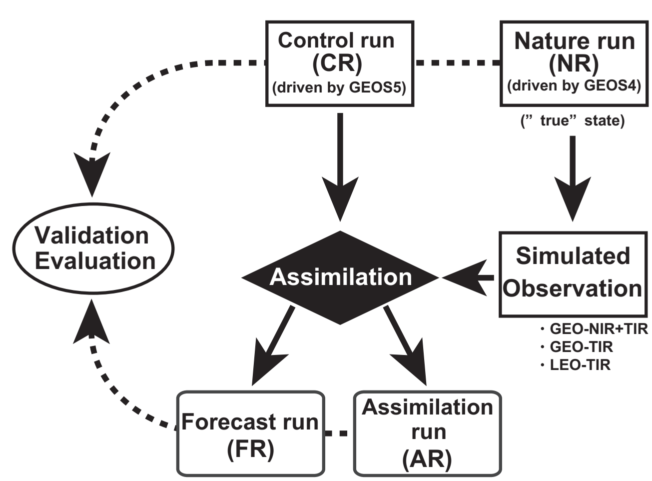

Fig. 1. Schematic diagram of the observing system simulation experiment (OSSE) framework.