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Application of online-coupled WRF/Chem-MADRID in East Asia: Model evaluation and climatic effects of anthropogenic aerosols

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HIGHLIGHTS

- WRF/Chem-MADRID is firstly used in East Asia and evaluated its performance.
- The seasonality of anthropogenic aerosols direct and indirect effects is identified.
- Greater aerosol direct and indirect effects in East Asia than in the U.S. and Europe.

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ABSTRACT

The online-coupled Weather Research and Forecasting model with Chemistry with the Model of Aerosol Dynamics, Reaction, Ionization, and Dissolution (referred to as WRF/Chem-MADRID) is applied to simulate meteorological fields, air quality, and the direct and indirect effects of anthropogenic aerosols over East Asia in four months (January, April, July, and October) in 2008. Model evaluation against available surface and satellite measurements shows that despite some model biases, WRF/Chem-MADRID is able to reproduce reasonably well the spatial and seasonal variations of most meteorological fields and chemical concentrations. Large model biases for chemical concentrations are attributed to uncertainties in emissions and their spatial and vertical allocations, simulated meteorological fields, imperfectness of model representations of aerosol formation processes, uncertainties in the observations based on air pollution index, and the use of a coarse grid resolution. The results show that anthropogenic aerosols can reduce net shortwave flux at the surface by up to 40.5–57.2 W m^{-2}, Temperature at 2-m by up to 0.5–0.8 °C, NO_2 photolytic rates by up to 0.06–0.1 min^{-1} and the planetary boundary layer height by up to 83.6–130.4 m. Anthropogenic aerosols contribute to the number concentrations of aerosols by up to $6.2–8.6 \times 10^4$ cm^{-3} and the surface cloud concentration nuclei at a supersaturation of 0.5% by up to $1.0–1.6 \times 10^4$ cm^{-3}. They increase the column cloud droplet number concentrations by up to $3.6–11.7 \times 10^8$ cm^{-2} and cloud optical thickness by up to 19.8–33.2. However, anthropogenic aerosols decrease daily precipitation in most areas by up to 3.9–18.6 mm during the 4 months. These results indicate the importance of anthropogenic aerosols in modulating regional climate changes in East Asia through aerosol direct and indirect effects, as well as the need to further improve the performance of online-coupled models.

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1. Introduction

Aerosols are known to affect air quality, health, and ecosystems, but the extent to which they affect climate change is unclear and remains a cause for concern (IPCC, 2013). The uncertainty regarding the effects of aerosols on radiative forcing is much higher than that of greenhouse gases (IPCC, 2013). The direct effects of aerosols

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involve the absorption and scattering of solar radiation, whereas indirect effects involve interactions between aerosols and clouds. Aerosol indirect effects through acting as cloud condensation nuclei (CCN) or ice nuclei (IN) affect cloud formation and optical properties. Twomey (1974) indicated that a decrease in cloud droplet effective radius results in increases of both cloud optical thickness (COT) and cloud albedo, which is referred to as the first indirect effect of aerosols. A decrease in precipitation efficiency can prolong the cloud lifetime, associated with an increase of cloud droplet number concentrations (CDNC) and a decrease of the cloud droplet effective radius, is referred to as the second indirect effect (Albercht, 1989). The direct and indirect effects of aerosols have been studied using satellites (Sekiguchi et al., 2003), field observations (Coakley and Walsh, 2002), and numerical models such as general circulation models (GCMs) (Quaas et al., 2006) and online-coupled regional meteorology/climate-chemistry models (Fast et al., 2006; Zhang et al., 2010a, b; 2012a, b). GCMs have more advantages than satellite-derived and field observations (e.g., they can simulate historical and future scenarios and multi-scale regions). However, the spatial resolutions of GCMs are too coarse to represent the effects of regional changes caused by local aerosol emissions and meteorology, which can be well represented by the regional online-coupled models.

The Weather Research and Forecasting Model with chemistry (WRF/Chem) of Grell et al. (2005) is an online model that has recently been developed to simulate the meteorology and chemistry interactions. Since its initial release in 2002, WRF/Chem has been widely applied for air quality and meteorology research (Zhang et al., 2010a, b; Zhang et al., 2012b, 2013a, b; Wang et al., 2015b). In particular, several studies have applied WRF/Chem to simulate aerosol direct and indirect effects over regional domains such as the U.S. and Europe, and over the global domain (Zhang et al., 2010b, 2012a, b, 2013a). WRF/Chem has also been applied in China or East Asia in a number of studies. Among these studies, only a few of them simulate the climatic impacts of anthropogenic aerosols (e.g., Gao et al., 2014; Cai et al., 2014; Zhang, 2014). In addition, the other online coupled regional climate-chemistry-aerosol model namely RIEMS-Chemaero had been developed by Han (2010), Han et al. (2011, 2012) and namely RegCCMS (Zhuang et al., 2013b) also had been used to simulate the aerosol effects over East Asia besides WRF/Chem, the former model only addresses aerosol direct effects, whereas both aerosol direct and indirect effects could be addressed from the latter model (Zhuang et al., 2013a). East Asia, especially China, has become a major source region of anthropogenic aerosols and their precursors with dramatically developing during the past 30 years (Zhang et al., 2009). Such as continuous increase of anthropogenic emissions over this region will affect both regional and global climate change, especially the occurrence of the widespread, persistent, and severe haze in January 2013 over northern and eastern China (Jiang et al., 2014) and in December 2013 over the Yangtze River delta (YRD) (Wang et al., 2015a). Although many studies give the climatic effect of one aerosol or multi aerosols or all aerosols over this region (Han, 2010; Han et al., 2011, 2012; Zhuang et al., 2013a, b), few studies focus on seasonality of both direct and indirect climatic effects of anthropogenic aerosols. In addition, aerosol direct effects were estimated over East Asia (China) by many papers, however, few studied involved in aerosol indirect effects so far. So the understanding between climate change and anthropogenic aerosols is not enough to make strategies and policies of reducing pollutants emissions and slowing climate change.

Comparing to previous studies, this work is unique in several aspects. First, this study performs a comprehensive evaluation using surface and satellite data, in particular, the observations-derived Air pollution indexes (API), which were published by national and local governments, used in this study cover almost the entire China. Second, this study estimates the direct and indirect effects of anthropogenic aerosols over East Asia in 2008 which is similar to Cai et al. (2014) in which such effects are estimated for 2001. Compared to Cai et al. (2014) that used the released version of WRF/Chem, this work uses WRF/Chem with the Model of Aerosol Dynamics, Reaction, Ionization, and Dissolution (MADRID) (i.e., WRF/Chem-MADRID, Zhang et al., 2010a) with a different gas-phase chemical mechanism and aerosol module from those used in Cai et al. (2014). Third, WRF/Chem-MADRID was firstly used in East Asia to evaluation its performance and estimate seasonality of anthropogenic aerosols direct and indirect effects.

The aims of this study are to evaluate the online-coupled WRF/Chem-MADRID with various feedback mechanisms and to estimate the direct and indirect effects of anthropogenic aerosols over East Asia. In this paper, Section 2 describes the model configuration, emissions, and observational data used. In Section 3, the model performance is evaluated against observed chemical concentrations and satellite data. Section 4 presents results of the direct and indirect effects of anthropogenic aerosols over East Asia in the four selected months of 2008, and Section 5 summarizes the major findings and limitations of this work.

2. Model setup and evaluation protocols

2.1. Model domain and setup

WRF/Chem-MADRID is applied to East Asia at a vertical resolution of 23 layers (from the surface to the tropopause) and a horizontal resolution of 36-km. WRF/Chem-MADRID has been applied for retrospective simulations of air quality and its interactions with meteorology in the U.S. and Europe as well as real-time air quality forecasting of O_3 and $PM_{2.5}$ in the U.S. (Zhang et al., 2010a, 2012a, 2013a, b; Chuang et al., 2011; Yahya et al., 2014), and showed promising skill in reproducing both meteorological and chemical observations and forecasting short-term air quality. The WRF/Chem configuration options used in this study are listed in Table S-1.

MADRID uses a sectional representation of aerosol size distribution (8 size section, 0.0215–10 μm) to simulate both the mass and the numbers in each aerosol size bin, which is similar with the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) and different with Modal Aerosol Dynamics Model for Europe coupled with Secondary Organic Aerosol Model (MADE/SORGAM). In present study, internal mixing is assumed to within each aerosol size bin, while external mixing is treated between different aerosol size bins. ISORROPIA is used to simulate inorganic aerosol thermodynamic equilibrium and a mechanistic representation that simulates both hydrophilic and hydrophobic particles is used to simulate SOA formation (Pun et al., 2002). And binary nucleation of sulfuric acid and water vapor is used to simulate the formation of new particles through homogeneous nucleation, and the moving-center scheme approach (Jacobson, 1997) is used to simulate the growth of particles over sections with fixed size boundaries. WRF/Chem-MADRID uses the same scheme for aerosol hygroscopic growth as does WRF/Chem, i.e., the scheme of Leaitch et al. (1986), which is included as part of the aerosol activation/droplet nucleation parameterization of Abdul-Razzak and Ghan (2000) used in WRF/Chem. The aerosol species comprised sulfate, nitrate, ammonium, EC (Element carbon), OC (Organic carbon), Cl^- (Chloride ion), Na^+ (sodium), the other inorganics, and aerosol water. The calculations of the optical and microphysical properties are performed using several physical schemes separately from the aerosol modules in WRF/Chem. Such calculations are therefore the

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