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Fine-scale application of WRF-CAM5 during a dust storm episode over East Asia: Sensitivity to grid resolutions and aerosol activation parameterizations

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ABSTRACT

An advanced online-coupled meteorology and chemistry model WRF-CAM5 has been applied to East Asia using triple-nested domains at different grid resolutions (i.e., 36-, 12-, and 4-km) to simulate a severe dust storm period in spring 2010. Analyses are performed to evaluate the model performance and investigate model sensitivity to different horizontal grid sizes and aerosol activation parameterizations and to examine aerosol-cloud interactions and their impacts on the air quality. A comprehensive model evaluation of the baseline simulations using the default Abdul-Razzak and Ghan (AG) aerosol activation scheme shows that the model can well predict major meteorological variables such as 2-m temperature (T2), water vapor mixing ratio (Q2), 10-m wind speed (WS10) and wind direction (WD10), and shortwave and longwave radiation across different resolutions with domain-average normalized mean biases typically within ± 15%. The baseline simulations also show moderate biases for precipitation and moderate-to-large underpredictions for other major variables associated with aerosol-cloud interactions such as cloud droplet number concentration (CDNC), cloud optical thickness (COT), and cloud liquid water path (LWP) due to uncertainties or limitations in the aerosol-cloud treatments. The model performance is sensitive to grid resolutions, especially for surface meteorological variables such as T2, Q2, WS10, and WD10, with the performance generally improving at finer grid resolutions for those variables. Comparison of the sensitivity simulations with an alternative (i.e., the Fountoukis and Nenes (FN) series scheme) and the default (i.e., AG scheme) aerosol activation scheme shows that the former predicts larger values for cloud variables such as CDNC and COT across all grid resolutions and improves the overall domain-average model performance for many cloud/radiation variables and precipitation. Sensitivity simulations using the FN series scheme also have large impacts on radiations, T2, precipitation, and air quality (e.g., decreasing O_3) through complex aerosol-radiation-cloud-chemistry feedbacks. The inclusion of adsorptive activation of dust particles in the FN series scheme has similar impacts on the meteorology and air quality but to lesser extent as compared to differences between the FN series and AG schemes. Compared to the overall differences between the FN series and AG schemes, impacts of adsorptive activation of dust particles can contribute significantly to the increase of total CDNC (~45%) during dust storm events and indicate their importance in modulating regional climate over East Asia.

1. Introduction

Aerosols play complicated and important roles in global and regional climate by directly changing the earth radiation balance through scattering or absorbing of solar radiation or indirectly affecting cloud formation, lifetime, and properties through activation as cloud condensation nuclei (CCN) or ice nuclei (IN) (Yu, 2000; Yu et al., 2014). Among the major processes associated with aerosol particles, aerosol-cloud interactions have been widely recognized as the most important and uncertain aspect of climate changes (Boucher et al., 2013). To better understand and assess the impacts of aerosols on climate, it is essential to examine major processes such as aerosol activation (also

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known as cloud droplet nucleation) that are critical to aerosol-cloud interactions. Aerosol activation affects not only cloud droplet number concentration (CDNC) but also other cloud properties such as cloud liquid water content and cloud optical thickness (COT).

Due to the lack of a complete aerosol activation theory, aerosol activation has been parameterized in all climate models (Abdul-Razzak and Ghan, 2000). Many physically-based aerosol activation parameterizations that account for aerosol size distribution, chemical composition, and ambient atmospheric conditions have been developed in the past (Abdul-Razzak and Ghan, 2000; Cohard et al., 2000; Nenes and Seinfeld, 2003; Fountoukis and Nenes, 2005; Ming et al., 2006). Among them, two parameterizations are most commonly used including those developed by Abdul-Razzak and Ghan (2000) (hereafter referred to as AG00) and Fountoukis and Nenes (2005) (hereafter referred to as the base FN05) based on the Köhler theory (Köhler, 1936). AG00 uses a semi-empirical formula to calculate the supersaturation and has been widely used in many global and regional models (Ghan et al., 2012). The base FN05 scheme explicitly calculates supersaturation through numerical iterations. A recent study by Ghan et al. (2011) found that FN05 can predict more consistent activation fraction of aerosols than the AG00 scheme when compared to numerical solutions. Several updates have been added to the base FN05 recently, which include the effect of convective entrainment on aerosol activation (Barahona and Nenes, 2007) (hereafter referred to as BN07), the adsorptive activation pathway for insoluble particles such as dust (Kumar et al., 2009) (hereafter referred to as K09), and the treatment of kinetic limitations of giant CCN (Barahona et al., 2010) (hereafter referred to as B10). The base FN05 scheme with the aforementioned updates of BN07, K09, and B10 (hereafter referred to as FN series) has been recently implemented into both global (Gantt et al., 2014) and regional models (Zhang, 2014; Zhang et al., 2015a). Compared to AG00, FN series is found to generally better predict variables representing aerosol-cloud interactions such as CDNC, cloud liquid water path (LWP), and COT.

In the past two decades, East Asia, especially China, has experienced rapid economic and population growth and fast industrialization and urbanization (Wang et al., 2010). Hence this region has emerged as one of the largest contributors to global climate change (Boucher et al., 2013). Large amounts of anthropogenic and natural emissions of aerosols (especially dust) from East Asia resulted in extremely high aerosol concentrations and significantly degraded the regional air quality locally and downwind (e.g., North America) through long-range transport (Heald et al., 2006; Wang et al., 2009, 2012). In addition to high aerosol concentrations, East Asia encompasses regions with complex topography and distinct weather system that may further complicate the interactions of air quality and regional climate (Akimoto, 2003). During springtime, strong mid-latitude cyclones that pass through western China may lift dust particles from the surface of Taklimakan Desert and Gobi Desert to high altitude (Chen et al., 2013), which allows them to be transported to northern and eastern China (Bian et al., 2011) where anthropogenic aerosol concentrations are very high. During the transport, dust particles become aging and mix with other soluble secondary aerosols and can act as efficient CCN and IN (Kumar et al., 2009). Therefore, dust particles from dust storm events may have large influences on aerosol-cloud interactions in East Asia. In spring 2010, due to the worst drought in the century over western and southwestern China, several dust storm events have been reported (Bian et al., 2011; Li et al., 2011; Zhao et al., 2011), which provide ideal testbeds for studying the impacts of dust on aerosol-cloud interactions and air quality.

It has been reported in the past that the skill of climate/air quality models in simulating meteorology and air quality can be highly dependent on grid resolutions especially over areas with high pollutants and/or with complex terrains (Fountoukis et al., 2013; Zhang et al., 2013; Kuik et al., 2016). For example, Fountoukis et al. (2013) reported that the use of high grid resolution can decrease model biases for certain aerosol species such as black carbon (BC). Kuik et al. (2016) found that by using the Weather Research and Forecasting model coupled with chemistry (WRF/Chem), the model performance was improved from 15-km to 3-km resolution for major meteorological and chemical variables, but this is not the case from 3-km to 1-km resolution. Very few studies have examined aerosol-cloud interactions using fine grid resolutions (e.g., 4-km) and complex aerosol activation mechanisms over highly polluted areas such as East Asia. Such studies will provide valuable information to guide future modeling studies for East Asia.

To improve our understanding of aerosol-cloud interactions under extreme high aerosol conditions, we apply the regional air quality/climate model, the WRF model coupled with the physics package of Community Atmospheric Model version 5 (WRF-CAM5) (Ma et al., 2013; Lim et al., 2014; Chen et al., 2015; Zhang et al., 2015a,b) in spring 2010 to investigate the impacts of high aerosol concentrations, different horizontal grid resolutions, and different aerosol activation parameterizations on aerosol-cloud interactions over East Asia. The objectives of this study are to (1) perform a comprehensive model evaluation of WRF-CAM5 at different grid resolutions by conducting triple-nested simulations at 36-, 12-, and 4-km grid resolutions; (2) investigate the impacts of two aerosol activation schemes (i.e., AG00 and FN series) on simulating aerosol-cloud interactions and regional air quality through feedbacks across different grid resolutions and the contribution of dust particles to aerosol-cloud interactions through the adsorptive activation mechanism (i.e., K09).

2. Model description, simulation setup, and evaluation protocols

2.1. Model description

The WRFv3.4-CAM5 model initially developed at the Pacific Northwest National Laboratory (PNNL) (Ma et al., 2013) incorporated the physical and aerosol packages of the global model CAM5 into the WRF/Chem model (Grell et al., 2005). Compared to other online-coupled models, this model is designed to investigate atmospheric processes in a multi-scale framework and provide a regional modeling framework for evaluating physics and aerosol parameterizations used in global climate models (Ma et al., 2013). The WRF-CAM5 model includes state-of-science cloud schemes such as the Morrison two-moment cloud microphysics scheme (Morrison and Gettelman, 2008), and the Zhang-MacFarlane (ZM) convective cloud scheme (Zhang and McFarlane, 1995) with explicit aerosol-convective cloud feedbacks (Song and Zhang, 2011) implemented and evaluated by Lim et al. (2014), and an up-to-date ice-nucleation parameterization for mixed-phase and ice clouds (Niemand et al., 2012). The 3-mode Modal Aerosol Module (MAM3) (Liu et al., 2012) has been fully implemented and tested in this version of WRF-CAM5. MAM3 includes three modes: Aitken, accumulation, and coarse modes, with different internally-mixed aerosol components such as sulfate (SO_4^{2-}), primary organic aerosols (POA), secondary organic aerosols (SOA), BC, dust, and sea-salt. Ammonium (NH_4^+) is implicitly simulated and assumed to co-exist with SO_4^{2-} as ammonium bisulfate (NH_4HSO_4). Nitrate (NO_3^-) is not simulated in MAM3 which may introduce uncertainties in simulating aerosols. There is a simplified SOA scheme in WRF-CAM5 in which five volatile organic compounds (VOCs) can generate SOA with fixed mass yields (i.e., 5% for big alkanes, 5% for big alkenes, 15% for toluene, 4% for isoprene, and 25% for monoterpenes).

The original WRF-CAM5 model is further developed recently at North Carolina State University through implementation of an alternative aerosol activation parameterization (i.e., the FN series) (Zhang, 2014; Zhang et al., 2015a). Major differences between AG00 and the base FN05 include 1) different approaches to calculate the maximum supersaturation; 2) different values of condensation coefficient (i.e., 1.0 in AG00 vs 0.06 in FN05); 3) absence (AG00) or inclusion (FN05) of gas kinetic effect on aerosol activation; and 4) different dependency of