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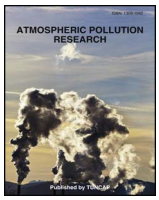

Changes in the diurnal variations of clouds and precipitation induced by anthropogenic aerosols over East China in August 2008

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ABSTRACT

We investigated the impacts of all anthropogenic aerosols and black carbon (BC) on the diurnal variations of cloud and precipitation over East China during August 2008 using a coupled meteorology and chemistry model (WRF-Chem). Comparison of the model results with observations showed that the model reproduced reasonably well the distribution patterns of the aerosol optical depth (AOD), the horizontal wind, precipitation, and the liquid water path (LWP). The results from ensemble numerical experiments showed the aerosol-induced cloud droplet number concentration (CDNC) increased by 20–160 cm^{-3} over East China. The aerosol-induced cloud fraction (CF) increased by 0.03–0.08 below 850 hPa and at around 750 hPa over East China; it decreased by up to 0.06 between 750 and 850 hPa at around 25°N and over Central China. These increases were larger at early morning and nighttime, whereas the decreases were larger in the afternoon and evening. Other scattering aerosols were the main contributor to the increase of CDNC and offset the decrease induced by BC. The decrease of CF over Central China was mainly caused by BC. The precipitation induced by aerosols decreased by 20–200 mm over South and North China with the largest decrease over the North China Plain and southwest China. There was an increase of 20–100 mm over Central China. The decrease in precipitation over South and North China mainly occurred during the day, whereas the increase in precipitation over Central China mainly occurred at night which was caused by BC.

1. Introduction

Atmospheric aerosols alter cloud properties and precipitation by acting as cloud condensation and ice nuclei. They can therefore change the amount of cloud and the cloud lifetime (indirect effects) (Warner and Twomey, 1967; Twomey, 1974; Albrecht, 1989; Hansen et al., 1997; Ramanathan et al., 2001; Li et al., 2011). These earlier studies showed that aerosols suppress light and warm rain processes by decreasing the effective radius of clouds and burning off the clouds. More recent studies (Andreae et al., 2004; Lin et al., 2006; Jiang et al., 2008; Koren et al., 2008; Rosenfeld et al., 2008; Tao et al., 2012) have shown that aerosols also invigorate large convections by suppressing the onset of precipitation, pulling in more moisture, releasing more latent heat, pushing moisture to higher altitudes, and forming more ice clouds. The net effect is to suppress light precipitation and to enhance heavy precipitation. By contrast, the radiative effects of aerosols (i.e., the absorption and scattering of solar radiation, also referred to as direct effects) can perturb the thermodynamic profile of the atmosphere and affect the initialization of convection. The overall effects of aerosols on clouds and the amount and intensity of precipitation remain uncertain (Levin and Cotton, 2009; Boucher et al., 2013).

East China (20–45°N, 110–122°E) is the most developed region in China, with a huge population and many industries. The aerosol concentrations over this region are very high and the aerosol species are very complex including sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), black carbon (BC), organic carbon (OC), and mineral dust (e.g., Chan and Yao, 2008; Zhang et al., 2009a). The effects of aerosols on clouds, convection and precipitation over East China have been extensively studied. Previous studies based on long-term observations and model simulations in East China from 1956 to 2005 (e.g., Qian et al., 2009; Guo et al., 2014a) found that high concentrations of aerosols can significantly increase the cloud droplet number

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concentration (CDNC), reduce droplet sizes, delay raindrop formation, and eventually decrease the frequency and amount of precipitation. Wu et al. (2009) used the Community Atmosphere Model (CAM) to simulate the direct effect of aerosols (SO_4^{2-}, dust, BC, and OC) on precipitation during the period 1960–2000 and showed that precipitation was significantly increased by a maximum of 9% in north and northwest China, but decreased by up to 12% in the southern part of the Tibetan Plateau, the Sichuan Basin, and most of south, southeast, and northeast China. Similar modeling studies (Wu and Han, 2011; Wu et al., 2013) also showed that the effects of aerosols on precipitation during the East Asian summer monsoon was different over different regions in China. Some modeling studies (Wang et al., 2011; Guo et al., 2014b) focused on convective precipitation over several days and the sensitivity numerical tests showed that aerosols can enhance heavy precipitation while suppressing light precipitation over some polluted areas in China (e.g. the Pearl-River-Delta of southern China and northern China). Fan et al. (2012) used the Weather Research and Forecasting (WRF) model with a sophisticated spectral bin cloud microphysics scheme and showed the crucial role of anthropogenic aerosols in regulating the efficiency of precipitation under typical cloud regimes of the warm and cold seasons in southeast China. Fan et al. (2015) later applied the WRF-Chem model to study the role of aerosols during a flood over the Sichuan Basin on July 8–9, 2013 and showed that aerosols enhanced the intensity of rainfall over mountainous areas through aerosol-enhanced conditional instability.

As a result of its specific absorption of solar radiation, the radiative effects of BC are different from those of scattering aerosols such as sulfate. In an assessment of the role of BC, Bond et al. (2013) suggested that the total global mean climate forcing of BC is 1.1 W m^{-2} indicating that BC is the second most important climate forcing agent in the present day atmosphere. In addition to a dimming effect, BC also affects the hydrological cycle via atmospheric heating which will lead to the reduction of humidity, cloud cover and the liquid water path (LWP) and modulation of the associated local circulation (Menon et al., 2002; Wang, 2002; Ramanathan et al., 2005; Ackerman et al., 2000; Hansen et al., 1997). Menon et al. (2002) used a global model to study the climate effects of BC aerosols and showed that the phenomenon of “northern drought/southern flooding”, which has occurred in China during the summer months for the past 50 years, may be related to BC aerosols. Taking the effects of both BC and OC into account, Zhang et al. (2009b) used the modeling results of CAM3 over China to give contradictory results to those reported by Menon et al. (2002). Wu et al. (2008) used RegCM3 to show that the precipitation induced by BC increased by 0.4–0.6 mm day^{-1} in south China, but decreased in north China during the period 1993–2003 based on the BC emission inventory for the year 2000. Wang et al. (2013) showed that absorbing aerosol layers, which frequently occur over South and East Asia, produce a temperature inversion in the lower troposphere, a larger negative energy associated with convective inhibition, and a higher convection condensation level. Pollution plumes induced a larger convective available potential energy above the convection condensation level, facilitating more intense vertical development above the base of clouds. Such a radiative effect of absorbing aerosols operates on the intensity of precipitation in the same direction as the more prominent aerosol microphysical effects.

Diurnal variations in cloud and precipitation modulate soil moisture, runoff, evaporation, and sensible heat flux over land, are very important for the hydrological cycle and agriculture and have a strong influence on the local weather and global climate (Dai, 2001; Zhou et al., 2008; He and Zhang, 2010). Recently, the extreme precipitation become more frequently over East China which is always on a small time scale (Wang and Zhou, 2005). On the other hand, numerical weather and climate models still have large deficiencies in simulating the diurnal characteristics of cloud and precipitation (Lin et al., 2000). In this study, we aim to investigate the effects of all anthropogenic aerosols and BC aerosols alone on the diurnal variation of clouds and precipitation rather than average seasonal or annual changes over East China by conducting ensemble simulations during August 2008 using the Weather Research and Forecasting-Chemistry (WRF-Chem) model which is a coupled meteorology and chemistry model. The study of aerosol contribution on the diurnal variation enables us to better understand how the aerosol interacts with cloud and precipitation and the role of aerosol in the formation of extreme precipitation. In addition, the annul/monthly mean results can be given more clear physical interpretations by revealing at what time during the day a model tends to behave well or badly. Our results also provide a reference of modeled diurnal characteristics of cloud and precipitation with aerosol impacts for other studies. We begin by introducing WRF-Chem and the handling of emissions in the numerical experiments in Section 2 and describe the observation data in Section 3. The model results including the impacts of all anthropogenic aerosols and BC on the CDNC, the cloud fraction (CF), the LWP, and precipitation are presented in Section 4. The conclusion of our results is given in Section 5.

2. Model description

2.1. WRF-Chem model

WRF-Chem is a version of the Weather Research Forecast (WRF) model (Skamarock et al., 2008) that can simulate trace gases and aerosols simultaneously with the meteorological fields (Grell et al., 2005). There are two chemistry mechanisms in WRF-Chem: one is RADM2 (Regional Acid Deposition Model 2) photochemical mechanism (Stockwell et al., 1990) and MADE/SORGAM (Modal Aerosol Dynamics Model for Europe (MADE) and Secondary Organic Aerosol Model (SORGAM)) aerosol model (Ackermann et al., 1998; Schell et al., 2001) and the other one is CBMZ (Carbon Bond Mechanism) photochemical mechanism (Zaveri and Peters, 1999) and MOSAIC (Model for Simulating Aerosol Interactions and Chemistry) aerosol model (Zaveri et al., 2008) which was implemented by Fast et al. (2006). We used the version v3.2.1 including the RADM2 chemistry mechanism, MADE/SORGAM aerosol model with the Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) dust emission model (Zhao et al., 2010). MADE/SORGAM uses the modal approach with three lognormal modes (Aikten, accumulation and coarse mode). All the major components of aerosols are treated in the model, including SO_4^{2-}, NO_3^-, NH_4^+, BC, OC, sea salt, mineral dust, and aerosol water. Aerosol processes in the MADE/SORGAM include nucleation, condensation of both inorganic and organic aerosol, coagulation, dry/wet deposition, gas phase and aqueous phase chemistry, and water uptake of aerosols. The Rapid Radiative Transfer Model for General Circulation Models (RRTMG) radiation scheme was used to include the aerosol direct radiative effect (Zhao et al., 2011), which were released in v3.3. The Lin cloud microphysics scheme was used to include aerosol–cloud interactions for the aerosol first and second indirect effects (Gustafson et al., 2007). Aerosol activation is parameterized in terms of the updraft velocity and the properties (number, size, and hygroscopicity) of all the aerosol modes (Abdul-Razzak and Ghan, 2000). The auto conversion of cloud water to rain water depends on the cloud droplet number, following Liu et al. (2005).

2.2. Numerical experiments

In this study, WRF-Chem was configured to cover China (10–50.5°N, 70–150°E) with 110 (south–north) × 160 (west–east) grid points, a 36 km horizontal resolution centered on central China (30°N, 110°E), and 35 vertical layers up to 10 hPa. The study domain (17–47°N, 102–133°E) which covers East China is shown in Fig. 1. The initial meteorological fields and boundary conditions were from the National Centers for Environmental Prediction (NCEP) FNL reanalysis data. The initial and boundary chemical conditions were from the default profiles in WRF-Chem following McKeen et al. (2002).

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