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A numerical study of the effect of different aerosol types on East Asian summer clouds and precipitation

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HIGHLIGHTS

► We investigate aerosol effects on summer monsoon clouds and precipitation in East Asia.
► Anthropogenic sulfate and POM suppress precipitation in North China.
► Anthropogenic BC induced precipitation change is not statistically significant.
► The effect of all anthropogenic aerosols more resembles that from anthropogenic sulfate and POM.

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ABSTRACT

In this study, the anthropogenic aerosol impact on the summer monsoon clouds and precipitation in East Asia is investigated using the NCAR Community Atmospheric Model version 5 (CAM5), a state-of-the-art climate model considering aerosol direct, semi-direct and indirect effects. The effects of all anthropogenic aerosols, and anthropogenic black carbon (BC), sulfate, and primary organic matter (POM) are decomposed from different sensitivity simulations. Anthropogenic sulfate and POM reduce the solar flux reaching the surface directly by scattering the solar radiation, and indirectly by increasing the cloud droplet number concentration and cloud liquid water path over East China. The surface air temperature over land is reduced, and the precipitation in North China is suppressed. Unlike anthropogenic sulfate and POM, anthropogenic BC does not have a significant effect on the air temperature at the surface, because of the reduction of the cloud liquid water path and the weakening of shortwave cloud forcing by its semi-direct effect. The anthropogenic BC strengthens the southwesterly wind over South China and leads to stronger deep convection at the 25°N–30°N latitudinal band. The effect of all anthropogenic aerosols on air temperature, clouds, and precipitation is not a linear summation of effects from individual anthropogenic sulfate, BC and POM. Overall all anthropogenic aerosols suppress the precipitation in North China and enhance the precipitation in South China and adjacent ocean regions.

1. Introduction

East Asia, especially East China is one of the most polluted regions in the world because of its rapid economic development in recent decades. Total sulfur dioxide (SO_2) emission in China has increased by more than a factor of 5 from the 1950s to the 2000s, with most of the increase taking place after the 1970s (State Environmental Protection Administration of China, 2005). Anthropogenic aerosols produced from air pollution can affect the atmospheric radiation budget, clouds, and precipitation in East Asia by scattering and absorbing the solar and terrestrial radiation (direct effect), heating the cloud layers (semi-direct effect), and by modifying the cloud microphysics (e.g., cloud droplet number concentration, cloud droplet effective radius and cloud water content), the cloud macrophysics (e.g., cloud cover and cloud lifetime), and precipitation efficiency (indirect effect) (Twomey, 1977; Albrecht, 1989).

The East Asian summer monsoon (EASM) driven by temperature differences between the Asian continent and the Indian and Pacific Oceans, influences the climate in most of the East Asian countries. Since the later 1970s, the EASM has been experiencing a considerable weakening trend, and a southward shift of rain belt (known as the southern flooding and northern drought) is

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observed (Yu et al., 2004; Yang et al., 2005; Yang and Zhu, 2008; Ding et al., 2008). This variability of the EASM has been suggested to be caused by many factors (Zhou et al., 2009), including sea surface temperature (SST) variability (Yang et al., 2005; Yang and Zhu, 2008; Li et al., 2010), sensible heat flux over the Tibetan Plateau (Ding et al., 2009), anthropogenic aerosol (Xu, 2001; Menon et al., 2002), and natural decadal variability (Lei et al., 2011).

Many observational data analysis as well as modeling studies have been conducted to understand the role of aerosols on the EASM rainfall. Xu (2001) related the trend of southern flooding and northern drought in China to the radiative (direct) effect of sulfate aerosol based on statistical analysis. Zhao et al. (2006) found that the reduction of precipitation in central China is strongly correlated with the high concentrations of aerosols there, and atmospheric stability in the troposphere has been increasing, based on the analysis of meteorological sounding data. In earlier climate modeling studies, the observed aerosol optical depth (AOD) and the prescribed single scattering albedo (SSA) were often used to describe the aerosol radiative properties in global circulation models (GCMs). Using observed AOD over China and a prescribed SSA of 0.85, Menon et al. (2002) found that solar absorption by black carbon (BC) heats the air and strengthens the convection in South China, which increases the summer monsoon rainfall in South China and decreases the rainfall in North China. Using the same AOD data and prescribed aerosol composition (90% sulfate and 10% soot), Gu et al. (2006) found that precipitation decreases in the Yangtze River valley and increases in southern coast of China in July because of the sulfate radiative effect. Inclusion of BC in their model does not reproduce the observed “southern flooding and northern drought” pattern. However, the prescribed SSA of 0.85 in Menon et al. (2002) is not consistent with the SSA of $\sim$0.90 observed in China (Lee et al., 2007). Thus the absorption effect of BC may be exaggerated in Menon et al. (2002). In addition, the prescribed aerosol properties and chemical composition may not reflect the large temporal and spatial variations of aerosols in China, which are significantly affected by the summer monsoon system (Zhang et al., 2010).

Aerosol may affect the EASM through its influence on precipitation in South Asia during the monsoon and pre-monsoon seasons. Lau et al. (2006) examined the results from their GCM simulations with prescribed aerosol distributions, and found that atmospheric heating by the absorbing aerosols (mineral dust and black carbon), through an “elevated heat pump” mechanism, may strengthen the South Asian monsoon and result in an eastward extension of the Western Pacific Subtropical High. The high-pressure ridge causes a north shift of the East Asian (Mei-yu) rain belt and produces a southwesterly wind anomaly over central East China. Using a fully coupled atmosphere–ocean GCM with prescribed aerosol distributions, Meehl et al. (2008) found that precipitation over India is increased in the pre-monsoon season and slightly reduced in the monsoon season because of the radiative effect of BC, while the summer precipitation over China is generally decreased.

Some recent modeling studies considered the aerosol–climate interactions and allowed the climatic feedback to aerosol distributions in the models. Wang et al. (2009) used an interactive aerosol–climate model coupled with a slab ocean model to study the direct effects of anthropogenic absorbing and scattering aerosols on Indian summer monsoon. Cowan and Cai (2011) used a fully coupled GCM with the direct and indirect aerosol effects and found that non-Asian aerosols substantially exacerbate the impact of Asian aerosols on the cooling of land surface as well as the reduction of summer monsoon precipitation across the Indian and East Asian monsoon domain. Ganguly et al. (2012a) used a coupled atmosphere–slab ocean model including an interactive aerosol module to study the total effects (direct, indirect and semi-direct effects) of anthropogenic and biomass burning aerosol on the South Asian summer monsoon system. The discrepancies between AOD simulated by their model and observations in South Asian regions clearly indicate the needed improvement of regional aerosol emissions and better treatment of aerosol wet removal in the model.

In this study we use the latest version of the Community Atmosphere Model version 5 (CAM5) that considers the aerosol direct, semi-direct and indirect effects to investigate the impact of different types of anthropogenic aerosols (sulfate, BC, and primary organic matter (POM)) on the EASM clouds and precipitation. We attempt to investigate the effects of different types of anthropogenic aerosols on the cloud properties, air temperature and precipitation. The paper is organized as follows: Section 2 introduces the model and the numerical experiments we performed. Section 3 presents the model results of aerosol effects. Conclusions of this study are summarized in Section 4.

2. Model and experiments

The CAM5 model (Neale et al., 2010) is used in this study. A new modal aerosol module (MAM) is implemented in CAM5 to treat interactively the properties and processes of major aerosol species (sulfate, BC, POM, secondary organic aerosol (SOA), mineral dust and sea salt) in the atmosphere (Liu et al., 2012). Aerosol size distributions are represented by three log-normal modes: Aitken, accumulation and coarse modes. Mass mixing ratios of different aerosol species and the number mixing ratio are predicted for each mode. Aerosol species are assumed to be internally mixed within each mode, and externally mixed among different modes. Aerosol optical properties and hygroscopicity for each aerosol mode are calculated using the volume-mixing for different aerosol species within a mode (Ghan and Zaveri, 2007). POM and SOA are treated independently in MAM. While POM is produced from the primary emission, SOA is formed from the condensation of SOAG (a lumped semi-volatile organic species) onto the preexisting aerosols. The MAM is able to capture the spatial distributions of AOD in East Asia when compared to the satellite observations (Liu et al., 2012). The MAM also reproduces the seasonal variations of AOD when compared to the Aerosol Robotic Network (AERONET) data (e.g., lower AOD in the summer than in the winter in South China because of the aerosol scavenging by the EASM precipitation), although the modeled AOD is lower (by a factor of 2) than observations at urban sites.

The stratiform cloud microphysics of CAM5 is a two-moment scheme, predicting mass and number mixing ratios of cloud liquid and cloud ice (Morrison and Gettelman, 2008; Gettelman et al., 2010). The aerosol effect on stratiform cloud microphysics through droplet activation is parameterized in terms of sub-grid cloud scale vertical velocity, and size distribution and volume-mean hygroscopicity of aerosol modes (Abdul-Razzak and Ghan, 2000). The moisture boundary layer turbulence scheme is based on Bretherton and Park (2009). The liquid cloud macrophysics closure is described by Park et al. (submitted for publication). The radiation scheme is based on the Rapid Radiative Transfer Method for GCMs (RRTMG) (Iacono et al., 2008).

These new schemes make CAM5 substantially different from earlier versions of CAM (e.g., CAM3 and CAM4) in terms of aerosol–cloud–climate interactions in the following aspects. First, the MAM aerosol module in CAM5 has a more realistic representation of mixing states of different aerosol species and their impacts on aerosol optical properties. This is especially important for the BC absorption of solar radiation (Jacobson, 2001). We note that