Atmospheric Research 183 (2017) 224–236

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Impact of anthropogenic aerosols from global, East Asian, and non-East Asian sources on East Asian summer monsoon system

Qiuyan Wang [a,b], Zhili Wang [b,a,*], Hua Zhang [c,a]

[a] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China
[b] State Key Laboratory of Severe Weather & Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing, China
[c] Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing, China

ARTICLE INFO

Article history:
Received 11 May 2016
Received in revised form 1 August 2016
Accepted 30 August 2016
Available online 31 August 2016

Keywords:
EASM
Anthropogenic aerosols
East Asian emissions
Non-East Asian emissions

ABSTRACT

The impact of the total effects due to anthropogenic aerosols from global, East Asian, and non-East Asian sources on East Asian summer monsoon (EASM) system is studied using an aerosol-climate online model BCC_AGCM2.0.1_CUACE/Aero. The results show that the summer mean net all-sky shortwave fluxes averaged over East Asian monsoon region (EAMR) at the top of the atmosphere (TOA) and surface reduce by 4.8 and 5.0 W m^{-2}, respectively, due to the increases of global aerosol emissions in 2000 relative to 1850. Changes in radiations and their resulting changes in heat and water transport and cloud fraction contribute together to the surface cooling over EAMR in summer. The increases in global anthropogenic aerosols lead to a decrease of 2.1 K in summer mean surface temperature and an increase of 0.4 hPa in summer mean surface pressure averaged over EAMR, respectively. It is shown that the changes in surface temperature and pressure are significantly larger over land than ocean, thus decreasing the contrast of land-sea surface temperature and pressure. This results in the marked anomalies of north and northeast winds over eastern and southern China and the surrounding oceans in summer, thereby weakening the EASM. The summer mean precipitation averaged over the EAMR reduces by 12%. The changes in non-East Asian aerosol emissions play a more important role in inducing the changes of local temperature and pressure, and thus significantly exacerbate the weakness of the EASM circulation due to local aerosol changes. The weakening of circulation due to both is comparable, and even the effect of non-local aerosols is larger in individual regions. The changes of local and non-local aerosols contribute comparably to the reductions in precipitation over oceans, whereas cause opposite changes over eastern China. Our results highlight the importance of aerosol changes outside East Asia in the impact of the changes of anthropogenic aerosols on EASM.

1. Introduction

The East Asian summer monsoon (EASM) is the most important climate system in East Asia, and its changes have significant effects on East Asian weather and climate (Ding and Chan, 2005; Ding et al., 2008; Lei et al., 2011). The EASM circulation has experienced a marked weakening tendency during the past several decades, which is characterized by a decrease of low-level southwesterly wind, southward shift of East Asian subtropical jet, and an increase of sea level pressure over East Asia (Yu and Zhou, 2007). The possible reasons that lead to the weakening of EASM include natural factors (solar variability, volcanic eruptions, and internal variability) and anthropogenic factors (greenhouse gases (GHGs) and anthropogenic aerosols) (Song et al., 2014).

Aerosols can affect the radiation budget of the Earth's climate system by scattering and absorbing solar radiation (aerosol-radiation interaction), or change the cloud microphysical and radiative properties by acting as cloud condensation nuclei (CCN) or ice nuclei (IN) (aerosol-cloud interaction), thus affecting climate (Boucher et al., 2013; Myhre et al., 2013a). East Asia, especially eastern China, has a sharp increase in aerosol emissions over the past several decades. Aerosols have become an important external forcing factor over the East Asian monsoon region (EAMR). The impact of aerosols on the EASM has attracted great attention as the livelihood, health, and economy for about 20% of the world's population highly depend on monsoon precipitation. Multiple National Basic Research Programs of China have been founded continuously by the Chinese Ministry of Science and Technology to study the interaction processes between aerosols and East Asian monsoon over recent decades.

The EASM is substantially induced by the thermal contrast between the ocean and the land. Land masses heat up more prominently than the surrounding oceans during summer in East Asia, thus forming a large

* Corresponding author at: State Key Laboratory of Severe Weather & Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, ZhongGuanCun South Ave. 46, HaiDian District, Beijing 100081, China.
E-mail address: wangzl@camscma.cn (Z. Wang).

http://dx.doi.org/10.1016/j.atmosres.2016.08.023
0169-8095/

temperature gradient that can drive wind blowing from the ocean toward the land, whereas this reverses in winter (Ding et al., 2015). The spatially inhomogeneous distribution of anthropogenic aerosol emission sources, the slower response of oceans to aerosol forcing, and the short atmospheric lifetime of aerosols all cause different influences on climate of the land and ocean. This can alter the land-sea thermal contrast in the EAMR, thus significantly affecting the monsoon circulation and precipitation (Liu et al., 2009; Liu et al., 2011; Zhang et al., 2012; Jiang et al., 2013). Multi-model ensemble research also indicated that the aerosol forcing played a primary role in the weakening of EASM during the period 1958–2001 among natural forcing, GHG forcing and aerosol forcing (Song et al., 2014). Zhang et al. (2009) found that the direct and semi-direct effects of carbonaceous aerosols can weaken the EASM circulation and result in an increase (decrease) of precipitation in northern (southern) China. Using a regional climate model coupled with an atmospheric chemical model, Li et al. (2009) and Han et al. (2011) suggested that the increases of major anthropogenic aerosols in China produced a marked negative radiative forcing at the top of the atmosphere (TOA), which led to the cooling of local land surface and reduction in precipitation. Simulations made by Zhang et al. (2012) using an aerosol-climate model coupled with a slab ocean model showed that the total direct radiative effects of sulfate, black carbon (BC) and organic carbon (OC) led to a significantly larger cooling over the land than the ocean over East Asia in summer. This weakened the differences of land-sea thermal contrast in the EAMR, and led to the weakening of the EASM circulation and precipitation. Guo et al. (2013) found that regional sulfate aerosols had a more important impact on the EASM than BC, and the impacts of aerosols were more significant during the withdrawal phase of the EASM (September) rather than active phase (June–July–August, JJA).

The aerosol emissions have obviously regional features, and thus their changes can significantly affect the local radiation, temperature, circulation, and precipitation (Qian et al., 2009; Ganguly et al., 2012a). Moreover, many studies have revealed the importance of the effect of changes in remote aerosol emissions on Indian Summer Monsoon (e.g., Cowan and Cai, 2011; Ganguly et al., 2012a; Bollasina et al., 2014). Dong et al. (2016) explored the impacts of local and non-local emissions of anthropogenic sulfur dioxide (Asia vs. Europe) on the EASM and found that both weakened the EASM circulation. However, the impacts of changes in total anthropogenic aerosol emissions over East Asia or non-East Asia on the circulation and precipitation of EASM have not yet been concerned.

In this study, we investigate the impact of changes in global anthropogenic aerosol (sulfate, BC, OC) emissions on the EASM system since the start of the industrial era using an aerosol-climate online model combined with the aerosol emission inventories from Lamarque et al. (2010). We then separate the contributions of changes in East Asian and non-East Asian aerosol emissions to the impact. Compared to the previous work (i.e., Y. Liu et al., 2009; X. Liu et al., 2011; Zhang et al., 2012; Jiang et al., 2013; Dong et al., 2016), this study can provide a new sight in considering the impact of total aerosol effects (direct, semi-direct, and indirect effects) and the responses of oceans to aerosol forcings simultaneously. Studies found that the responses of oceans to aerosol forcings may play a more important role in the aerosol-climate interactions (Ganguly et al., 2012b; Xu and Xie, 2015). The paper is organized as follows: Section 2 describes the model and the simulations that are performed in the study. Section 3 presents the main results. Our discussion and conclusions are given in Section 4. The EASM is designated as the region 0°N–50°N, 100°E–140°E.

2. Methodology

2.1. Model description

We used the aerosol-climate model BCC_AGCM2.0.1_CUACE/Aero (Atmospheric General Circulation Model developed by the Beijing Climate Center of China Meteorological Administration coupled with China Meteorological Administration Unified Atmospheric Chemistry Environment for Aerosols) (Zhang et al., 2012, 2014; Wang et al., 2014, 2015). The aerosol direct, semi-direct, and indirect effects for liquid phase clouds have been included in the model. Aerosol indirect effect by acting as IN can produce a positive forcing (Gettelman et al., 2012; Myhre et al., 2013a), which may weaken the aerosol net cooling effect obtained by this model. BCC_AGCM2.0.1 adopts a horizontal resolution of T42 (approximately 2.8° latitude × 2.8° longitude) and a 26 layer hybrid sigma-pressure coordinate system in the vertical direction, with a rigid lid at 2.9 hPa (Wu et al., 2010). The cloud overlap scheme of the Monte Carlo independent column approximation (McICA) (Pincus et al., 2003), the new Beijing Climate Center radiation transfer model (BCC-RAD) (Zhang et al., 2014), and a two-moment bulk cloud microphysical scheme (Morrison and Gettelman, 2008) were employed in the model (Zhang et al., 2014; Wang et al., 2014). The aerosol model CUACE/Aero, a size-segregated multicomponent aerosol module, was detailed by Zhou et al. (2012). Each type of aerosol is divided into 12 bins as a geometric series for radii between 0.005 and 20.48 μm in the model. CUACE/Aero can calculate the mass concentrations of the five tropospheric aerosol species, i.e., sulfate, BC, OC, dust, and sea salt. The aerosol transport processes include emission, advection, diffusion, gaseous chemistry, interactions with clouds and dry and wet depositions. Aerosol optical properties were obtained based on Wei and Zhang (2011) and Zhang et al. (2012). A slab ocean model (SOM) was coupled with the BCC_AGCM2.0.1_CUACE/Aero to take into account the feedback of ocean.

BCC_AGCM2.0.1_CUACE/Aero has been evaluated in detail by Zhang et al. (2014) and Wang et al. (2014). They showed that the model can simulate aerosols and meteorological fields well. The model has participated the AeroCom Phase II intercomparison of aerosol direct radiative forcing and organic aerosol (Myhre et al., 2013b; Tsigaridis et al., 2014). It has also been used to study the effects of aerosols on climate, e.g., the impact of aerosol direct radiative effect on East Asian climate (Zhang et al., 2012), the effect of the presence of BC in cloud droplets on cloud optical properties and climate (Wang et al., 2013a), non-spherical effect of dust aerosol (Wang et al., 2013b), the impact of dust aerosol direct effect on arid and semi-arid regions (Zhao et al., 2015), and the effect of anthropogenic aerosols on future climate (Wang et al., 2015, 2016; Zhang et al., 2016). Fig. 1 shows the comparisons of simulated JJA mean 850 hPa wind vectors and precipitation over the Asian monsoon regions with observations. The observation data of 850 hPa wind is from the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996), and the precipitation data is from the Climate Prediction Center Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1997). The simulated westerly flows that extend from the Arabian Sea to the South China Sea and even to the western Pacific are stronger than the observations. This leads to a stronger precipitation band from 10°N to 20°N in the simulation due to abundant moisture transport. However, the simulated southerly flows from the Bay of Bengal to the South China Sea are weaker than the observations, thus less precipitation appears in eastern and southern China due to less moisture transport northward from oceans (Fig. 1). Despite these deficiencies, the model reproduces the spatial pattern of 850 hPa wind and precipitation over the Asian monsoon regions well. Thus, it's appropriate for the model to investigate the impact of anthropogenic aerosols on the EASM.

2.2. Simulations

We first performed two simulations with prescribed sea surface temperature and sea ice cover separately by using the emissions of aerosols and their precursors in 1850 (defined as preindustrial, PI) and 2000 (defined as present-day, PD) (Lamarque et al., 2010) to calculate the anthropogenic aerosol effective radiative forcing (ERF) (Myhre et al., 2013a). Each simulation was run for 20 years, with only the final