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Research paper

Simulation of bulk aerosol direct radiative effects and its climatic feedbacks in South Africa using RegCM4

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ABSTRACT

In this study, 12 year runs of the Regional Climate Model (RegCM4) have been used to analyze the bulk aerosol radiative effects and its climatic feedbacks in South Africa. Due to the geographical locations where the aerosol potential source regions are situated and the regional dynamics, the South African aerosol spatial-distribution has a unique feature. Across the west and southwest areas, desert dust particles are dominant. However, sulfate and carbonaceous aerosols are primarily distributed over the east and northern regions of the country. Analysis of the Radiative Effects (RE) shows that in South Africa the bulk aerosols play a role in reducing the net radiation absorbed by the surface via enhancing the net radiative heating in the atmosphere. Hence, across all seasons, the bulk aerosol-radiation-climate interaction induced statistically significant positive feedback on the net atmospheric heating rate. Over the western and central parts of South Africa, the overall radiative feedbacks of bulk aerosol predominantly induces statistically significant Cloud Cover (CC) enhancements. Whereas, over the east and southeast coastal areas, it induces minimum reductions in CC. The CC enhancement and RE of aerosols jointly induce radiative cooling at the surface which in turn results in the reduction of Surface Temperature (ST: up to −1 K) and Surface Sensible Heat Flux (SSHF: up to −24 W/m^2). The ST and SSHF decreases cause a weakening of the convectively driven turbulences and surface buoyancy fluxes which lead to the reduction of the boundary layer height, surface pressure enhancement and dynamical changes. Throughout the year, the maximum values of direct and semi-direct effects of bulk aerosol were found in areas of South Africa which are dominated by desert dust particles. This signals the need for a strategic regional plan on how to reduce the dust production and monitoring of the dust dispersion as well as it initiate the need of further research on different aspects of dust particle in South Africa.

1. Introduction

Atmospheric aerosols as well as aerosol-precursor gases can originate from both natural events (such as volcanic eruptions, wildfires, mechanical action of the wind on the Earth surface) and human activities (such as combustion of biomass and fossil fuels, and different industrial processes). Relative to greenhouse gases, atmospheric aerosols usually exhibit higher heterogeneity, in terms of their spatio-temporal distribution as well as physico-chemical properties. However, among several species of atmospheric aerosols, wind-blown dust and sea salt particles, as well as sulfates, nitrates, ammonium and carbonaceous aerosols have been found to be the dominant species (e.g., Ghan and Schwartz, 2007). Aerosols can substantially influence the Earth's climatic system in several ways. For instance, through scattering and absorbing radiation, as well as depending on their size and composition by emitting thermal radiation; aerosols can alter the Earth energy budget (direct effect) (e.g., Penner et al., 2001). The radiative influences of aerosols (especially shortwave absorbing aerosols such as black carbon and mineral dust particles) may

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cause changes on the thermal, hydrological and dynamical variables of the climate, particularly on cloud fields (this is known as semi-direct effect) (e.g., Johnson, 2003; Miller et al., 2004a, 2004b; Perlwitz and Miller, 2010; Yue et al., 2010b). Aerosols often act as cloud condensation nuclei and therefore influence the physico-optical properties of clouds as well as its lifetimes (known as an indirect effect) (e.g., Lohmann and Diehl, 2006; Lohmann et al., 2007). Additionally, atmospheric aerosols provide reactive surfaces where various heterogeneous chemical reactions can take place. As a result, aerosols play an important role in modulating chemical processes within the atmosphere (Dentener et al., 1996; Dickerson et al., 1997). The extent to which aerosol interact with and modify the radiation and various components of the earth climatic system has been addressed by using both observational analysis as well as models of varying complexity (Forster et al., 2007; Randall et al., 2007). Overall, due to multi-environmental roles of aerosols, they became increasingly an important subject in environmental as well as climate change studies.

Once aerosols are released into (formed in) the atmosphere, they may be transport to remote areas relative to their sources locations. In addition, as aerosols stay in the atmosphere, depending on the meteorological situation and chemical composition of the background atmosphere, they may experience physico-chemical transformations (e.g., Sullivan et al., 2007, 2009). This may induce modification on optical properties of aerosols as well as on their radiative and climatic roles (e.g., Bond and Bergstrom, 2006; Fuzzi et al., 2006; Fan et al., 2008). Compared to greenhouse gases, tropospheric aerosols have short atmospheric lifetimes (e.g., Shindell et al., 2008) implying that their concentration and environmental effects are more important in the vicinity of their source regions (e.g., Giorgi et al., 2002; Roeckner et al., 2006; Wu et al., 2008). Hence, it becomes crucial to assess the distribution as well as the effects of aerosols on a regional scale rather than global averaged basis (e.g., Solmon et al., 2006; Wu et al., 2008; Tesfaye et al., 2011). In global-scale models, because of their coarse grid resolution; there exists a large bias in simulated meteorological fields which govern the aerosol/chemistry-atmosphere-radiation interactions (Todd et al., 2008; Croft et al., 2012 and references therein). This may impose remarkable inaccuracies on computations of regional-scale aerosol processes and their climatic effects (e.g., Luo et al., 2003; Darmenova and Sokolik, 2007). In this regard, the high-resolution Regional Climate Model (RegCM) which is interactively coupled with aerosol modules becomes an important tool to simulate small-scale aerosol processes and their climatic effects with better accuracies (e.g., Wang et al., 2004; Solmon et al., 2006; Zakey et al., 2006; Darmenova et al., 2009; Giorgi et al., 2012).

South Africa is well known for its extensive usage of coal for electricity generation, fuel production, industrial purposes and different domestic usages. The country also has different mining and metallurgical industries, sugar refineries, agricultural and different manufacturing sectors. Besides the occasionally occurring wildfires, biomass combustions in South Africa are frequently related with agricultural practices, particularly during the dry season (i.e., July–October) (e.g., Scholes et al., 1996). These and other human activities become the major sources of anthropogenic aerosols/aerosol-precursor gases in and around South Africa (e.g., Tummon, 2011 and references therein). Previously, the authors of this study reported the mass distribution, direct and semi-direct climatic effects of different species of aerosols which are induced from anthropogenic sectors (Tesfaye et al., 2014a) and open biomass burning activities (Tesfaye et al., 2014b), over South Africa. These studies have been carried out using the version 4 of International Centre for Theoretical Physics (ICTP) Regional Climate Model (RegCM4) which is interactively coupled with anthropogenic/chemistry-desert dust schemes (RegCM4-aerosol model) (Giorgi et al., 2012). The results of Tesfaye et al. (2014a, 2014b) demonstrated that the northern and eastern parts of South Africa (i.e., Gauteng, Mpumalanga, Limpopo and KwaZulu-Natal provinces) are the major local source areas for anthropogenic and biomass burning aerosols. Additionally, Tesfaye et al. (2015) examined the distribution and climatic effects of naturally induced desert dust particles in South Africa.

Kalahari desert covers much of Botswana, eastern parts of Namibia and northern areas of the Northern Cape Province of South Africa. The Namib desert is located across the coastal areas of Namibia. These desert regions are the main source areas of desert dust particles in southern Africa (e.g., Engelstaedter and Washington, 2007; Vickery et al., 2013). Tesfaye et al. (2015) showed that desert dust particles, emitted from aforementioned arid regions, are dispersed towards the South African regions by the well-known southern African anti-cyclonic air mass flow system (Tyson and Preston-Whyte, 2000). Overall, Tesfaye et al. (2014a, 2014b, 2015), as well as other observational and modeling studies (Tummon (2011) and references therein) indicated that due to various natural and anthropogenic activities, the South African atmosphere is burdened by most of the major types of atmospheric aerosols. For instance, Tesfaye et al. (2011) remarked that even if it is spatio-temporally constricted incidence, following the enhancement in south-easterly wind which brows from the surrounding oceans, the coastal areas of South Africa experience the marine aerosol load.

Tesfaye et al. (2014a, 2014b, 2015) have illustrated that the scattering of solar radiation primarily by sulfates and small dust particles results in a reduction of Short-Wave (SW) radiative flux at the surface. Additionally, the SW absorption predominantly by Black Carbon (BC) and partially by dust and Organic Carbon (OC) particles reduce incoming solar radiation reaching the ground via enhancing SW radiative heating within the atmospheric column. Moreover, Tesfaye et al. (2015) showed that the interaction of large size dust particles with Long-Wave (LW) radiation, as well as their ability of emitting thermal radiation, cause the enhancement of incoming LW radiative flux at the surface as well as reduce the LW radiative heating within the troposphere. When we compare the radiative effects of different species of aerosols in South Africa [i.e., by using the simulation results of Tesfaye et al. (2014a, 2014b, 2015)], the maximum radiative influences (both at the surface and within the atmosphere) were caused by desert dust particles. Following the desert dust particles, aerosols that are generated by anthropogenic sectors have radiative influence higher than that of aerosol particles produced from open biomass burning activities. Furthermore, Tesfaye et al. (2014a, 2014b) showed that the total aerosol radiative forcing is not only dependent on physico-optical properties of aerosol constituents but also it is highly reliant on the fractional contributions of each aerosol species to the total aerosol burden.

Aerosol studies in South Africa which are conducted using RegCM4-aerosol modeling approach, such as Tummon et al. (2010), Tummon (2011) and Tesfaye et al. (2014a, 2014b, 2015), provide detailed climate consequences of different radiatively interacting aerosol species. The climatic feedback analysis reported in these studies showed that aerosols induced climatic modifications (especially on cloud fields) were not only dependent on the amount of aerosol loads and their radiation perturbations but were also influenced by the spatio-seasonal variations of different meteorological conditions of the background atmosphere. Overall, these aforementioned studies provided insightful information regarding the spatio-seasonal distribution as well as the detailed analysis on climatic effects of radiatively interactive aerosols which are attributed from particular sources, in and around South Africa.

Assessing climatic influences of different types of atmospheric particulates which are produced from specific sources (activities)