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Mineral dust aerosol distributions, its direct and semi-direct effects over South Africa based on regional climate model simulation

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ABSTRACT

The present contribution investigates the seasonal mean mass distributions, direct and semi-direct climatic effects of desert dust aerosols over South Africa, using the 12 year runs of Regional Climate Model (RegCM4). The results have shown that the desert dust particles which burden the western and southern regions of South Africa are mainly produced from the Kalahari and Namib Desert areas. At the surface and within the atmosphere, the short- and long-wave radiative forcing (RF) of dust showed contrasting effects. However, due to the dust short-wave RF dominant influence, the Net-RF of dust causes reduction on net radiation absorbed by the surface via enhancing radiative heating in the atmosphere. The radiative feedbacks of desert dust particles predominantly result in a positive response on net atmospheric radiative heating rate, Cloud Cover (CC) and cloud liquid water path. The CC enhancement and Net-RF of dust, cooperatively, induce reduction in surface temperature (up to −1.1 K) and surface sensible heat flux (up to −24 W/m^2). The presence of desert dust aerosol also causes boundary layer height reduction, surface pressure enhancement and dynamical changes. Overall, the present contribution underscores the importance of including the effects of wind-eroded dust particles in climate change studies over South Africa.

1. Introduction

Desert dust emission is initiated by different natural processes, such as saltation, which also leads to another process known as sandblasting (e.g., Grini et al., 2002). Once emitted, dust particles can be lifted up into free tropospheric regions through turbulent diffusion and vertical advection, which is called the process of suspension (Zakey et al., 2006). Afterwards, depending on the dynamical situations of the free troposphere, they can be dispersed further away from their source regions. Especially, the fine-mode dust particles can stay in the atmosphere for a week or more (Han and Zender, 2010) and can be easily transported over large distances from their source region (Prospero, 1999; Luo et al., 2003; Engelstaedter et al., 2006). Overall, mineral dust particles are the main aerosol component in and around the arid regions of the world (e.g., Ginoux et al., 2001; Prospero et al., 2002; Tegen et al., 2002). Also, anthropogenic activities induced land surface degradation and plant cover changes, may facilitate the production of wind-eroded dust particles and transportation (e.g., Tegen et al., 2004; Ginoux et al., 2012). Due to the emissions of dust from both natural and anthropogenic activities, it contributes a large portion of aerosol mass to the total mass of aerosols in the troposphere (e.g., Zender et al., 2004). Owing to the high variability of anthropogenic events, the estimation of human activities induced dust particles spatio-temporal distribution is quite difficult. Therefore, the present contribution will focus on the regional distribution and climatic effects of naturally induced desert dust particles.

Soil dust aerosols can substantially influence the Earth's climatic system in several ways. By scattering and absorbing both short- and long-wave radiation, as well as by emitting thermal radiation; dust particles play a significant role in modulating the Earth-atmosphere system radiation budgets (direct effect) (e.g., Weaver et al., 2002; Mallet et al., 2009). Basically, the sign and magnitudes of the dust radiative forcing are controlled by its physico-

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chemical and optical properties [i.e., its concentration, size distribution, mixing state, shape and mineralogical composition (refractive index)] (Wang et al., 2006; Balkanski et al., 2007; McConnell et al., 2008; Osborne et al., 2008; Mishra et al., 2010). The dust aerosol radiative perturbations may consequence several climatic implications, which are known as semi-direct effects (Miller et al., 2004a, 2004b; Yue et al., 2010b and references therein). The semi-direct effect is the overall feedback of the thermal, hydrological and dynamical fields of the climate to the radiative influences of aerosols (Johnson, 2003; Perlwitz and Miller, 2010). Such as, changes in temperature, surface heat and moisture fluxes, cloud cover, precipitation efficiency as well as atmospheric dynamics (e.g., Miller et al., 2004a, 2004b; Yue et al., 2010b; Stanelle et al., 2010; Mallet et al., 2009; Solmon et al., 2012; Tesfaye et al., 2014). Radiatively interactive dust particle induced climatic variable changes, may also modulate the dust production itself [i.e., two way dust–climate interaction] (Perlwitz et al., 2001; Miller et al., 2004a; Stanelle et al., 2010; Yue et al., 2010b). Also, as described in different studies, both direct and semi-direct effects of aerosols occur concurrently (e.g., Johnson, 2003). Thus, contingent on different circumstances, these two effects occasionally may reinforce or offset each other (Johnson, 2003; Tesfaye et al., 2014). Hence, to better understand the overall radiative role of dust aerosols, their direct and semi-direct effects need to be examined together. Usually, upon emission mineral dust particles are hydrophobic. Nevertheless, as they stay in the atmosphere, depending on the meteorological situation and chemical composition of the background atmosphere, dust aerosols may undergo various heterogeneous chemical ageing processes. These processes induce changes in dust aerosol hygroscopicity, physico-optical properties and consequently, their radiative and climatic roles (e.g., Sullivan et al., 2007, 2009). For instance, dust particles which experience chemical ageing, by acting as cloud condensation nuclei, play an important role in modulating the microphysical processes and optical properties of clouds as well as the cloud lifetimes (which is known as an indirect effect) (e.g., Wurzler et al., 2000; Lohmann and Diehl, 2006; Hoose et al., 2008). For additional delineation about the role of dust aerosols in various fields the reader may refer to Mahowald et al. (2010) and references therein.

Due to the role the dust particles play in many environmental processes, assessing different properties of dust aerosols becomes an increasingly intense research topic in many observational and modelling studies. The dust experiments, such as Bodélé Dust Experiment-2005 (BoDEx-2005), provide valuable information about the mechanism of dust emission, transportation and atmospheric processes (e.g., Washington et al., 2006a; Todd et al., 2007; Warren et al., 2007). Also, using different observational data and numerical techniques Washington et al. (2006b) addresses the links among different environmental factors which play important roles in controlling dust production. Various studies which focus on surface and/or airborne *in-situ* characterization of desert dust aerosols offer noteworthy information about the dust aerosol chemical composition, deposition processes, optical properties and source allocation (e.g., Gao and Anderson, 2001; Blanco et al., 2003; O'Hara et al., 2006; McConnell, 2009; Rodríguez et al., 2012 and references therein). Remote sensing measurements have been instrumental in providing long-term trends and vertical distribution of wavelength, mixing state plus climatic condition dependent dust aerosol optical properties (e.g., Eck et al., 1999; Heese et al., 2009; von Hoyningen-Huene et al., 2008; Tesfaye et al., 2011; Vandenbussche et al., 2013). The physico-chemical and optical properties of dust derived from *in-situ* and remote sensing observations are important to quantify the atmospheric processes and radiative influence of dust aerosols with better accuracy (e.g., Dubovik et al., 2000; Solmon et al., 2006). The desert dust source regions across the globe have differences in topography, surface properties and meteorological fields which are vital in governing dust emission processes. Therefore, the soil dust aerosol production and properties exhibit higher spatio-temporal heterogeneities. On a large scale, the analysis of satellite products has increased our knowledge of mineral dust source areas and their geomorphology, desert dust emission rates, dust storm temporal trends and long-range transport (e.g., Prospero et al., 2002; Washington et al., 2003; Koren et al., 2006; Engelstaedter and Washington, 2007a; Bullard et al., 2008; Doherty et al., 2008; Baddock et al., 2009; Ginoux et al., 2012). In addition, different studies such as Engelstaedter and Washington, (2007b) showed the importance of cooperative analysis of satellite derived dust results and meteorological datasets, in understanding the climatic variables and processes which control the dust plume temporal cycle. Further than enhancing our understanding of dust processes and its properties, dust observational studies also provide crucial information for the development of well optimized dust emission schemes in climate models. However, quantifying the large-scale atmospheric processes of dust particles as well as capturing the dust–climate interactions and feedbacks through field experiments or different observation techniques, is very challenging. In this regard, online-coupled desert dust–climate models are a beneficial tool to simulate dust aerosol/chemistry–radiation–climate interactions and feedbacks (e.g., Darmenova et al., 2009; Zhang et al., 2010; Tummon, 2011; Tesfaye et al., 2013). In addition, interactively coupled dust–climate models are essential for estimating the past and projecting the future climatic role of desert dust particles (e.g., Woodward et al., 2005; Mahowald et al., 2006).

The process of desert dust production basically depends on the near-surface dynamics. Thus, its computation involves different meteorological fields such as, surface wind speed as well as land surface characterization; for e.g., soil texture, moisture, the roughness due to the presence of non-erodible elements, vegetation cover and other factors (e.g., Zakey et al., 2006; Darmenova et al., 2009 and references therein). The dust particle atmospheric processes (i.e., transportation, ageing and deposition) are highly reliant on the climatic conditions as well as their physico-chemical properties (e.g., Han and Zender, 2010; Han et al., 2012). Currently, using different level parameterization, several global and regional climate models couple the desert dust aerosol emission and atmospheric processes. Global Models (GMs) has been used to perform dust–climate simulations in order to examine the large-scale climatic variables which controls the dust load, long-range transportation and deposition (e.g., Yue et al., 2009; Ridley et al., 2014 and references therein). Studies such as Maher et al. (2010) and Mahowald et al. (2010) provide important insights on desert dust variability as well as the global links among the dust deposition and its consequential role in biogeochemistry. Likewise, different GM studies offer noteworthy information about the desert dust radiative influences and its sensitivity to the dust particle physico-optical properties (e.g., Colarco et al., 2014; Miller et al., 2004b). The global scale desert dust–climate interactions and feedback mechanisms have also been reported in various other studies (e.g., Miller et al., 2004a, 2004b; Yoshioka et al., 2007; Lau et al., 2009; Kim et al., 2010; Yue et al., 2010b; Mahowald et al., 2011; Rotstayn et al., 2011; Gu et al., 2012; Sajani et al., 2012 and references therein). On the other hand, employing GM, Woodward et al. (2005) reported that in the future due to the climate change-induced desertification, the global burden as well as radiative influences of desert dust particles may considerably increase. Overall, the GM dust–climate simulations provide vital information on large-scale distribution and wide range of environmental roles of desert dust particles in the past, present and predict the future.