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Simulation of African dust properties and radiative effects during the 2015 SHADOW campaign in Senegal

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ABSTRACT

The aim of this work is to estimate optical and radiative properties of dust aerosols and their potential feedbacks on atmospheric properties over Western Africa for the period 20 March–28 April 2015, by using numerical simulations and different sets of remote-sensing and in-situ measurements. Comparisons of simulations made by the on-line coupled meteorological-chemistry model WRF-CHEM with MODIS, AERONET and in-situ observations result in a general agreement for the spatio-temporal variations of aerosol extinction at both local and regional scales. Simulated SSA reached elevated values between 0.88 and 0.96 along the visible/near-infrared in close agreement with AERONET inversions, suggesting the predominance of dust over Western Africa during this specific period. This predominance of dust is confirmed by in-situ measurements of the aerosol size distribution, fitting well with the aerosols size distribution simulated by WRF-CHEM. The impact of this large dust load on the radiative fluxes leads to large modifications of the shortwave and longwave radiative budget both at the ground and at the top of the atmosphere. In return, the response of the atmosphere to these dust-induced radiative changes is the alteration of the surface air temperature and wind fields, with non-negligible impact on the dust emission and transport.

1. Introduction

Aerosols are known to play an important role on climate change by perturbing the radiative equilibrium of the earth's surface (Boucher et al., 2013). This is the so-called aerosol radiative forcing. A positive radiative forcing (increasing energy) tends to warm the earth system while a negative one (decreasing energy) tends to cool it. The aerosol direct radiative forcing is the direct interaction of particles with solar and telluric radiation (Yu et al., 2006; Toll and Männik, 2015). By modifying cloud microphysics, aerosol can also indirectly affect the earth's radiative budget through cloud albedo (first indirect effect) and cloud lifetime (second indirect effect) (Lohmann and Feichter, 2005; Goren and Rosenfeld, 2014). In addition, atmospheric heating by absorbing aerosols can modify the temperature and humidity gradients, thus affecting cloud formation (Wilcox, 2012). This aerosol effect on the radiative budget can, in turn, have an impact on the atmospheric dynamics at regional scale, such as a stabilization of the boundary layer (Péré et al., 2014).

However, our understanding of aerosols properties and their effects on climate remains low (Boucher et al., 2013). Numerical models, space-borne and ground-based monitoring systems are generally used to study aerosol spatial distribution, properties as well as their interactions with the climate system. West Africa is one of the largest sources of mineral dust with an estimation of aerosol generated over this region between 60 and 200 million tons per year (Prospero and Lamb, 2003). At global scale, mineral dust emissions from arid regions represent 40% of the total annual mass of aerosol released in the troposphere (Andreae et al., 2005). West Africa can be affected by biomass burning aerosols and important dust events, especially during the dry season (Marticorena et al., 2010). Many researches on aerosol properties and impacts focused on biomass burning and dust aerosols (Tanré et al., 2003; Mallet et al., 2008; Otto et al., 2009; Agacawak et al., 2015). Such studies showed that mineral dust affect both shortwave (SW) and longwave (LW) radiations, with some potential consequences on the regional climate. For instance, Agacawak et al. (2015) find out that the transport of dust from West Africa to Turkey tends to reduce downward

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SW solar radiation at the surface and at top of the atmosphere (daily mean values of −(62–71) W·m^{-2} and −(29–33) W·m^{-2} respectively) with an overall tendency of mineral particles to cool the Earth-atmosphere system. Those effects are enhanced by dust non-sphericity as shown in Otto et al. (2009). However, the dust radiative effects on the atmosphere still remain uncertain because of difficulties to characterize their transport, vertical distribution and their microphysical and optical properties (Sokolik et al., 2001). For example, the variety of dust size will influence its transport and deposition and hence its radiative and environmental impact (Ryder et al., 2013). Furthermore, the large panel of values for the measured single scattering albedo (from 0.73 to 0.99 at 550 nm, see Knippertz and Stuut, 2014) leads to uncertainties in the sign and magnitude of dust radiative forcing.

In this context, the overall aim of this work is to study aerosol optical and physical properties and their impacts on the radiative budget over West Africa, with a focus over M'Bour (Senegal). This site is interesting because it has been a long-term AERONET station (Derimian et al., 2008; Léon et al., 2009; Mortier et al., 2016) and is frequently overflown by air masses originating from the Sahara that move westward off the African continent. It allows aerosol studies over the most important dust sources in Africa with potentially large radiative effect. For instance, a climatological study by Mortier et al. (2016) revealed that M'Bour is influenced all year-round by desert dust and that up to 38% of the solar clear-sky atmospheric heating is due to aerosols over this site.

We focused our investigations on the aerosol microphysical properties, their direct radiative forcing and their impact on some atmospheric properties (temperature, wind). To achieve such objectives, numerical simulations combined with aerosol microphysical and optical measurements (in situ and remote sensing) have been used. Simulations were conducted by the online coupled meteorology-chemistry meso-scale model WRF-CHEM (Grell et al., 2005). We focused our study on the end of the 2015 dry season (20th March–28th April 2015), when an intensive measurements campaign over M'Bour took place (SHADOW campaign, i.e. Study of Saharan Dust over West Africa, Veselovskii et al., 2016). This paper is organized as follows: the second section presents the methodology including a presentation of the different instruments used for the monitoring of aerosols and a detailed description of the numerical simulations. Results on dust microphysical and optical properties and their direct radiative forcing over West Africa (with a focus over M'Bour) are discussed in the third section. Finally, conclusions and perspectives are given in Section 4.

2. Methodology

To investigate the dust microphysical and optical properties and their direct radiative forcing, an original approach integrating modelling, in situ and remote sensing observations was used. A description of each is given herein.

2.1. The online coupled meteorology-chemistry meso-scale model WRF-CHEM

The Weather Research and Forecasting model (WRF) (Skamarock et al., 2008) is a meso-scale weather model designed for the prediction and analysis of weather. The chemistry module (Grell et al., 2005) was developed and incorporated into the WRF meteorological model so that both models run interactively. Some applications of the WRF-CHEM numerical system are analysis of emission, transport, mixing, and chemical transformation of trace gases and aerosols and their possible interactions with the meteorology. In this study, the version 3.5.1 of the model was used and the contribution of dust and sea-salt only has been simulated. Here are the following options that have been chosen for the main physical and chemical processes (summarized in Table 1): The sophisticated Lin et al.'s (1983) scheme including ice, snow and graupel processes for the microphysics module, the Grell-3D scheme for the sub-grid scale effects of convective and shallow clouds (Grell and Devenyi, 2002), the NOAH land surface module of Chen and Dudhia (2001) with soil temperature and moisture in four layers, fractional snow cover and frozen soil physics, and the Mellor-Yamada-Janjic planetary boundary layer scheme (Janjic, 2002) for vertical sub-grid-scale fluxes due to eddy transports in the whole atmospheric column. For calculation of shortwave radiation, the Goddard model (Chou and Suarez, 1994), with 11 spectral bands from 0.2 to 6 μm, is used. Previous studies that evaluated the Goddard shortwave radiative transfer simulations with solar measurements have demonstrated their skills to simulate surface visible radiation, especially under aerosol pollution conditions (Fast et al., 2006; Mashayekhi et al., 2009; Péré et al., 2011). For long-wave radiation, the Rapid Radiative Transfer model (RRTM) (Mlawer et al., 1997), with 16 spectral bands from 6 to 1000 μm, was chosen.

Table 1
Main physical and chemical options of WRF-CHEM used in this study.

Options	Name list variable	Module
Microphysics	mp-physics = 2	Lin et al. (1983)
Cumulus	cu-physics = 5	Grell-3D
Land surface	sf-surface-physics = 2	NOAH land-surface
Boundary layer	bl-pbl-physics = 2	Mellor-Yamada-Janjic
Shortwave radiation	ra-sw-physics = 2	Goddard
Longwave radiation	ra-lw-physics = 1	RRTM
Chemistry	chem-opt = 300	GOCART
Dust emission	dust-opt = 3	GOCART-AFWA

The Goddard Chemistry Aerosol Radiation and Transport (GOCART) is used to simulate dust life cycle. Dust particles are considered in the model in 5 size bins with geometric radius of 0.05, 1.4, 2.4, 4.5, and 8 μm. The main parameters influencing dust emission are the threshold friction velocity (minimum wind speed at which a given particle begins to move) and the horizontal/vertical dust flux combining both the saltation and sandblasting. Saltation corresponds to horizontal flux of soil particles, which mainly depends on surface wind velocity and local surface roughness length. Particles in saltation interact then with soil aggregates leading to their suspension, this effect is called sandblasting. These dust physical processes are simulated with the GOCART-AFWA scheme based on parametrizations developed by Marticorena and Bergametti (1995). Improvements have been recently made and implemented in this version of WRF such as changes to the saltation algorithm and emitted particle size distribution, as well as modifications to the method for determining soil moisture impact on the dust lifting threshold (Jones et al., 2012). The dust optical properties, i.e aerosol optical thickness (AOT), single scattering albedo (SSA) and asymmetry parameter (g) are computed at 300 nm, 400 nm, 600 nm and 999 nm according to the methodology described in details by Barnard et al. (2010). The model also provides the aerosol extinction coefficient at 550 nm. The AOT quantifies the extinction of radiation by aerosols integrated over the whole atmospheric column. The SSA is the ratio between the scattering and the extinction (scattering + absorption) coefficients. It gives information on the absorption properties of particles. The asymmetry parameter is defined as the cosine weighted averaged of the phase function, where the phase function is the probability of radiation being scattered in a given direction. g varies from −1 for a complete backward scattering and +1 for a complete forward scattering. Typical values for aerosols are comprised between 0 and 1.

In the WRF-CHEM model, the calculation of the dust emission is dependent of meteorological factors (such as surface wind speed) and the soil characteristics of the dust source that can vary from a region to another. A detailed representation of the dust source regions, in terms of soil texture and erodibility, is taken into account through a land surface database at a $0.25 \times 0.25^{\circ}$ resolution obtained from the Advanced Very High-Resolution-Radiometer data (Defries and Townshend, 1994). However, no particle mineral composition is explicitly simulated by the WRF-CHEM model and dust aerosols are