

Dust Source, Vertical Profile and Climate Impact by RegCM3 Regional Climate Model over West Africa during 2006

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Abstract

This study aims to evaluate dust impact on climate parameters over the Sahel region by RegCM3 regional model during 2006. Indeed, aerosols are one of the main uncertainties in climate models. The aerosol optical depth (AOD) derived from RegCM3 model has been validated with various observed datasets. The aerosol sources are identified over North Algeria and East of Sahel (Bodele depression). Discrepancies are noted when considering dust temporal and spatial distribution. Dust season extends between March and October, with two peaks of AOD recorded in March (spring) and June (summer). The dust vertical distribution showed that the mineral aerosol layer is located between 850 hPa and 300 hPa (1.5 km to 7 km). The RegCM3 model simulates fairly well the transport in the upper layers, especially in the Saharan Air Layer (SAL) during the summer. However, RegCM3 simulates poorly the transport and sedimentation of particles in the lower layers (below 2 km). The investigation of dust radiative impact shows a general cooling. The maximum of radiative forcing is located around 18° N - 20° N, with values of about -80 W/m^2 in June - August (JJA) and -40 W/m² at the surface during March - May (MAM). This study also showed the indirect effect of dust with a decrease in precipitation about -0.7 mm/day around 15 - 20°N during the rainy season.

Keywords

Dust, RegCM3, Sahel, Lidar, AERONET, Temperature, Rainfall, West Africa

1. Introduction

The African continent is the biggest dust source of the world with 40% of global

emissions when considering tropospheric aerosols [1] [2] [3] [4] [5] and particles from biomass burning. The West African region is characterized by dust outbreaks throughout the year [6] and biomass burning in winter [7]. The African continent is not well equipped in terms of measurement tools for assessing the climate and its evolution. However, it is the continent where climate change impacts are felt the most (drought in 1970). Indeed, global models do not highlight regional specificities such as Sahara dust. Therefore, to better understand and study the variations of climate over Africa, the use of regional climate models is of great importance. These types of models have the advantage of using fine resolutions and taking into account local meteorological processes.

In West Africa, the years of continuous rain deficits are characterized by abnormalities in the dynamics of West African monsoon system, and a continuous increase in dust emissions. Several measurement campaigns (ABAT, AMMA) were conducted to study the impact of dust on regional climate [8]. In this study, we use the regional climate model RegCM3 to assess the impact of desert aerosols on climate over the Sahel in 2006. The model outputs have been validated with ground instruments and satellite observations. This validation study is followed by an estimation of dust impact on Sahel climate.

2. Data and Methodology

2.1. The Regional Climate Model RegCM3

Unlike the regional climate models, many global models were developed to simulate the summer cycle of desert dust [9] [10] [11]. Few dust studies using the regional climate models are available in the literature [12]. RegCM3 is a regional hydrostatic model developed at Abdu Salam Centre for Theoretical Physics (ICTP) [13]. Zakey *et al.* (2006) [14] have developed and tested in 2004 a dust module included in the ICTP Regional Climate RegCM3 [13] [15]. This dust module is widely described in [14] [16]. In this study, two sets of runs have been done: a control run (no dust effects, AOD = 0) and a dust run which takes into account dust radiative effects. The resolution of the model is 60 km.

2.2. Validation Data

AERONET network data are the main validation products used in this study [7]. The stations (Figure 1) considered are: Banizoumbou (Niger), Agoufou (Mali), Ouagadougou (Burkina Faso) and Dakar (Senegal). AERONET instruments (photometers) provide the spectral optical thickness AT 550 nm. The vertical distribution of dust is validated by the profiles of the lidar stationed in Dakar. The Moderate Resolution Imaging Spectrometer (MODIS) [17] [18] [19], the Multi-Angle Imaging Spectro Radiometer (MISR) sensors [20] and the Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) are used to characterize the dust seasonal cycle [21].



Figure 1. Representation of the study area (West Africa) with AERONET stations used.

3. Results and Discussion

3.1. Validation of RegCM3 Regional Climate Model

3.1.1. Annual Seasonal and Daily Pattern of Dust

We begin by showing in **Figure 2**, the annual average of aerosol optical depth (AOD) obtained with models (RegCM3 and GOCART) and by two radiometers on orbit (MODIS and MISR) in 2006. This annual AOD is used to identify the aerosol sources. Two source areas have been identified: one is the border between Mauritania (East) and North-Western Mali and the other is from Niger (North-East) to the Western of Chad near Bodele depression. These maximum are located between 15 and 20°N latitude and longitude about 8°W according to RegCM3; then GOCART and MISR locate these sources in the band 15°N - 18°N and 15°E. Besides MODIS, all other remote sensing sensors indicate clearly these source areas. And finally, we note that the models tend to overestimate the optical thickness (observations) especially for RegCM3.

Next we examine, the dust seasonal cycle in West Africa. **Figure 3** shows the seasonal (March-April-May and June-July-August) cycle of AOD in West Africa using RegCM3 model and MISR measurements. Sources of aerosols (dust maximum) are mainly located at the border of Mauritania/Mali, southern Algeria and near to the Bodele depression (Chad). The seasonal distribution shows the predominance of dust during the wet season compared to dry season. **Table 1** summarizes the mean annual AOD (550 nm) to MODIS, AERONET and RegCM3



Figure 2. Annual averages of aerosols optical depth derived from models and observations in 2006 (Dust sources in Africa). The left figures represent the MISR observations (a) and MODIS (b); while those on the right are model outputs RegCM3 (c) and GOCART (d).

Table 1. Annuel average values of AOD from in situ measurement (AERONET), satellite sensor (MODIS) and model (RegCM3) for Banizoumbou, Agoufou, Ouagadougou and Dakar stations.

AOD	AERONET	MODIS	RegCM3
Banizoubou	0.54	0.31	0.36
Agoufou	0.53	0.37	0.28
Ouagadougou	0.48	0.35	0.45
Dakar	0.49	0.40	0.50

for four stations in West Africa. Indeed, RegCM3 underestimates the dust loading compared to AERONET for the Eastern stations (Banizoumbou, Ouagadougou) and overestimates it in western stations (Dakar, Cape Verde). Overall, model results range between in situ measurements and satellite observations. For



Figure 3. Seasonal cycle of the aerosol in Sahel using MISR sensor and RegCM3 output during 2006. Comparison between the dry (MAM) and rainy season (JJA).

instance, in Banizoumbou, the annual average of AOD is 0.54 for AERONET, 0.31 for MODIS and 0.36 for RegCM3.

In this section, we perform the validation of aerosol daily distribution (AOD 550 nm) from the Julian day number. For this, we compare the AERONET in situ data with that of RegCM3 model for each of the stations in the region. Consequently, **Figure 4** shows the daily cycle of AOD observed (AERONET) and simulated (RegCM3) in 2006. From East to West the locations are the AOD: at Banizoumbou (Niger), Ouagadougou (Burkina-Faso), Agoufou (Mali), Dakar (Senegal) and Sal (Cape Verde). Overall, RegCM3 follows the same trend as observations for these five stations. In agreement with [22] [23], we note that the model slightly overestimates the observation in the Western stations (Dakar and Capo Verde) and underestimated it for Eastern stations (Banizoumbou, Agoufou and Ouagadougou). In the continental stations (Eastern station), the model does not take into account the proximity of others sources of dust. These



Figure 4. AOD daily evolution (Julian Day Number) in West Africa in 2006. Comparison between the AERONET observations (black) and RegCM3 simulation (red) at Banizoumbou (Niger), Ouagadougou (Burkina Fasso), Agoufou (Mali), Dakar (Senegal) and Sal (Cape Verde) stations.

are sources in the North (Northern Mauritania to Tamanrasset in Algeria) which may produce dust transportable toward Banizoumbou and Ouagadougou. Indeed, these stations are the nearest sources of biomass burning which may explain their presence. The high Angstrom coefficient shows that the biomass burning is more important in East than in the West of this region. A defect in the modeling of transport and deposition of dust may explain the overestimation of observation in the Western stations (Dakar and Cape. Verde). The statistical study shows disparities from east to west. The correlations are best on the coastal (Western) stations with scores of about 70% in Dakar and 51% in Sal (Cape Verde). This study is based on 150 days in Cape Verde and 277 days of observation in Dakar. The worst correlation is noted at Banizoumbou (39%) with 324 AERONET observations days available. The correlation was 40% in Ouagadougou and 50% in Agoufou. For instance, during the dry season in 2006, a maximum of AOD is clearly visible on all stations between 9 and 14 March 2006 (JD = 69). The RegCM3 model is in good agreement with AERONET for this event.

3.1.2. Dust Vertical Distribution

In the following, we study the vertical distribution of dust with the model. **Figure 5** shows the monthly cross section for RegCM3 extinction coefficient in Banizoumbou, Ouagadougou, Agoufou and Dakar stations. The results show that the dust extends from the surface to 300 hpa (9 km). The maximum of extinction is noted in spring and summer. Also, we observe two peaks in aerosol extinction during March and July for all stations. The Eastern stations (Banizoumbou and



Figure 5. Monthly vertical cross section of aerosol extinction for different stations (Banizoumbou, Ouagadougou, Agoufou et de Dakar) by RegCM3 in West Africa during 2006.

Ouagadougou) are more affected by dust in March with an aerosol extinction value of the order of 0.08 km¹ and these maximums are located in the lower levels around 850 hPa (1.4 km). However, the western stations are characterized in June (summer) by a maximum of dust located in the Saharan Air Layer toward 700 hPa (9 km).

To validate these vertical profiles, we represent in **Figure 6** a comparison between RegCM3 simulation and the Lidar observation in Dakar. Overall, the model underestimated the measurements. In March, the transport of dust occurs



Figure 6. Comparison between monthly observed extinction profiles (Lidar retrieval) and simulated by RegCM3 at Mbour (Dakar) in 2006.

in the lower layers (1 - 2 km) and the model has difficulties to reproduce this lower-layer transport. During the wet season (June), RegCM3 simulates fairly well the aerosol layer located in the Saharan Air Layer (3 - 5 km). In January (winter), the Lidar detected two aerosol layers above Dakar. The first is located around 1 km while the second around 2 km. However, the model simulated only those located in the low layer at 1 km. Recent studies have shown that this layer is composed of biomass burning aerosols [18] [22]. Consequently, February 2006 is characterized by an anomaly in AOD that could be due to a lack of transport in the lower layers [18]. However, RegCM3 does not show this anomaly of air masses transport and simulate a layer between 1.5 and 3 km with a maximum suppression of 0.08 km¹.

For spring, the lidar has only worked for two months (March and April). In March, the model simulates a dust layer between 0.5 and 3.5 km with an extinction maximum of 0.14 km¹. Because of a transport to a lower level, the Lidar is between 1.5 and 2.5 km with a maximum extinction of about 0.22 km¹. However, RegCM3 simulates the data from April quite well. The dust layer is located, for the model and measurement, between 1 and 4 km. We note that the maximum of aerosol extinction observed (0.16 km¹) is twice as important as the RegCM3 simulation (0.08 km¹). In April the model simulates quite well the level of aerosol transport while underestimating the total AOD.

June was the month with the most important dust loading in Mbour in 2006, with a maximum extinction of 0.22 km¹ located at 3 km in the SAL (Saharan Air

Layer). The Angstrom coefficient measured during month shows clearly a dust layer located between 2 and 5 km [21]. RegCM3 simulates well the shape of dust extinction profile in June. However, it detects dust concentrations below those of Lidar. The model estimates the maximum of extinction at 0.012 km¹. From July to August, the model simulates very well the dust layer between 2 and 5 km. The extinction maximums are detected for both products (RegCM3 and Lidar) with a value of 0.12 km¹ in July and 0.10 km¹ in August located around 3.5 km. However, aerosols in the lower layer are not detected by the model. The same analysis is reproduced in autumn than in summer. Finally, the analysis cannot be made in the month of December because of unavailable data.

3.2. Dust Climate Impact by RegCM3 Regional Climate Model

In recent decades, several efforts were made to determine the radiative impact of dust on climate in West Africa [24]-[33].

Figure 7 shows the radiative impact of dust (shortwave) at the surface during



Figure 7. Dust radiative forcing over Sahel in 2006. Comparison between dry (MAM) and wet season (JJA) using RegCM3. (a) Radiation budget at the surface (left) and (b) Radiation budget at the height of atmosphere (right).

the dry season (left) and the wet season (right). This study was conducted to the surface (BOA) and the top of the atmosphere (TOA). Overall, it shows cooling in this region with an average radiative forcing of about -35 W/m^2 on the surface. Forcing is more important during the wet season than dry season to the surface. In dry season, the maximum is located north of the Mauritania-Mali border (20°N) with a forcing of about -45 W/m^2 . The explanation for this maximum in Spring (MAM) results in the fact that the sources of aerosols are very active in this season. However, the maximum of cooling is registered near the source of dust in the wet season with a radiative forcing of about -80 W/m^2 at the Mali/Mauritania border. This maximum is due to the coupled effects of Harmattan and convection in the summer [34].

Ultimately, we examine the impact of dust on meteorological parameters such as precipitation and surface temperature. **Figure 8** illustrates the impact of dust on surface temperature (left) and rainfall (right) over 17° W and 20° N during the wet season (JJA) of the latitudes (Lon = 17° W - 10° E). The cooling causes a decrease in surface temperature over Sahel region. The maximum cooling is located near 21° N with an intensity about to -1.7° K. The increase of dust (can serve as cloud condensation nuclei) favored the indirect effect. Rainfall has decreased by 0.6 mm/day between 5° N and 15° N during JJA. These results are consistent with recent work indicating that the dust causes a reduction in temperature [35] [36] [37] by their direct effect and a drought (rain reduction) of their indirect effect [38] [39] [40].



Figure 8. Impact of dust on the surface temperature (red in kelvin) and rainfall (green in mm/day) in West Africa during summer 2006 (JJA). Difference between dusty and no-dusty atmosphere as a function of the latitudes (Lon = 17° W - 10° E) using RegCM3.

4. Conclusion

RegCM3 regional model was used to simulate and evaluate the impact of dust on climate parameters over Sahel. Ground (AERONET and LIDAR) and satellite (MODIS, MISR) measurements are used to validate this model. Dust season extends between March and October. There were two maxima: one during the dry season (March) and another during the wet season (July). The dust is located in the lower layers (1 - 2 km) in the dry season and in the Saharan Air Layer (3 - 5 km) during the boreal summer. However, the model reproduces poorly the transport and sedimentation of dust in the lower layers (<2 km) mainly in dry season. Dust impact on climate found these particles favored a cooling. The maximum in radiative forcing is located around 18°N - 20°N, with values of about -80 W/m² in June - July - August (JJA) and -40 W/m² at the surface during March-April-May (MAM). Dust induces a reduction of rainfall in the order of about -0.65 mm/day and the surface temperature of -1.9°K near 15°N during the rainy season. And finally, this study has shown that proliferation of dust will increase à probability of drought in Sahel. Nevertheless, this model has difficulty in reproducing the dust in the atmosphere low layers. Therefore it is not suitable for air pollution studies.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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