GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L24705, doi:10.1029/2008GL035900, 2008

Dust aerosol impact on regional precipitation over western Africa, mechanisms and sensitivity to absorption properties

Fabien Solmon,[1] Marc Mallet,[1] Nellie Elguindi,[1] Filippo Giorgi,[2] Ashraf Zakey,[2] and Abdourahamane Konaré[3]

Received 4 September 2008; revised 6 November 2008; accepted 11 November 2008; published 27 December 2008.

[1] We investigate the climatic impact of shortwave and longwave radiative forcing of Saharan dust on the West African monsoon and Sahel precipitation using a regional climate model (RCM) interactively coupled to a dust model and running for the period 1996–2006. Two competing effects are found. First a reduction of monsoon intensity in the lower troposphere induced by the dust surface cooling causes a reduction of precipitation, and second an 'elevated heat pump effect' in the higher troposphere induced by the dust diabatic warming causes an increase of precipitation. In the standard model configuration, the net impact of these effects is a reduction of precipitation over most of the Sahelian region (by about 8% on average) except over a Northern Sahel - Southern Sahara band, where precipitation increases. These patterns are very sensitive to the dust absorbing properties, which modulate the intensity of the patterns and the boundary between enhanced and decreased precipitation areas. Finally we show that taking into account dust in the RCM could reduce the model bias compared to available observations. **Citation:** Solmon, F., M. Mallet, N. Elguindi, F. Giorgi, A. Zakey, and A. Konaré (2008), Dust aerosol impact on regional precipitation over western Africa, mechanisms and sensitivity to absorption properties, *Geophys. Res. Lett.*, *35*, L24705, doi:10.1029/2008GL035900.

1. Introduction

[2] Dust aerosol direct radiative effects are thought to be important in modulating global and regional climate. Recent studies over West Africa and based on climate models suggest significant effects of dust on the West African monsoon (WAM) development and Sahelian precipitation [*Yoshioka et al.*, 2007; *Konaré et al.*, 2008; *Miller et al.*, 2004; *Lau and Kim*, 2006]. One remarkable fact emerging from these studies is that no clear definitive consensus has been reached on whether the atmospheric feedbacks associated with the presence of dust are more likely to increase or decrease precipitation over the Sahelian region. One of the main reasons for such contrasting arguments lies in the difficulty to accurately represent the regional radiative forcing associated to dust aerosol [*Balkanski et al.*, 2007]. This forcing occurs at the surface and within the atmosphere and can trigger some differential warming/cooling effects and thus contrasting climatic responses. Dust radiative forcing occurs in the short wave (SW or solar) and long wave (LW or thermal) spectral regions and depends on the surface albedo, the presence of clouds and the dust spatial distribution and optical properties [*Liao and Seinfeld*, 1998].

[3] Dust optical properties depend on particle size distribution, particle shape and absorbing/scattering properties (refractive index). Different measurements show that these factors are extremely variable and hence very difficult to represent in climate models [*Balkanski et al.*, 2007]. Published dust particle single scattering albedo (SSA) values used to characterize the diffusive or absorbing nature of dust, are highly variable. Recent in situ measurements [*Osborne et al.*, 2008; *Dubovik et al.*, 2002; *McConnell et al.*, 2008; *Tegen et al.*, 2006] report high values of Saharan dust accumulation mode SSA, ranging from 0.95 to 0.99 (at ~500 nm). From satellite measurements, *Tanré et al.* [2001] estimate Sahara bulk dust SSA around 0.97 ± 0.02 (at 550 nm). These latter estimates contrast with lower bulk SSA values reported in the range 0.75–0.95 (at ~500 nm) [*Otto et al.*, 2007; *Slingo et al.*, 2006; *Raut and Chazette*, 2008; *Haywood et al.*, 2001]. The dust source mineralogy (iron oxide content), dust coating by absorbing aerosol (e.g., biomass burning), size distribution of particles and measurement techniques are all factors that contribute to the variability of observations. For example, *McConnell et al.* [2008] showed that the addition of the coarse mode in dust SSA retrieval induced a significant change from 0.98 to 0.90 (at 550 nm).

[4] Many studies have detailed the impact of dust absorption properties on radiative forcing [*Balkanski et al.*, 2007; *Wang et al.*, 2006; *Li et al.*, 2004]. Fewer have however focused on the characterization of possible climate responses to this variability, especially concerning regional scale precipitation [*Rodwell and Jung*, 2008; *Miller et al.*, 2004].

[5] Our objectives are (i) to study the regional interactions between dust aerosol, West African Monsoon (WAM) and Sahelian precipitation using a regional climate model (RCM), (ii) to assess whether the RCM simulations are improved compared to observations when dust aerosols are explicitly accounted for, and (iii) to study the impact of variability in estimates of dust absorption properties on WAM-dust interactions.

2. Simulation Setup

[6] The RCM used in this work is the third generation version of the regional modeling system RegCM [*Giorgi et al.*, 1993; *Pal et al.*, 2007] which has notably been applied over West Africa by *Jenkins et al.* [2005].

[1]Laboratoire d'Aérologie, Université de Toulouse, Toulouse, France.
[2]Earth System Physics, Abdus Salam International Center for Theoretical Physics, Trieste, Italy.
[3]Laboratoire de Physique de l'Atmosphère, Université de Cocody, Abidjan, Côte d'Ivoire.

0094-8276/08/2008GL035900$05.00

Table 1. Standard Dust SW Optical Properties for the RegCM Radiation Scheme Visible Band[a]

Dust Bins Size Diameter (μm)	K_{ext} ($m^2.g^{-1}$)	g	SSA
0.01 – 1	2.45	0.71	0.95
1 – 2.5	0.85	0.76	0.89
2.5 – 5	0.38	0.81	0.80
5 – 20	0.17	0.87	0.70

[a]350 – 640 nm. See Table S1 for details. A sensitivity study is performed by modifying standard SSA bin values of +5 and −5%.

[7] An on-line dust scheme is included in RegCM, accounting for emission, transport and deposition of four particle size-bins [*Zakey et al.*, 2006]. Standard dust SW optical properties are listed in Table 1. The dust LW emissivity and absorptivity are calculated using prognostic dust bin concentrations, LW refractive indices and absorption cross sections consistent with *Wang et al.* [2006]. Inclusion of the dust LW forcing in RegCM complement the study of *Konaré et al.* [2008] which was based on SW forcing only.

[8] Regional simulations for the period 1996–2006 are performed over an African domain (Figure 1) at 60 km horizontal resolution using the NCEP reanalysis as boundary conditions. Only seasonal June, July, August (JJA) averages are discussed here. Simulated dust aerosol optical depths (AOD) (Figure 1b) have been previously validated using satellite and ground based photometer data [*Zakey et al.*, 2006; *Konaré et al.*, 2008] and won't be further discussed here.

[9] In order to characterize the impact of dust on the WAM and its dependence on the dust SSA estimate, we perform a set of simulations including: (i) a control simulation with no dust effects (NODUST), (ii) a simulation where the dust scheme is activated and standard optical properties are used (DUST) and (iii) two sets of simulation where the dust SSA is modified (see section 4).

3. Dust Regional Climatic Impact on WAM and Precipitation

3.1. Radiative Forcing

[10] Figure 1a displays the clear sky top of the atmosphere dust radiative forcing (SW + LW TOARF) for the standard simulation. The TOARF measures the radiative cooling or warming effect of dust on the surface-atmosphere system before any climatic adjustment takes place. Over the desert region, the TOARF is positive or close to zero as a result of high surface albedo values, which reduce the SW radiative forcing. Moreover, large dust loads (Figure 1b) and high temperatures in the Saharan dust source regions contribute to a maximum of LW absorption/emission and a positive TOARF. The change of the TOARF sign along 15N (Figure 1a) is due to a sharp decrease of surface albedo between desert and savannah land cover type and a decrease

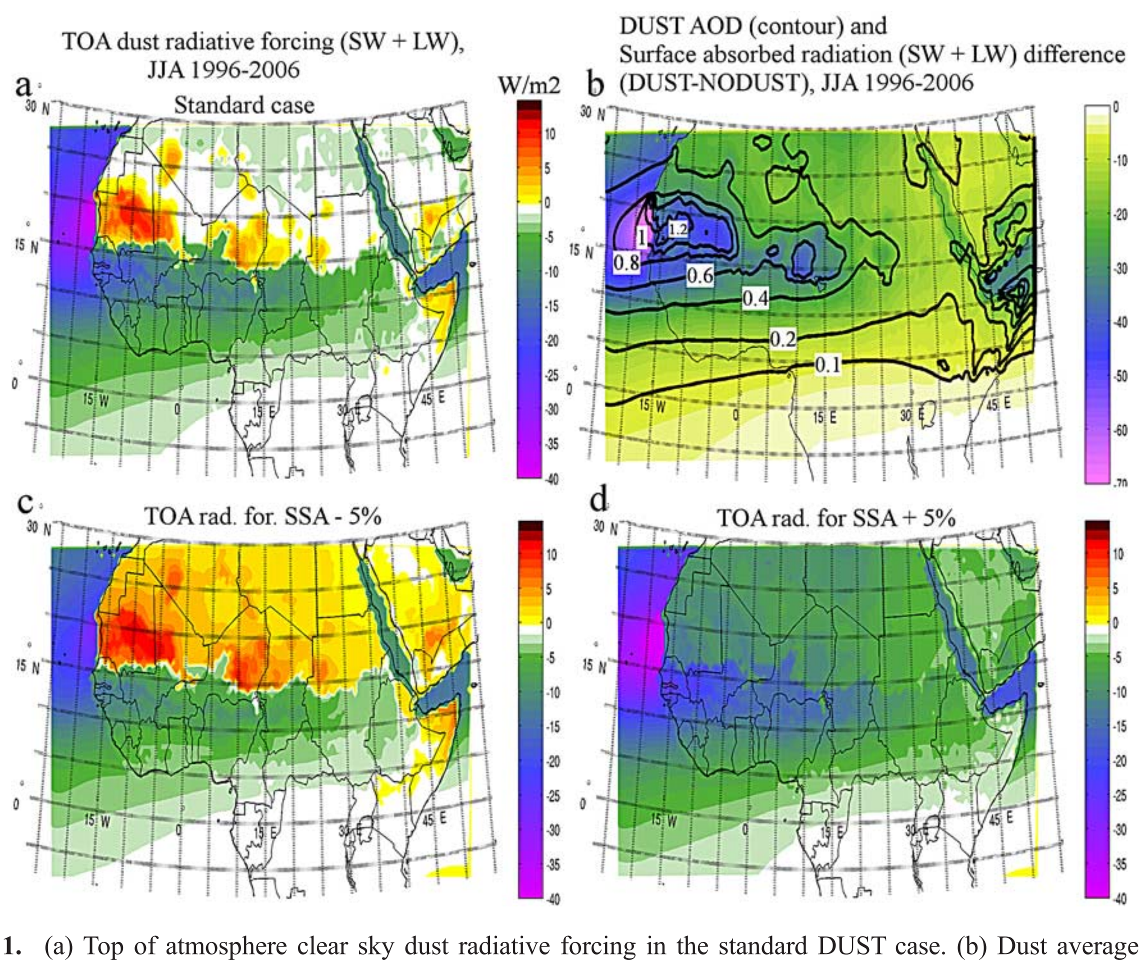

Figure 1. (a) Top of atmosphere clear sky dust radiative forcing in the standard DUST case. (b) Dust average aerosol optical depth (contour) and surface forcing defined by surface absorbed radiation (SW + LW) difference DUST − NODUST. (c) TOA radiative forcing for standard case SSA − 5%. (d) TOA radiative forcing for standard case SSA + 5%.

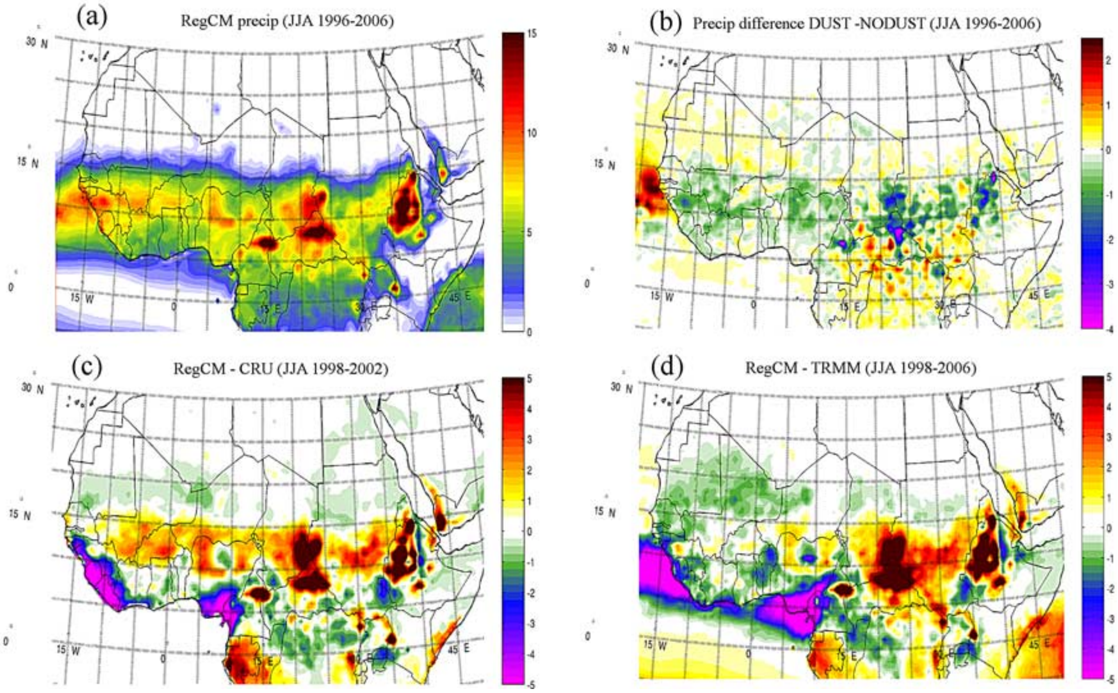

Figure 2. (a) Average precipitation rate simulated by RegCM (mm/day, NODUST). (b) Precipitation difference between DUST and NODUST simulations. (c) Precipitation bias compared to CRU data (NODUST-CRU). (d) Precipitation bias compared to TRMM data.

of average dust load away from the source regions. Overall, the simulated values of TOARF are consistent with the *Balkanski et al.* [2007] updated estimates. Because of lower surface albedos, the TOA SW forcing is more effective over the ocean, where it can reach -35 w.m^{-2} for AOD values between 0.8 and 1 consistent with observations [*Li et al.*, 2004].

[11] The surface absorbed radiative forcing (SW + LW) is overall negative (Figure 1b) and indicates a strong average surface cooling by dust, maximum in regions of large AOD. This cooling is due to a strong attenuation of the surface incoming SW radiation, and this effect offsets the LW surface warming consistently with observations [*Slingo et al.*, 2006].

3.2. Impact of Dust on Average Monsoon Circulation and Precipitations

[12] The impact of dust aerosol on the WAM is estimated by comparing the NODUST and DUST experiments. Figures 2a and 2b show the average precipitation pattern for the NODUST case and the precipitation difference when dust is accounted for. Figure 3d displays a meridional cross section of precipitation rate difference averaged over a 15W–15E band.

[13] The main effect of dust radiative forcing is a reduction of simulated precipitation over the Sahel region from 5N to 15N (Figures 2b and 3d). The decrease of precipitation is associated with a meridional differential circulation opposite to the normal monsoon circulation in the lower troposphere (0$\sim$4000 m) and intensified subsidence between 15 and 20N (Figures 3a and 3d). These features illustrate an average decrease of the ‘monsoon pump intensity’ induced by dust effects. We also note that in the lower troposphere (Figure 3a) the average cloud liquid water is reduced in the middle troposphere when dust is accounted for. This reduction of cloud thickness is consistent with the decrease of precipitation. These results are in line with the argument that the dust surface cooling and the associated reduction of surface energy flux, moist static energy meridional gradient and convection over the Sahel are the dominant mechanisms leading to a reduction of precipitation [*Konaré et al.*, 2008; *Yoshioka et al.*, 2007; *Paeth and Feichter*, 2005].

[14] However, in the middle to upper troposphere (above 4000 m), we note that the differential circulation (Figure 3a) shows an ascendant circulation pattern similar to the ‘elevated heat pump’ mechanism proposed by *Lau and Kim* [2006] over India. This pattern is likely to result from dust atmospheric diabatic heating (see also section 4), and is associated with an increase of upper troposphere cloud water mixing ratio which is more pronounced north of 16N (Figure 3a).

[15] Regionally, the overall effect of dust on precipitation is results from these two ‘competing’ circulation branches. In our standard DUST case, the ‘anti monsoon circulation’ associated with lower cloud and precipitation reduction is dominant up to 17N. North of $\sim$17N, a precipitation enhancement is obtained as a result of the elevated heat pump branch (Figures 1b and 3e).

[16] As discussed and illustrated in the auxiliary material the African easterly jet intensity tends to be enhanced and shifted southward when dust are accounted for.[1]

3.3. Dust Effect on the Precipitation Bias

[17] Can the effects linked to dust explain some of the model biases? To address this question, we compare in

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035900.

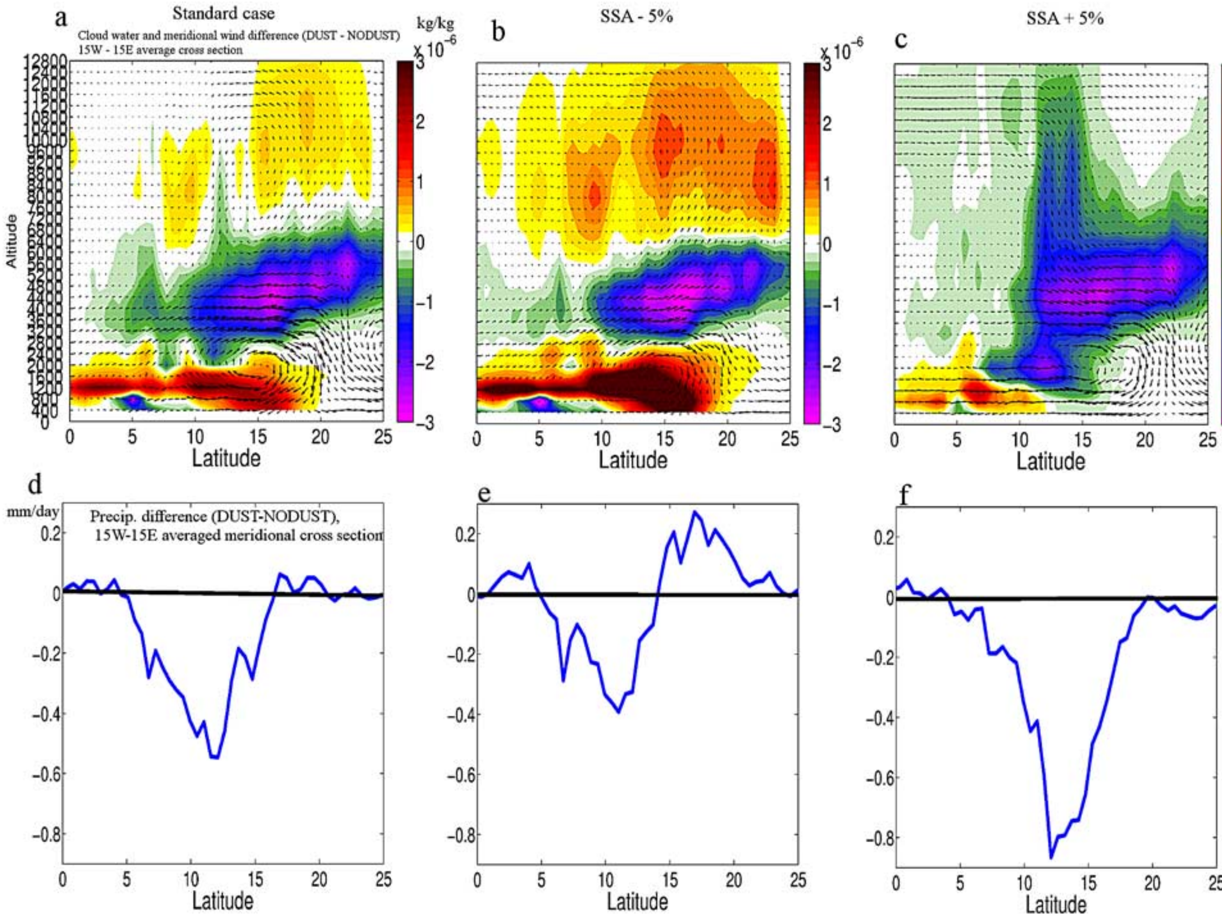

Figure 3. Differential meridional circulation and cloud water mixing ratio calculated between dust (DUST) and control (NODUST) cases for JJA 1996–2006. (a) DUST standard case, (b) DUST (SSA − 5%) case, (c) DUST (SSA + 5%) case. (d) DUST − NODUST precipitation difference meridional cross section. (e) Same as Figure 3d but for SSA + 5%. (f) Same as Figure 3d but for SSA − 5%. Meridional cross sections represent a −15 + 15 longitudinal band average.

Figure 2 and Table 2 the DUST − NODUST precipitation difference with the model bias in the NODUST case relative to both the CRU observations for the period 1996–2002 and TRMM blended satellite data [*Nicholson et al.*, 2003] for the period 1998–2006.

[18] From 5 to 10N, the model underestimates precipitation compared to both the CRU and TRMM data, with the strongest biases over the coastal areas of Guinea and Nigeria. Despite a slight enhancement of precipitation in the DUST simulation over the Guinea gulf coastal region (Figure 3b), there is no obvious bias improvement when dust is accounted for (Table 1). Reasons for model biases over this region could lie in the surface parameterization and convection scheme (A. L. Steiner et al., Land surface coupling in regional climate simulations of the West African monsoon, submitted to *Climate Dynamics*, 2008) and are not discussed further here.

Table 2. Comparison of Model Precipitation Bias and Effect of Dust on Precipitation[a]

Region (15W–15E Box)	Bias (mm/day and %)	(DUST–NODUST) (mm/day and %)	Improvement?
		CRU	
5N–10N	−1.23 (−20.3%)	−0.18 (−3.0%)	no
10N–17N	+1.09 (+20%)	−0.42 (−7.9%)	yes
17N–20N	−0.23 (+41%)	+0.04 (+7.4%)	yes
		TRMM	
5N–10N	−1.23 (−24%)	−0.19 (−3.8%)	no
10N–17N	+0.06 (+1.4%)	−0.28 (−6.1%)	yes
17N–20N	−0.41 (−92%)	+0.05 (+11.3%)	yes

[a]Quantities are calculated for 3 bands of latitude and represent a 15W–15E longitude average. Bias is calculated with regards to CRU (1996–2002) and TRMM (1998–2006) data as NODUST—OBS. Normalised biases, calculated as (NODUST—OBS) / NODUST, are also given in percent. DUST-NODUST precipitation differences are averaged over the corresponding CRU or TRMM observation years. Relative differences are calculated as (DUST-NODUST) / NODUST.

[19] From 10 to 15∼16 N, the comparison with CRU data shows a marked precipitation overestimation in the NODUST experiment, which is also found compared to the TRMM data although less pronounced over the western portions of Africa. For this region, the DUST-NODUST precipitation difference shows a matching inverse spatial pattern, i.e., a precipitation decrease (section 3.2). Dust effects over the Sahelian region induce an ∼8% precipitation decrease, which partially compensates the −20% bias based on the CRU data (Table 2). This implies a ∼40% reduction of the bias by dust effects. This improvement is less obvious when comparing simulations and TRMM data over the WAM domain (Table 2 and Figures 2b and 2d).

[20] The 17 to 20N region shows little precipitation in both model and observations. However, the NODUST run underestimates significantly precipitation there compared to observations (Table 2 and Figures 3c and 3d), and over this arid band dust induces enhanced precipitation (see sections 3.2 and 4) thereby improving the model bias.

4. Sensitivity of Climate Response to Dust Absorbing Properties

[21] As mentioned above, the regional climatic response to dust aerosol is likely to depend on many factors and particularly on the dust SSA. In order to investigate the model sensitivity to this parameter, we performed an experiment in which dust bin SSAs were modified by plus and minus five percent compared to standard value (Table 1). This variation falls in the range of the observed estimates used in climate modelling (section 1).

[22] As illustrated in Figures 1c and 1d, a variation of SSA can strongly modify the TOA radiative forcing over our domain. For the more absorbing SSA case, the warming tendency is enhanced over bright desert areas and over the Saharan dust source region, whereas radiative cooling is now less efficient over Sahel and ocean. Consequently, the SW diabatic heating in the atmospheric column is enhanced (cf. auxiliary material). Conversely, for the high SSA case (Figure 1d) we obtain a TOA cooling generalised over the domain, even over bright desert areas. It means that the dust SSA are always over the 'critical SSA' depending on surface albedo and defined by *Liao and Seinfeld* [1998]. Over the Sahel and Ocean, the cooling obtained in the standard case is now more intense due to higher aerosol diffusivity.

[23] Concerning the regional climate responses, in the SSA −5% case (Figure 3b) we still obtain an 'anti monsoon' differential circulation induced by surface cooling in the lower troposphere (below 5000 m), but the elevated pump branch (above 5000 m) is now strengthened as a result of enhanced atmospheric absorption and warming. The net effect on precipitation (Figure 3e) is to reduce the standard dust drying over the Sahel (between 10 and 15 N) and to increase precipitation over the Northern Sahel / Southern Sahara region.

[24] When dust is considered as a stronger diffuser (standard SSA + 5% case), we note a total cancellation of the elevated heat pump differential circulation (Figure 3c), which is replaced by subsidence at all tropospheric levels and reduction of cloud water. In the lower troposphere, the anti monsoon differential circulation is still very active and the dust drying effect is larger than in the standard case, while no increase of precipitation is obtained over the Sahel (Figure 3f).

5. Conclusions

[25] Using a RCM including an on line parameterization of dust aerosol radiative forcing, we showed that dust has an impact on simulated precipitation over west Africa. Contrary to previous studies showing substantial drying or moistening effect induced by dust over the Sahel [*Konaré et al.*, 2008; *Yoshioka et al.*, 2007; *Miller et al.*, 2004], our results suggest finer regional precipitation responses based on coexisting differential circulations patterns induced by the dust radiative forcing at different tropospheric levels. Dust surface and lower troposphere cooling is responsible for a decrease of the monsoon pump intensity whereas atmospheric diabatic warming over the source areas could trigger an elevated heat pump effect resulting in enhanced moisture transport and cloud formation in the higher troposphere over the Sahel. The overall regional impact of dust on average precipitation results from these coexisting effects.

[26] The balance between these effects is very sensitive to the dust SSA and it determines the intensity of precipitation decrease vs. increase as well as the latitudinal limit between these two responses. Using a range of current estimates of dust SSA values, we show that the drying and moistening patterns over the Sahel region can significantly change. This dependency of precipitation and circulation to the 'amount of absorption' by dust is consistent with results of *Rodwell and Jung* [2008]. Overall, a better characterization of the size distribution and dust optical properties over west Africa is still crucial for the accurate estimated of the dust climatic effects over the region.

[27] Using the standard optical properties along with precipitation observations, we show that the model biases in simulating precipitation over the region can be improved by taking into account dust effects. When compared to CRU data, dust could contribute to a ∼40% of the precipitation positive model bias. Although a strict causality is difficult to establish because of other model imperfections responsible for biases, our results are still indicative of the importance of including dust in forecast and climate models. Finally it should be recalled that other factors can potentially modify the simulated climatic signals obtained, as the number of dust bins, the potential effect of dust on cloud microphysics, the use of different land surface, convection and interactively coupled ocean schemes.

[28] **Acknowledgments.** Based on a French initiative, AMMA was built by an international scientific group and is currently funded by a large number of agencies, especially from France, UK, US and Africa. It has been the beneficiary of a major financial contribution from the European Community's Sixth Framework Research Programme. Detailed information on scientific coordination and funding is available on the AMMA International website http://www.amma-international.org.

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N. Elguindi, M. Mallet, and F. Solmon, Laboratoire d'Aérologie, Université de Toulouse, 14 avenue Edouard Belin, F-31100 Toulouse CEDEX, France. (solf@aero.obs-mip.fr)

F. Giorgi and A. Zakey, Earth System Physics, Abdus Salam International Center for Theoretical Physics, ICTP P.O. Box 586, I-34100 Trieste, Italy.

A. Konaré, Laboratoire de Physique de l'Atmosphère, Université de Cocody, BP 582, Abidjan 22, Côte d'Ivoire.