Sensitivity of the Middle East–North African Tropical Rainbelt to Dust Shortwave Absorption: A High-Resolution AGCM Experiment

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ABSTRACT

Shortwave absorption is one of the most important, but the most uncertain, components of direct radiative effect by mineral dust. It has a broad range of estimates from different observational and modeling studies and there is no consensus on the strength of absorption. To elucidate the sensitivity of the Middle East–North African (MENA) tropical summer rainbelt to a plausible range of uncertainty in dust shortwave absorption, AMIP-style global high-resolution (25 km) simulations are conducted with and without dust, using the High-Resolution Atmospheric Model (HiRAM). Simulations with dust comprise three different cases by assuming dust as a very efficient, as a standard, and as an inefficient absorber. Intercomparison of these simulations shows that the response of the MENA tropical rainbelt is extremely sensitive to the strength of shortwave absorption. Further analyses reveal that the sensitivity of the rainbelt stems from the sensitivity of the multiscale circulations that define the rainbelt. The maximum response and sensitivity are predicted over the northern edge of the rainbelt, geographically over the Sahel. The sensitivity of the responses over the Sahel, especially that of precipitation, is comparable to the mean state. Locally, the response in precipitation reaches up to 50% of the mean, while dust is assumed to be a very efficient absorber. Taking into account that the Sahel has a very high climate variability and is extremely vulnerable to changes in precipitation, the present study suggests the importance of reducing uncertainty in dust shortwave absorption for a better simulation and interpretation of the Sahel climate.

1. Introduction

As a ubiquitous and arguably dominant portion of aerosols in the atmosphere, the role of dust in the climate system has long been appreciated (e.g., Carlson and Benjamin 1980; Cess et al. 1985; Ramaswamy and Kiehl 1985; Tegen et al. 1996). It has also long been recognized that dust influences Earth's radiation budget directly (direct radiative effect) by scattering and absorbing both

solar and planetary radiation and by emitting the latter (e.g., Sokolik and Toon 1996; Liao and Seinfeld 1998; Miller and Tegen 1998). However, in recent years, there has been a specific growing interest in the role of dust-induced atmospheric circulation changes on the strength and latitudinal extent of the tropical rainbelt across the Middle East and North Africa (MENA) (e.g., Bangalath and Stenchikov 2015). This is partly due to the rainbelt's proximity to the “dust belt” associated with world's biggest deserts, and partly because of the much-discussed rainfall variability of the region (“Sahel drought”). Although prior studies demonstrated various plausible mechanisms involved in the dust–rainbelt interaction, especially over West Africa, significant uncertainty still remains in both quantitative and qualitative conclusions among these studies. Many of the prior modeling studies showed strengthening of the summer rainbelt across MENA, in response to dust direct radiative effect (e.g., Bangalath and Stenchikov 2015; Lau et al. 2009; Yue et al. 2011a; Miller et al. 2014), while others predict its weakening (e.g., Yoshioka et al. 2007; Yue et al. 2011b). The uncertainty in the dust refractive index estimates

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and the consequent uncertainty in the dust shortwave absorption are proposed to be a major cause of the disparity (e.g., [Solmon et al. 2008](#); [Miller et al. 2004](#)).

It has been shown that the values of the imaginary part of the shortwave refractive index, which decides the amount of shortwave absorption, vary by an order of magnitude among various studies ([Balkanski et al. 2007](#)). As a result, the single scattering albedo (SSA), an optical measure that characterizes the ratio between scattering and absorption in the total extinction, also varies significantly. Among various estimates, the value of bulk SSA (at 500 nm) ranges from highly absorbing values (0.7–0.9) (e.g., [Otto et al. 2009](#); [Slingo et al. 2006](#); [Raut and Chazette 2008](#); [Haywood et al. 2001](#)) to almost nonabsorbing values that go higher up to 0.99 (e.g., [Tanré et al. 2001](#); [Osborne et al. 2008](#); [Dubovik et al. 2002](#)). Furthermore, measurements from in situ dust samples generally infer higher shortwave absorption than that from remote sensing techniques (e.g., [Haywood et al. 2003](#); [Kaufman et al. 2001](#)). In short, there is no general agreement on the strength of dust shortwave absorption and the value of SSA. This disagreement among various estimates continues to be an area of active debate among climate scientists.

The large uncertainty in the dust SSA estimates among various observational and modeling studies could induce similar uncertainties in the sign and magnitude of radiative forcing and corresponding climate responses. Many previous studies attempted to quantify the uncertainty in radiative forcing related to shortwave absorption (e.g., [Balkanski et al. 2007](#)); however, very few attempted to estimate the sensitivity of the resulting climate responses, especially on a regional scale. That said, a broad scrutiny of the previous modeling studies shows that the simulations that predicted weakening of the MENA rainbelt in response to dust radiative effect used less absorbing dust (large SSA) (e.g., [Yoshioka et al. 2007](#); [Yue et al. 2011b](#)), whereas those that predicted a strengthening of the rainbelt used highly absorbing dust (e.g., [Lau et al. 2009](#); [Yue et al. 2011a](#); [Bangalath and Stenchikov 2015](#); [Miller et al. 2014](#)). However, models used in these previous studies differ from each other not only in the strength of dust shortwave absorption but also in other aspects such as total dust loading and its spatiotemporal variability, various optical properties of dust, model resolution, model components, and models' internal variability. Therefore, an intercomparison of these previous studies cannot faithfully draw conclusions on the sensitivity of climate response to dust shortwave absorption. It all boils down to the need for simulations from a single model with varying amounts of dust shortwave absorption, to avoid uncertainties associated with intermodel differences in the sensitivity analyses. There were some specific efforts along this line, which were conducted using either

coarse-resolution global models or regional climate models. The global experiments with general circulation models (GCMs) generally focus on global-scale responses and they refrain from detailed regional analysis mainly due to their conventional coarser spatial resolution (e.g., [Colarco et al. 2014](#)). On the contrary, the experiments using regional climate models (RCMs) (e.g., [Solmon et al. 2008](#)) fail to incorporate the global-scale circulation response to dust radiative forcing that span outside the domain of RCM, although they represent regional-scale responses in detail. An original and forthright solution to overcoming these issues is to use high-resolution global simulation.

Taking into consideration the abovementioned facts, the present study investigates the sensitivity of the summer [June–August (JJA)] tropical rainbelt over MENA and the causative multiscale circulation responses to varying dust shortwave absorption, using a high-resolution atmospheric general circulation model (AGCM). AMIP-style numerical simulations are conducted with the High Resolution Atmospheric Model (HiRAM) at a horizontal resolution of 25 km, with three different datasets of dust optical properties, representing dust as an inefficient, as a standard, and as a very efficient shortwave absorber. These three sets of dust optical properties are calculated based on three different refractive indices estimated by [Balkanski et al. \(2007\)](#), which bracket the possible range of dust shortwave absorption. It should be noted that the present study specifically investigates the sensitivity of the atmosphere-only response to dust shortwave absorption using AMIP-style simulations by prescribing observed sea surface temperature (SST) as the bottom boundary condition.

The rainbelt across MENA can primarily be seen as the ascending branch of the local Hadley circulation. However, there are many distinct regional circulation features embedded within this large-scale averaged circulation, such as the West African monsoon (WAM), African easterly jet (AEJ), tropical easterly jet (TEJ), and West African westerly jet (WAWJ), which are also found to be significant drivers of the rainbelt (e.g., [Nicholson 2009](#); [Cook 1999](#); [Thorncroft and Blackburn 1999](#)). Therefore, incorporation of both global and regional circulations and the complex multiscale interplay among these circulations are crucial for an accurate simulation of the rainbelt across MENA. Recently, high-resolution GCMs have emerged as an efficient way to accomplish this with the advent of petascale computing infrastructures. For instance, [Bangalath and Stenchikov \(2015\)](#) effectively used HIRAM simulations at 25-km spatial resolution, to investigate regional climate responses to globally inhomogeneous dust forcing. The high-resolution (25 km) simulations ensure better

representation of the relatively narrow band (a few degrees of latitude) of precipitation belt and the sharp gradients in the climate variables across this region, which are crucial entities for an accurate simulation of the region's climate. Improved resolution also enables better representation of orographic heterogeneity and other finescale forcings that are decisive factors for the regional climate (e.g., Sylla et al. 2012; Paeth et al. 2005).

It was shown in Bangalath and Stenchikov (2015) that the dust-induced off-equatorial atmospheric heating in the MENA domain, associated with major dust source regions, alters the strength and position of the local Hadley circulation and regional circulations such as the WAM and AEJ. These multiscale circulation responses in turn strengthen and widen the rainbelt northward. It is noteworthy that the maximum response occurs at the northern edges of the rainbelt in their experiments. Importantly, the northern edge of the summer rainbelt is geographically over the Sahel—a semiarid strip between the Sahara desert and the Sudanian savanna that stretches between the Atlantic Ocean and the Red Sea. The Sahel is a unique ecoclimatic region that experienced persistent drought from the 1960s to the 1980s and recovery in later years, the cause of which is an ongoing debate in climate science (e.g., Nicholson 1980; Folland et al. 1986; Held et al. 2005). The twentieth-century evolution of Sahel rainfall, which has had severe impacts on the region's economy and life of the local population, has been widely recognized as the most severe change in the hydrological climate of any region in the era of instrumental records. Although this variability is mainly explained by the influence of slowly varying climate components, such as SST (e.g., Folland et al. 1986; Giannini et al. 2003; Hagos and Cook 2008) and land conditions (e.g., Charney 1975), variability in dust radiative forcing is also considered to be a causative mechanism (e.g., Brooks and Legrand 2000; Biasutti and Giannini 2006; Nicholson 2000; Yoshioka et al. 2007). At the minimum, dust radiative effects could modulate the climate variability of this region as Saharan/Sahelian dust emission has high variability from millennial to diurnal scales. Therefore, it is extremely important to estimate the sensitivity of the tropical rainbelt to dust shortwave absorption for a better interpretation of the simulation of the historical and future climate of the MENA region in general, and of the Sahel in particular.

The rest of this article is organized as follows. Section 2 describes the model and experimental design. Sensitivity of the rainbelt and the related multiscale circulation to the dust shortwave absorption are discussed in section 3.

A detailed discussion and summary follow in sections 4 and 5, respectively.

2. Model and experiment design

Global simulations at horizontal resolution of 25 km and even higher are becoming possible nowadays because of improved supercomputing infrastructure and highly scalable dynamical cores (e.g., Zhao et al. 2009; Shaffrey et al. 2009; Lin 2004; Putman et al. 2005; Hack et al. 2006). At this range of spatial resolution, models explicitly resolve important mesoscale features and weather events (e.g., Zhao et al. 2009; Jung et al. 2012) and better simulate the orographically induced circulations and associated precipitation modulations (e.g., Boyle and Klein 2010; Lau and Ploshay 2009). In the present study experiments are conducted using such a high-resolution AGCM, HiRAM, developed at Geophysical Fluid Dynamics Laboratory (GFDL) (Zhao et al. 2009). HiRAM was designed to provide an improved representation of weather events in a GCM and to use for applications ranging from weekly forecast to climate projections. The model is developed based on the GFDL Atmospheric Model version 2 (AM2) with certain modifications, as explained in Zhao et al. (2009). It has horizontal resolution flexibility up to a few kilometers and has an improved vertical resolution (32 levels) compared to AM2. HiRAM employs a finite-volume cubed-sphere dynamical core (Lin 2004; Putman and Lin 2007). The present study uses the C360 version of HiRAM, which has 25-km horizontal grid spacing with 360 by 360 finite-volume cells on each face of the cube. A nonintrusive shallow convective scheme (Bretherton et al. 2004) replaces the customary deep convective scheme by extending the former to simulate deep convection (Zhao et al. 2009). The model preserves most of the parameterizations of its parent model AM2, including radiative transfer, surface flux, boundary layer, orographic gravity wave drag parameterizations, and large-scale cloud microphysics, with necessary modifications as resolution increases. The present study conducts AMIP-style simulations forced with the observed monthly SST from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al. 2003). Therefore, the simulations do not account for the SST feedback, which is an important factor for the hydrologic cycle. In other words, the analyses and interpretations in the present study should be understood as those based on the atmosphere-only processes. The model is coupled to the new GFDL land model version 3 (LM3), as the land component.

A seasonally varying dust concentration is prescribed in HiRAM. The aerosol concentrations, including dust,

TABLE 1. Experiment design.

Experiment	Description
NoDUST	Omit dust radiative effect in the simulation
DUST0.9	Include dust radiative effect with optical properties assuming 0.9% of hematite content by volume.
DUST1.5	Include dust radiative effect with optical properties assuming 1.5% of hematite content by volume.
DUST2.7	Include dust radiative effect with optical properties assuming 2.7% of hematite content by volume.

are prescribed from the offline calculations of a global chemistry transport model, the Model for Ozone and Related Chemical Tracers (MOZART) (Horowitz et al. 2003). Details of the offline estimates of the aerosol concentrations are explained in Ginoux et al. (2006). Dust concentrations are found to be within a factor of 2 of the observed values (Ginoux et al. 2006). Sources of dust are from the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (Ginoux et al. 2001). Size distribution of dust aerosol is discretized into eight bins from 0.1 to 10 μm . Optical properties are estimated by assuming all dust particles originate from the Sahara. The specific extinction coefficients of dust are calculated from Mie theory using refractive indices from the recent estimates of Balkanski et al. (2007) for shortwave bands, and from Volz (1973) for longwave bands. Calculations assume three different cases of hematite content in dust by volume, 2.7%, 1.5%, and 0.9%, which represent dust as a very efficient, standard, and inefficient shortwave absorber, respectively (Balkanski et al. 2007).

The general experiment design in this study is similar to that in Bangalath and Stenchikov (2015), except that the current study investigates specifically the sensitivity of the rainbelt, and the various multiscale circulations that define the rainbelt, to dust shortwave absorption. Validation of the model performance in reproducing a realistic rainbelt over the MENA region was conducted in Bangalath and Stenchikov (2015), by comparing with observed data. The result showed that HiRAM simulates the rainbelt quite realistically and it captures the key features of the precipitation climatology, especially the local precipitation maxima associated with the orographic features. Further validation, especially that of the multiscale circulations, is provided in the supplementary material of the present paper, as comparisons against ERA-Interim reanalysis data. Four HiRAM experiments (Table 1) are conducted for an 11-yr period (1999–2009). Each of these experiments comprises three ensemble members simulated from slightly different initial conditions. One seasonal cycle (one year) is omitted from further analysis to avoid a spinup period. The NoDUST experiment omits dust radiative forcing in the simulations. The

three other simulations, named DUST0.9, DUST1.5, and DUST2.7, account for the radiative effect of dust with a hematite content of 0.9%, 1.5% and 2.7% respectively. The sensitivity of atmospheric response to varying dust shortwave absorption can be estimated by an intercomparison of the anomalies of climate variables in these three different simulations, compared to the NoDUST simulation.

3. Results

a. Direct radiative forcing and heating rate anomalies

To characterize the direct radiative effect of dust aerosols on the climate, radiative forcing and heating rate anomalies are calculated. Following Bangalath and Stenchikov (2015) and other relevant past studies (e.g., Hansen et al. 2005; Chin 2009), dust direct radiative forcing (DDRF) is defined as the net (longwave + shortwave) radiative flux difference between a state with dust loading and that without dust loading (downwelling minus upwelling), calculated under the same meteorological conditions. In this sense, positive DDRF corresponds to warming of the system and vice versa. The forcing is estimated separately at the top of the atmosphere (TOA), the surface, and within the atmosphere. The radiative fluxes with and without dust direct radiative effect are calculated in the simulations by calling the radiation routine twice at each radiation time step, once with dust radiative effect and the other without dust influence. However, the radiation calculation without dust influence does not feed back to the model evolution. Instead, this estimation is used only to calculate the DDRF and heating rate anomalies, by comparing it with the radiation calculation influenced by dust radiative effect.

Typically, satellite- or AERONET-based estimation of aerosol radiative forcing is done only under clear-sky conditions, as it is not straightforward to screen out the cloud effect on radiation from that of the aerosols, when they are collocated. Modeling studies generally prefer to estimate forcing under all-sky conditions, mainly due to the uncertainties in cloud-free scenes in the models (Chin 2009). However, keeping in mind the disagreement between satellite and modeling based estimates on dust absorption and DDRF (e.g., Haywood et al. 2003; Kaufman et al. 2001; Moulin et al. 2001), the present study estimates both clear-sky and all-sky forcing. Since clouds can mask the light scattered from aerosols, aerosol direct radiative forcing is generally less at all-sky conditions than that at clear-sky conditions (e.g., Schulz et al. 2006).

Annually averaged estimates of DDRF, for the three experiments assuming different shortwave absorption, are shown in Table 2. DDRF is averaged separately for

TABLE 2. Annual DDRF.

Experiment	Domain	DDRF TOA all sky			DDRF surface all sky			DDRF ATM all sky			DDRF TOA clear sky			DDRF surface clear sky			DDRF ATM clear sky			Average SSA (at 550nm)
		SW	LW	NET	SW	LW	NET	NET	SW	LW	NET	SW	LW	NET	SW	LW	NET			
DUST0.9	Global	-0.29	+0.11	-0.18	-0.83	+0.37	-0.46	+0.27	-0.48	+0.15	-0.34	-1.07	+0.45	-0.63	-0.29	+0.29	+0.29	0.94		
	MENA	-2.11	+1.08	-1.03	-7.47	+4.35	-3.12	+2.09	-2.68	+1.36	-1.32	-8.68	+5.01	-3.67	+2.35	+2.35	+2.35	0.93		
DUST1.5	Global	-0.20	+0.11	-0.09	-0.95	+0.36	-0.59	+0.49	-0.41	+0.15	-0.26	-1.23	+0.45	-0.78	+0.52	+0.52	+0.52	0.90		
	MENA	-1.28	+1.05	-0.23	-8.60	+4.22	-4.38	+4.15	-1.87	+1.33	-0.54	-10.05	+4.89	-5.16	+4.63	+4.63	+4.63	0.89		
DUST2.7	Global	-0.07	+0.11	+0.04	-1.15	+0.36	-0.79	+0.83	-0.28	+0.14	-0.14	-1.46	+0.44	-1.02	+0.88	+0.88	+0.88	0.86		
	MENA	-0.08	+1.04	+0.96	-10.49	+4.19	-6.30	+7.27	-0.63	+1.31	+0.68	-12.20	+4.86	-7.33	+8.02	+8.02	+8.02	0.84		

Global and MENA domain, to show the heightened regional impact over MENA. Averaged values of dust SSA corresponding to each experiment and domain are shown in the last column of the table. The globally averaged dust SSA estimates range from 0.94 (in DUST0.9) to 0.86 (in DUST2.7). As dust shortwave absorption increases, the SSA value naturally decreases as it is the ratio of scattering to total extinction.

The globally averaged DDRF at TOA is negative (cooling) in experiments assuming dust as an inefficient (DUST0.9) and standard (DUST1.5) absorber, in both clear-sky and all-sky conditions (Table 2). However, the negative value reduces as absorption increases and ultimately changes the sign (except for global clear sky) into positive (warming) in the efficient absorber experiment (DUST2.7). The globally averaged estimates range from -0.18 W m^{-2} (DUST0.9) to $+0.04 \text{ W m}^{-2}$ (DUST2.7) in all-sky condition and from -0.34 W m^{-2} (DUST0.9) to -0.14 W m^{-2} (DUST2.7) in clear-sky condition, as shortwave absorption increases. These values compare well with the previous estimates [see Table 1 in Yue et al. (2010) and Table 6 in Balkanski et al. (2007)]. Consistent with the previous studies, all-sky forcing is in general significantly less than clear-sky forcing. Regionally, over MENA the forcing is almost one order of magnitude higher than the global average.

At surface the net forcing is the sum of the radiative perturbations due to absorption and scattering in the atmosphere and hence is always negative (cooling). Since dust is a good absorber at short wavelengths, the magnitude of surface DDRF is always much higher than the TOA forcing. Surface forcing significantly increases as shortwave absorption increases (Table 2). The globally averaged values lie between -0.46 (DUST0.9) and -0.79 W m^{-2} (DUST2.7) in all-sky condition and between -0.63 (DUST0.9) and -1.02 W m^{-2} (DUST2.7) in clear-sky condition. Again, these forcing are much higher over MENA.

The DDRF within the atmosphere (difference between DDRF at TOA and at surface) can be deduced as the net dust-induced heating within the atmosphere, which ultimately perturbs the stability, cloud formation (semidirect effect) (e.g., Hansen et al. 1997), and consequently multiscale circulations and precipitation. The DDRF within the atmosphere is always warming (positive), which indicates that the shortwave heating dominates the long-wave cooling (Table 2). Atmospheric warming increases as shortwave absorption increases. The globally averaged forcing ranges from $+0.27$ to $+0.83 \text{ W m}^{-2}$ in all-sky conditions and from $+0.29$ to $+0.88 \text{ W m}^{-2}$ in clear-sky conditions.

In general, the MENA region experiences contrastingly high forcing at all levels compared to the global

FIG. 1. Mean summer (JJA) all-sky DDRF (W m^{-2}) at TOA while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave. Positive values represent warming of the system and negative values denote cooling of the system, by definition. The green rectangle in Fig. 1a outlines the borders of MENA region.

average and the difference is almost one order of magnitude. This is because the region has high dust loading associated with major source regions and a relatively higher ratio of coarse to fine mode dust particles (not shown) near these source regions. Higher coarse mode dust fraction leads to reduced SSA and increased absorption (e.g., Otto et al. 2009; Ryder et al. 2013). This is why the MENA region experiences reduced SSA compared to the global average (see Table 2).

As the present study specifically focuses on climate responses during the boreal summer season, the spatial pattern of summer DDRF are depicted for different experiments separately at the TOA, at the surface, and within the atmosphere. Figure 1 shows global patterns of all-sky DDRF at TOA during summer, for all three experiments, assuming varying dust shortwave absorption. Overall, the forcing is concentrated over the Northern Hemispheric subtropics, especially over

MENA, associated with the major dust source regions including the Sahara deserts, the Sahel, the Arabian deserts, and downwind of these source regions. The most noticeable feature of the TOA forcing, in general, is the change in the sign of the forcing regionally. Over bright deserts the forcing is positive (warming) and over darker ocean it is negative (cooling). This is due to the fact that the TOA aerosol forcing is highly dependent on the effective albedo of the underlying surface (albedo effect) in addition to its dependency on the physical, chemical and optical properties of the particles (e.g., Liao and Seinfeld 1998; Claquin et al. 1998; Stier et al. 2007; Chýlek and Coakley 1974; Kaufman 1987). In other words, if the combined aerosol and surface system reflects less solar radiation than does the surface alone, the TOA forcing becomes positive (warming the system). Over bright deserts, where surface albedo generally exceeds 0.3, the low SSA values of dust can lead to a combined dust–surface system that is darker than the underlying surface. Therefore, the value of dust SSA becomes a decisive factor in determining the sign of the TOA forcing over deserts. However, over dark surfaces like ocean, where surface albedo is generally less than 0.1, it is less probable to have positive forcing with the range of SSA that dust generally has. Moreover, absorbing aerosols such as dust, situated above a cloud layer, can induce positive TOA forcing in all-sky conditions, as the cloud layer can effectively act as a brighter underlying surface in this case (e.g., Schulz et al. 2006; Haywood and Ramaswamy 1998).

In terms of the sensitivity of the TOA forcing to varying dust shortwave absorption, the positive forcing (warming) over MENA diminishes and even changes the sign as SSA increases (going from DUST2.7 to DUST0.9), especially at regions like the Sahel. Similarly, the cooling over the oceanic region (negative TOA forcing) enhances as the shortwave absorption reduces. In effect there is a contrast even in the magnitude of the TOA forcing between adjacent land and ocean. As the shortwave absorption increases (from DUST0.9 to DUST2.7), positive TOA forcing over land intensifies and negative TOA forcing over ocean reduces significantly. It implies that if the dust assumes a high SSA value, the major impact will be over land (deserts) rather than the downwind oceanic region, in terms of TOA forcing. This differential TOA forcing over adjacent land and ocean could potentially influence local circulations originating from the land–sea thermal contrast, such as WAM and land–sea breezes.

Figure 2 depicts all-sky DDRF at surface. At the surface, the DDRF is always cooling (negative) as it is the combined effect of absorption and scattering in the atmosphere. Surface forcing is extremely sensitive to the SSA or hematite content, as it is a strong function of

the shortwave absorption within the atmosphere. Therefore, as the absorption reduces (from Fig. 2a to Fig. 2c), DDRF at surface also reduces. This indicates the significant role of atmospheric shortwave absorption to the surface DDRF.

Forcing within the atmosphere can be seen as the difference between TOA and surface forcing, which can induce a variety of climate effects by influencing the vertical stability, cloud formation (semidirect effect or cloud burning off) and circulation patterns. Elevated heat pump (EHP) hypotheses (Lau et al. 2009, 2006) (a regional manifestation of semidirect effect) are a typical example of how the heating within the atmosphere induced by dust will influence circulation. DDRF (all sky) within the atmosphere is estimated by subtracting forcing at the TOA from that at surface (Fig. 3). The forcing is always warming (positive) within the atmosphere, to which the atmosphere primarily responds dynamically. Also, the magnitude of the forcing is sensitive to shortwave absorption. As expected, warming reduces as shortwave absorption reduces. The heat trapped in the atmosphere (warming) in DUST1.5 experiment is almost twice that of DUST0.9, and it becomes 3 times larger in the DUST2.7 case.

The role of surface radiative forcing (reduced radiation in the present case) in the climate response is through changes in surface heat fluxes, dominantly in latent heat flux over the oceanic region. However, negative forcing at the ocean surface does not produce feedback as reduced latent heat flux in the present simulations, as the bottom boundary condition is prescribed by observed SST. Therefore, as we omit the main feedback from surface forcing, climate response is primarily to the forcing within the atmosphere (atmosphere-only response).

To explicitly portray the radiative perturbation within the atmosphere and its distribution aloft, vertical cross sections of the dust-induced heating rate anomalies are calculated. It was shown by Bangalath and Stenchikov (2015) that the dust-induced heating confined to the Northern Hemispheric deserts over MENA strengthen the local Hadley circulation and shift the Northern Hemispheric cell farther poleward. This is proposed to be the main driver for the climate response tropical rainbelt across MENA. To depict the sensitivity of this asymmetric heating pattern to shortwave absorption, zonally averaged (20°W–60°E) meridional cross sections of dust-induced heating rate anomalies are plotted for all three experiments (Fig. 4). Dust-induced heating is confined to the subtropical lower to middle troposphere, which could act as a potential off-equator heating source as shown by Bangalath and Stenchikov (2015). The heating rate is naturally sensitive to the shortwave absorption. As absorption increases (from DUST0.9 to

FIG. 2. Mean summer (JJA) all-sky DDRF (W m^{-2}) at surface while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave. Positive values represent warming of the system and negative values denote cooling of the system, by definition.

DUST2.7), the heating rate increases and hence the interhemispheric heating gradient also strengthens. This strengthening of interhemispheric heating gradient could potentially make the circulation response sensitive to dust shortwave absorption.

b. Sensitivity of rainbelt

The sensitivity of the tropical rainbelt across MENA to varying dust shortwave absorption is depicted primarily by the responses in the precipitation (Fig. 5) and

further by the response in total cloudiness (Fig. 6). The performance of the model in reproducing the summer rainbelt across MENA was validated in Bangalath and Stenchikov (2015) (further comparison can be found in Figs. S1 and S2 in the supplemental material of this paper). A two-tailed Student's *t* test is performed to estimate the statistical significance of the rainbelt response. The areas where the response is significant at 95% confidence level are marked by hatching. Figure 5 shows the responses in the mean summer precipitation

FIG. 3. Mean summer (JJA) all-sky DDRF (W m^{-2}) within the atmosphere while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave. Positive values represent warming of the system and negative values denote cooling of the system, by definition.

for all three cases. The thick red contour bounds the area where rainfall is above $3 \text{ kg m}^{-2} \text{ day}^{-1}$ to depict the position of the rainbelt. The shaded contours are the precipitation response in each experiment calculated by subtracting the mean summer precipitation of each experiment with dust from that of the NoDUST experiment. Therefore, the values can be inferred as the changes due to dust radiative effect. In response to dust forcing, the rainbelt strengthens and shifts northward (Fig. 5), which in turn develops a meridional dipole

pattern in the precipitation response, with an increase of precipitation in the northern half of the rainbelt and a reduction to the south. As shown by Bangalath and Stenchikov (2015), the response is more intense at the northern border of the rainbelt. It also means that the Sahel region experiences a stronger response than other regions. A comparison of the response among experiments shows that the rainbelt intensity and position of the rainbelt are sensitive to dust shortwave absorption. The rainbelt intensifies and shifts farther northward

FIG. 4. Vertical cross section of zonally averaged (20°W – 60°E) mean summer (JJA) radiative heating rate (shortwave + longwave) anomaly induced by dust (shaded contours) overlaid on net radiative heating rate as contour lines, while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave.

as the absorption increases (DUST0.9 to DUST2.7). Moreover, as absorption increases, larger areas of the rainbelt response become statistically significant. Furthermore, the dipole pattern in the response almost vanishes and the sign of the precipitation response changes from positive to negative in most parts of the rainbelt as absorption reduces (DUST0.9). These

results, especially the sensitivity of Sahel rainfall to dust shortwave absorption, are qualitatively in agreement with the study by Miller et al. (2014).

Figure 6 depicts the sensitivity of the total cloud amount to varying dust shortwave absorption. Overall, the cloud response is stronger and statistically significant in more areas, compared to the precipitation response. The thick

FIG. 5. Precipitation response ($\text{kg m}^{-2} \text{ day}^{-1}$) to dust radiative effect while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave, during summer (JJA). The responses are estimated as the difference between simulations with dust radiative effect and without dust radiative effect. Areas where the response is statistically significant (Student's t test) at 95% level are hatched. The thick red contour overlaid on the shaded response portrays area where rainfall is above $3 \text{ kg m}^{-2} \text{ day}^{-1}$, to depict the position of the rainbelt.

red contour bounds the areas with cloudiness above 70% as a proxy of the position of the rainbelt or the ascending branch of the Hadley cell. Unlike the precipitation response, the northward extent of cloud cover is more advanced. Cloudiness increases, especially to the north of the rainbelt, as shortwave absorption increases. In DUST0.9 experiment the sign of the response reverses in the

rainbelt, from positive to negative. Some patches of response with reduction in cloudiness are statistically significant over central Sahel in the DUST0.9 experiment.

In general, from the response of both cloud cover and precipitation, it is apparent that the tropical rainbelt enhances and moves farther north in response to dust-induced atmospheric heating and the magnitude

FIG. 6. Response in total cloud amount (%), to dust radiative effect while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave, during summer (JJA). The responses are estimated as the difference between simulations with dust radiative effect and without dust radiative effect. Areas where the response is statistically significant (Student's t test) at 95% level, are hatched. The thick red contour overlaid on the shaded response portrays area where cloudiness is above 70%, as a proxy for the position of the rainbelt.

and sign of these responses are especially sensitive to the amount of shortwave absorption.

c. Sensitivity of overturning circulation

The response in the rainbelt, as evident from both precipitation responses (Fig. 5) and cloudiness responses (Fig. 6), indicates a possible strengthening and northward shift of the ascending branch of the Hadley circulation. It is evident from the pattern of radiative forcing and heating rate (Figs. 1–3) that the dust-induced radiative perturbation in summer has a distinct hemispheric contrast over the MENA region, with the predominant forcing or heating rate over the Northern Hemispheric subtropics associated with the major dust source regions. Bangalath and Stenchikov (2015) demonstrated that this hemispheric contrast in forcing induces significant response in the local Hadley circulation. The observed response in the rainbelt is mainly attributed to this local Hadley circulation response, as the rainbelt is the manifestation of the ascending limb of the Hadley circulation. To explicitly demonstrate the sensitivity of the local Hadley circulation response to dust shortwave absorption, it is essential to partition the local three-dimensional overturning circulation to a pair of orthogonal two-dimensional circulations, local Hadley and Walker circulations. A recently introduced method by Schwendike et al. (2014), based on the ψ -vector method developed by Keyser et al. (1989), shows that the vertical mass flux can be decomposed locally in to its meridional (m_ϕ) and zonal (m_λ) component and can be portrayed as the local Hadley and Walker circulations, respectively. This method of separation has the advantage of allowing the two orthogonal circulations (local Hadley and Walker circulations) to sum to the original circulation even in a limited domain [see Schwendike et al. (2014, 2015) for a detailed explanation of the method]. It was shown by Bangalath and Stenchikov (2015) that this method is particularly useful for the kind of problem in the present study, where it has to be shown specifically whether the response comes from perturbations in the meridional or zonal gradients, especially in a limited domain.

The mean summer local Hadley and local Walker circulation responses over MENA are portrayed by the anomalies in the vertical mass flux at 500 hPa associated with meridional (m_ϕ) and zonal (m_λ) overturning circulations, respectively. Figure 7 depicts the mean summer response in the local Hadley circulation (m_ϕ) in the experiments. The response is shown as shaded contours and the mean m_ϕ in the respective experiment as contour lines, where thick contours represent ascending motion and dashed contours represent subsidence. Overall, the response is maximum at the northern edges. The general pattern of response is an

intense increase in vertical mass flux at the northern half of the ascending limb of the local Hadley cell and a decrease in the southern half, although it is relatively weaker. This dipole pattern of response in m_ϕ is consistent with the pattern of the rainbelt response (Figs. 5 and 6). In other words, it suggests that the predicted response of the rainbelt stems from the local Hadley circulation changes in response to a meridionally asymmetric heating gradient. This pattern of response and its strength are sensitive to the amount of dust shortwave absorption. As shortwave absorption weakens, the response also weakens and even reverses sign (Figs. 7a–c).

Figure 8 shows the mean summer response of local Walker circulation (m_λ) in all three experiments. Similar to Fig. 7, the response is shown as shaded contours and the mean m_λ as contour lines. In general the local Walker response is weaker compared to the local Hadley response (Fig. 7). Similar to the sensitivity of m_ϕ , the m_λ response weakens as absorption reduces (Figs. 8a–c). However, no clear pattern of prominent zonal circulation anomaly is predicted over MENA, except the local hotspot of response over the Ethiopian highlands and southern Red Sea. A strong zonally oriented dipole pattern of response is predicted here, with enhanced ascending to the east including the southern Red Sea and an enhanced subsidence to the west over the Ethiopian highlands. This region of intense convective activities is the ascending branch of global Walker circulation over East Africa during summer. The zonal dipole pattern in the response indicates the shift of this branch eastward, which might be caused by the response of the Indian summer monsoon (ISM) to dust radiative effect (This is beyond the domain and not shown). It has been shown (e.g., Funk et al. 2008; Williams and Funk 2011) that the changes in convective activities over the Indian Ocean could potentially influence tropical East African rainfall patterns through anomalous Walker-type circulation. This is another instance showing the advantage of using high-resolution global simulation to analyze regional climate response, as these simulations can incorporate the regional influences of a global circulation perturbation. The response in m_λ is also very sensitive to the strength of dust shortwave absorption. The response is strongest in the DUST2.7 case; it reduces and the dipole pattern vanishes as absorption reduces. The predicted response of the rainbelt (Fig. 5) consistently exhibits similar dipole pattern and sensitivity.

d. Sensitivity of AEJ and TEJ

Apart from the responses in the large-scale overturning circulations, Bangalath and Stenchikov (2015) showed that AEJ is also significantly influenced by dust radiative forcing. AEJ is an important regional circulation feature

FIG. 7. Response of local Hadley circulation over MENA, to dust radiative effect while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave, during summer (JJA). Local Hadley circulation, m_ϕ , is depicted as the vertical mass flux ($10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$) associated with meridional overturning, at 500-hPa level. The responses are estimated as the difference between simulations with dust radiative effect and without dust radiative effect.

vital for the rainbelt dynamics. Its response is crucial for the rainbelt's strength and position, as it is the main mechanism to provide midtropospheric shear, important for the development of deep convection and long-lived

mesoscale convective systems (e.g., Houze and Betts 1981). AEJ is also instrumental in providing sufficient instabilities (both baroclinic and barotropic) for African easterly waves (AEWs) (e.g., Thorncroft and Hoskins

FIG. 8. Response of local Walker circulation over MENA, to dust radiative effect while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave, during summer (JJA). Local Walker circulation, m_λ , is depicted as the vertical mass flux ($10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$) associated with zonal overturning, at 500-hPa level. The responses are estimated as the difference between simulations with dust radiative effect and without dust radiative effect.

1994a,b; Thorncroft 1995), to which the bulk of precipitation activities within the rainbelt are linked. Figure 9 depicts the response in AEJ as the mean summer wind response at 600 hPa. The wind speed anomaly is shown as

shaded contours and the mean wind speed in each experiment is shown by contour lines in respective figures. Similar to rainbelt and local Hadley circulation responses, the AEJ response exhibits a dipole pattern: an increase

FIG. 9. AEJ response (shaded contours) to dust radiative effect while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave, during summer (JJA). The response in AEJ is portrayed as the difference in 600-hPa mean wind speed (m s^{-2}) between simulations with dust radiative effect and without dust radiative effect. Mean wind in each experiment is overlaid as contour lines to illustrate the strength and position of the AEJ.

(decrease) in wind speed to the north (south), which ultimately moves the jet mean position northward. The strength of response weakens as absorption weakens (from DUST2.7 to DUST0.9) and even the dipole pattern of response nearly disappears in DUST0.9.

Similar to the AEJ, the TEJ is also an important mechanism influencing the rainbelt by providing upper-tropospheric shear and moisture supply at that level. However, the TEJ forms as a geostrophic

easterly flow from the ISM anticyclone (upper troposphere) (Koteswaram 1958). Bangalath and Stenchikov (2015) showed that the TEJ strongly responds to dust radiative effect. However, the response does not originate from the ISM region in their study; instead it begins over the East Africa and strengthens toward the Atlantic. Therefore, this response is considered to be a consequence of, rather than a cause for, the rainbelt response. Figure 10 shows the sensitivity of TEJ to varying

FIG. 10. TEJ response (shaded contours) to dust radiative effect while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave, during summer (JJA). The response in TEJ is portrayed as the difference in 150-hPa mean wind speed (m s^{-2}) between simulations with dust radiative effect and without dust radiative effect. Mean wind in each experiment is overlaid as contour lines to illustrate the strength and position of TEJ.

shortwave absorption. The jet strengthens with the increase in shortwave absorption and the resultant increase in the convective activity and strengthening of the rainbelt.

e. Sensitivity of lower atmospheric circulations

At the lower troposphere, WAM is the major synoptic circulation in the region. WAM circulation dominates the lower-tropospheric dynamics and thermodynamics over West Africa. It is a crucial component even in East

Africa, as this circulation serves as the major moisture supplier from the tropical Atlantic. Figure 11 shows the response in monsoon circulation depicted by the wind response at 925 hPa. The wind vectors represent the mean wind at each experiment and shaded contours are the responses. As explained in Bangalath and Stenchikov (2015), in general, WAM circulation strengthens and shifts farther north in response to dust forcing. A dipole pattern of response is evident at the convergence zone where moist

FIG. 11. Response in 925-hPa wind speed (m s^{-2}) (shaded contours) to dust radiative effect while dust is assumed to be a (a) very efficient (DUST2.7 case), (b) standard (DUST1.5 case), and (c) inefficient (DUST0.9 case) absorber at shortwave, during summer (JJA). Wind response at this level can effectively demonstrate the responses in the WAM and WAWJ. Mean wind vectors in each experiment are overlaid.

WAM circulation meets the dry harmattan wind. The wind weakens to the north of convergence (harmattan wind) and strengthens to the south (WAM circulation), which in turn produces a north–south dipole pattern. A comparison of the response from all three experiments shows that the strength and sign of the responses are sensitive to the dust shortwave absorption. The response in wind speed weakens as absorption reduces (Figs. 10a–c). At locations with maximum responses, such as the northern borders of Sahel, the wind anomaly reduces from around 2 m s^{-1} (DUST2.7)

to almost zero (DUST0.9) response. This sensitivity is about 20% of the mean wind speed here. In DUST0.9 the wind anomaly almost vanishes in West Africa.

Although the WAM is the major regional surface circulation in the domain, there are other local circulation features that are also important for the rainbelt and that respond strongly to dust forcing. The WAWJ (Grodsky et al. 2003), a low-level jet between 8° and 11°N over the eastern Atlantic and the West African coast during summer season, is one such circulation. The

jet is in nearly geostrophic balance during most of the summer and is supergeostrophic at mature stage, with a maximum speed exceeding 7 m s^{-1} at 925 hPa. The model simulates the mean wind speed and position of the jet quite well (see Fig. S6 in the supplemental material for a comparison against ERA-Interim data). The jet strongly responds to dust forcing, in general. However, unlike the response over land where the dipole pattern of response occurs just at the wind convergence zone, the entire jet enhances. Similar to other circulations, the WAWJ response is also very sensitive to the dust shortwave absorption. Going from experiment DUST2.7 to DUST0.9, the response weakens significantly and almost neutralizes in the inefficiently absorbing case (DUST0.9).

Since the jet is in geostrophic balance, the driving force of the jet is the meridional pressure gradient. Therefore, significant increase of wind speed at the jet core is due to strong response in meridional pressure gradient due to dust radiative forcing over this region. Notably, this is the only area where the surface circulation has significant response over the oceanic region. Even the WAM circulation, for instance over the Guinean coast, does not exhibit significant response over the ocean. Therefore, the heightened response of the WAWJ and its sensitivity to shortwave absorption is particularly important, as it functions as the major moisture flux perturbation from the ocean. In other words, the heightened response of the WAWJ also emphasizes the importance of high spatial resolution model to resolve these rather local-scale circulations.

Similarly, an enhanced response is predicted to the south of the Arabian Peninsula (including the Gulf of Aden), where the moist Somali low-level jet (SLLJ) meets the elevated terrain in the west and dry and hot northeasterlies from the interior of the peninsula in the east. As pointed out by Bangalath and Stenchikov (2015), although the SLLJ experiences weakening as a whole in response to the dust radiative effect, locally the wind response strengthens at the northern coast of the Arabian Sea adjacent to the Arabian Peninsula. This is because of the local amplification in the meridional heating gradient over this region, due to dust. Comparing the response in the experiments, it is shown that the jet response strongly depends on the dust shortwave absorption. The wind speed weakens as the dust shortwave absorption and the associated atmospheric heating reduce (Figs. 11a–c).

4. Discussion

The variability in the hematite content or SSA of dust is carefully chosen in the current study to bracket the spectrum of possible ranges of dust shortwave

absorption, which helps to demonstrate the corresponding sensitivity of climate responses. However, the shortwave absorption also depends on many other factors such as the albedo of the underlying surface, the dust size distribution, and the vertical structure of the dust loading. Therefore, the sign and magnitude of radiative forcing and climate response could vary under different environmental conditions, even for the same dust optical properties. In the present study, even in the least absorbing case (DUST0.9), TOA forcing is slightly positive over the bright Saharan and Arabian deserts. Nevertheless, a number of other factors could potentially change the sign of TOA forcing and corresponding climate responses. For instance, dust size distribution with a larger fraction of small particles or a darker surface albedo could change the sign of TOA forcing from positive to negative over those deserts, for the same set of dust refractive indices. This is why some studies estimated negative DDRF at TOA over these deserts (e.g., Yoshioka et al. 2007). Therefore, a final verdict on the possible range of the uncertainty related to dust shortwave absorption cannot be made by overlooking the uncertainty in the other factors on which dust shortwave absorption depends. However, the present study clearly demonstrates the sensitivity of the MENA dust belt, and the multiscale circulations associated with it, to a realistic range of dust shortwave absorptivity, by only changing the hematite content and keeping all other factors constant. Nevertheless, these results can be interpreted for changes in shortwave absorption due to any other reason.

Analysis of the precipitation response to shortwave absorption (Fig. 5) shows that the most sensitive part of the rainbelt to dust shortwave absorption is the northern edge. Geographically speaking, the maximum response occurs over the Sahel, the semiarid transition zone between the dry Saharan deserts to the north and the humid tropical savanna (Sudanian savanna) to the south. Precipitation response over this region varies from almost zero to $2 \text{ kg m}^{-2} \text{ day}^{-1}$ (in DUST2.7) as shortwave absorption increases (Fig. 5). The range of sensitivity is comparable to the mean summer precipitation over this region and is statistically significant. The response in the DUST2.7 experiment reaches up to 50% of the mean precipitation at some locations in the Sahel. The economies of most of the countries in the Sahel region largely depend on rain-fed agriculture. Even a small variability in the rainy season could affect the livelihood of millions of people (International Federation of Red Cross and Red Crescent Societies; <http://www.ifrc.org>). Therefore, accurate representation of dust shortwave absorption is very important for the Sahel climate simulation and prediction. Unfortunately, many of the operational

weather forecasting models, GCMs, and even reanalyses do not include dust radiative effect, although it is proven to be extremely important for the accuracy of radiation balance in numerical weather prediction models (e.g., Pérez et al. 2006; Alpert et al. 1998). One reason for avoiding dust radiative effect is its large uncertainty. Hence, considering the predicted sensitivity of the rainbelt, the present study suggests serious efforts to reduce uncertainty in dust shortwave absorption for better predictability of the region's weather and climate.

It was argued and portrayed in Bangalath and Stenchikov (2015) that dust acts as an off-equatorial additional heating source over MENA and it coincides with solar insolation maxima during summer. As a result, the interhemispheric temperature gradient enhances and it strengthens the local Hadley circulation and other embedded regional circulations such as the WAM and AEJ, and moves them farther northward to the summer hemisphere. The simulated responses in the current study are in good agreement with these arguments and are sensitive to the changes in shortwave absorption. As the dust-induced heating increases, the local Hadley circulation, WAM, WAWJ, and AEJ strengthen and move farther northward. In other words, the sensitivity of circulations to shortwave absorption is a further evidence for the mechanism proposed in Bangalath and Stenchikov (2015) regarding the dust–rainbelt interaction. Miller et al. (2014) conducted a similar sensitivity study by utilizing various estimates of dust optical properties. The present results are qualitatively in agreement with those results, especially the dependence of Sahel rainfall to dust shortwave absorption. However, neither a direct quantitative comparison of the results between these two studies nor validation of the mechanistic arguments presented in Miller et al. (2014) based on a simplified model is possible, as the studies use different models, assumptions, dust loading, and dust optical properties. Nevertheless, the dynamic responses and the precipitation response over Sahel predicted in the present study are in agreement with those arguments. For instance, the enhancement of the strength of the meridional overturning circulation in response to increasing dust shortwave absorption is explicitly portrayed in the present study.

It is also noteworthy that the response in the rainbelt (Fig. 5) and the associated circulation responses, such as local Hadley and Walker circulations (Figs. 7 and 8), AEJ (Fig. 9), and surface circulation (Fig. 11), have a significant east–west contrast. In general, the effects of shortwave absorption are stronger over East Africa, the southern Red Sea and the southwest tip of the Arabian Peninsula. This is an important feature and needs to be better understood. First of all, the forcing itself has an

east–west contrast in the present simulations with higher values in East Africa (Figs. 1 to 3), which could make heightened response there. Apart from this, analyses of Walker circulation (Fig. 8) demonstrate that East Africa (specifically the Ethiopian highlands and the southern Red Sea) experience significant response, unlike any other region. This differential response in the Walker circulation could also contribute to the predicted east–west contrast in the precipitation belt. In addition, from the surface circulation point of view (Fig. 11), West Africa has a more zonal component of wind associated with the WAM and WAWJ, whereas over East Africa the surface circulation is more meridional. Therefore, it is expected to predict a differential meridional circulation response over East Africa, provided that the large-scale forcing is primarily meridionally oriented (Fig. 4). Furthermore, East Africa has many “hot spots” in the climatological mean summer precipitation associated with orographic features such as the Ethiopian highlands and the Asir escarpment mountains in the southwest tip of the Arabian Peninsula, and areas with high local surface winds such as the Tokar Gap jet. These hot spots in the climatological mean precipitation and surface wind are well captured in our simulations (see Fig. S1) and they could influence the heightened response predicted over East Africa.

It is well known that the Atlantic SST in general, and specifically the near-equatorial SST gradient, plays an important role in the rainbelt over MENA region (e.g., Folland et al. 1986; Nicholson 2013; Davey et al. 2002; Cook 2008). However, the present study investigates the atmosphere-only sensitivity to dust shortwave absorption, using AMIP-type simulations with observed SST as bottom boundary conditions. This approach provides an ideal ocean forcing and helps to avoid the cold SST bias in equatorial ocean common to most of the coupled GCMs, and hence helps to improve the representation of the strength and position of the climatological mean rainbelt. On the other hand, any changes in SST due to dust radiative forcing could potentially alter the latent heat flux feedback and hence the sign and magnitude of the predicted response. Since SST is kept constant in AMIP-type simulations, the present study does not take the SST feedback into account. Simulations with fully coupled or mixed layer ocean simulations are necessary to incorporate this effect, which is beyond the scope of the present study.

5. Summary and conclusions

The present study explores the sensitivity of the tropical rainbelt across the MENA region and the driving circulations at various scales to a realistic range of dust shortwave absorption proposed by Balkanski et al. (2007). For

this purpose, AMIP-style simulations are conducted assuming three different cases of dust shortwave absorption, representing dust as a very efficient, standard, and inefficient shortwave absorber. The dust optical properties for these three cases are derived by assuming dust has a hematite content of 2.7%, 1.5%, and 0.9%, respectively (Balkanski et al. 2007). To efficiently incorporate various multiscale circulations that are crucial for the rainbelt maintenance and dynamics, global high-resolution simulations have been conducted at 25-km resolution using HiRAM. This method helps to overcome the two-way interaction issue arising from the forced boundary conditions in RCMs and the lack of sufficient resolution in conventional GCMs. The results show that the intensity and location of the tropical rainbelt are sensitive to the magnitude of dust shortwave absorption. As shortwave absorption increases, the rainbelt intensifies and moves farther northward. Maximum sensitivity is predicted at the northern edge of the rainbelt, which is geographically over the Sahel. Considering the social and ecological vulnerability of the Sahel region, the predicted sensitivity of rainbelt suggests the importance of accurate representation of dust shortwave absorption in the numerical models for accurate simulation of the region's climate and weather.

Dust-induced enhancement in the meridional heating gradient and the consequent increase in the interhemispheric temperature gradient act as the basic driving force for the rainbelt response. The interhemispheric heating gradient induced by dust intensifies the local Hadley circulation and moves it farther northward. The local Hadley circulation response is strongly sensitive to shortwave absorption; as absorption and associated heating increases, the Hadley circulation further enhances and moves farther poleward. Regional circulation features such as the WAM, AEJ, and WAWJ respond similarly, since they also strongly depend on the meridional heating/temperature gradient. These regional circulations intensify and move farther poleward as shortwave absorption increases. In brief, both overturning circulation and the embedded regional circulations contribute positively to rainbelt enhancement and its poleward shift in response to dust shortwave absorption. It all indicates that the sensitivity of the rainbelt stems from the sensitivity of these multiscale circulations to meridionally asymmetric shortwave heating induced by dust. To sum up, the present study demonstrates the sensitivity of the MENA rainbelt and the driving circulation to a plausible range of dust shortwave absorption. The results also demonstrate how the sensitivity in driving circulations determines the sensitivity of rainbelt to dust shortwave absorption.

There are some shortcomings and limitations in this study. First of all, the current study does not include

indirect radiative forcing, which is proven to be a significant contributor by modifying cloud properties. Furthermore, the study assumes constant optical properties spatially and temporally when in reality they change and have strong dependency on source regions (e.g., Perlwitz et al. 2015). It should also be noted that the present simulations are conducted by prescribing dust loading from an offline calculation. Therefore the study does not take into account the feedback of the rainbelt response on dust generation and its spatiotemporal distribution. Simulations with fully interactive dust might give different amount of dust loading and responses, since the perturbed precipitation can feed back on other factors such as soil erodibility and wet deposition. Such feedbacks could be either positive or negative (e.g., Yoshioka et al. 2007; Marsham et al. 2011; Colarco et al. 2014). However, addressing these issues is beyond the scope of the present study. All these issues should be addressed separately or together in future studies to better estimate the sensitivity.

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REFERENCES

- Alpert, P., Y. Kaufman, Y. Shay-El, D. Tanré, A. Da Silva, S. Schubert, and J. Joseph, 1998: Quantification of dust-forced heating of the lower troposphere. *Nature*, **395**, 367–370, doi:10.1038/26456.
- Balkanski, Y., M. Schulz, T. Claquin, and S. Guibert, 2007: Reevaluation of mineral aerosol radiative forcings suggests a better agreement with satellite and aeronet data. *Atmos. Chem. Phys.*, **7**, 81–95, doi:10.5194/acp-7-81-2007.
- Bangalath, H. K., and G. Stenchikov, 2015: Role of dust direct radiative effect on the tropical rainbelt over Middle East and North Africa: A high-resolution AGCM study. *J. Geophys. Res. Atmos.*, **120**, 4564–4584, doi:10.1002/2015JD023122.
- Biasutti, M., and A. Giannini, 2006: Robust Sahel drying in response to late 20th century forcings. *Geophys. Res. Lett.*, **33**, L11706, doi:10.1029/2006GL026067.
- Boyle, J., and S. A. Klein, 2010: Impact of horizontal resolution on climate model forecasts of tropical precipitation and diabatic heating for the TWP-ICE period. *J. Geophys. Res.*, **115**, D23113, doi:10.1029/2010JD014262.

- Bretherton, C. S., J. R. McCaa, and H. Grenier, 2004: A new parameterization for shallow cumulus convection and its application to marine subtropical cloud-topped boundary layers. Part I: Description and 1D results. *Mon. Wea. Rev.*, **132**, 864–882, doi:[10.1175/1520-0493\(2004\)132<0864:ANPFSC>2.0.CO;2](#).
- Brooks, N., and M. Legrand, 2000: Dust variability over northern Africa and rainfall in the Sahel. *Linking Climate Change to Land Surface Change*, S. J. McLaren and D. R. Kniveton, Eds., Springer, 1–25.
- Carlson, T. N., and S. G. Benjamin, 1980: Radiative heating rates for Saharan dust. *J. Atmos. Sci.*, **37**, 193–213, doi:[10.1175/1520-0469\(1980\)037<0193:RHRFSD>2.0.CO;2](#).
- Cess, R., G. Potter, S. Ghan, and W. Gates, 1985: The climatic effects of large injections of atmospheric smoke and dust—A study of climate feedback mechanisms with one- and three-dimensional climate models. *J. Geophys. Res.*, **90**, 12 937–12 950, doi:[10.1029/JD090iD07p12937](#).
- Charney, J. G., 1975: Dynamics of deserts and drought in the Sahel. *Quart. J. Roy. Meteor. Soc.*, **101**, 193–202, doi:[10.1002/qj.49710142802](#).
- Chin, M., 2009: *Atmospheric Aerosol Properties and Climate Impacts*. DIANE Publishing, 138 pp.
- Chýlek, P., and J. A. Coakley, 1974: Aerosols and climate. *Science*, **183**, 75–77, doi:[10.1126/science.183.4120.75](#).
- Claquin, T., M. Schulz, Y. Balkanski, and O. Boucher, 1998: Uncertainties in assessing radiative forcing by mineral dust. *Tellus*, **50B**, 491–505, doi:[10.1034/j.1600-0889.1998.t01-2-00007.x](#).
- Colarco, P. R., E. P. Nowottnick, C. A. Randles, B. Yi, P. Yang, K.-M. Kim, J. A. Smith, and C. G. Bardeen, 2014: Impact of radiatively interactive dust aerosols in the NASA GEOS-5 climate model: Sensitivity to dust particle shape and refractive index. *J. Geophys. Res. Atmos.*, **119**, 753–786, doi:[10.1002/2013JD020046](#).
- Cook, K. H., 1999: Generation of the African easterly jet and its role in determining West African precipitation. *J. Climate*, **12**, 1165–1184, doi:[10.1175/1520-0442\(1999\)012<1165:GOTAEJ>2.0.CO;2](#).
- , 2008: Climate science: The mysteries of Sahel droughts. *Nat. Geosci.*, **1**, 647–648, doi:[10.1038/ngeo320](#).
- Davey, M., and Coauthors, 2002: STOIC: A study of coupled model climatology and variability in tropical ocean regions. *Climate Dyn.*, **18**, 403–420, doi:[10.1007/s00382-001-0188-6](#).
- Dubovik, O., B. Holben, T. F. Eck, A. Smirnov, Y. J. Kaufman, M. D. King, D. Tanré, and I. Slutsker, 2002: Variability of absorption and optical properties of key aerosol types observed in worldwide locations. *J. Atmos. Sci.*, **59**, 590–608, doi:[10.1175/1520-0469\(2002\)059<0590:VOAAOP>2.0.CO;2](#).
- Folland, C., T. Palmer, and D. Parker, 1986: Sahel rainfall and worldwide sea temperatures, 1901–85. *Nature*, **320**, 602–607, doi:[10.1038/320602a0](#).
- Funk, C., M. D. Dettinger, J. C. Michaelsen, J. P. Verdin, M. E. Brown, M. Barlow, and A. Hoell, 2008: Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proc. Natl. Acad. Sci. USA*, **105**, 11 081–11 086, doi:[10.1073/pnas.0708196105](#).
- Giannini, A., R. Saravanan, and P. Chang, 2003: Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science*, **302**, 1027–1030, doi:[10.1126/science.1089357](#).
- Ginoux, P., M. Chin, I. Tegen, J. M. Prospero, B. Holben, O. Dubovik, and S.-J. Lin, 2001: Sources and distributions of dust aerosols simulated with the GOCART model. *J. Geophys. Res.*, **106** (D17), 20 255–20 273, doi:[10.1029/2000JD000053](#).
- , L. W. Horowitz, V. Ramaswamy, I. V. Geogdzhayev, B. N. Holben, G. Stenchikov, and X. Tie, 2006: Evaluation of aerosol distribution and optical depth in the geophysical fluid dynamics laboratory coupled model CM2.1 for present climate. *J. Geophys. Res.*, **111**, D22210, doi:[10.1029/2005JD006707](#).
- Grodsky, S. A., J. A. Carton, and S. Nigam, 2003: Near surface westerly wind jet in the Atlantic ITCZ. *Geophys. Res. Lett.*, **30**, 2009, doi:[10.1029/2003GL017867](#).
- Hack, J. J., J. M. Caron, G. Danabasoglu, K. W. Oleson, C. Bitz, and J. E. Truesdale, 2006: CCSM-CAM3 climate simulation sensitivity to changes in horizontal resolution. *J. Climate*, **19**, 2267–2289, doi:[10.1175/JCLI3764.1](#).
- Hagos, S. M., and K. H. Cook, 2008: Ocean warming and late-twentieth-century Sahel drought and recovery. *J. Climate*, **21**, 3797–3814, doi:[10.1175/2008JCLI2055.1](#).
- Hansen, J., M. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res.*, **102** (D6), 6831–6864, doi:[10.1029/96JD03436](#).
- , and Coauthors, 2005: Efficacy of climate forcings. *J. Geophys. Res.*, **110**, D18104, doi:[10.1029/2005JD005776](#).
- Haywood, J. M., and V. Ramaswamy, 1998: Global sensitivity studies of the direct radiative forcing due to anthropogenic sulfate and black carbon aerosols. *J. Geophys. Res.*, **103** (D6), 6043–6058, doi:[10.1029/97JD03426](#).
- , P. N. Francis, M. D. Glew, and J. P. Taylor, 2001: Optical properties and direct radiative effect of Saharan dust: A case study of two Saharan dust outbreaks using aircraft data. *J. Geophys. Res.*, **106** (D16), 18 417–18 430, doi:[10.1029/2000JD900319](#).
- , and Coauthors, 2003: Radiative properties and direct radiative effect of Saharan dust measured by the C-130 aircraft during shade: 1. Solar spectrum. *J. Geophys. Res.*, **108**, 8577, doi:[10.1029/2002JD002687](#).
- Held, I., T. Delworth, J. Lu, K. L. Findell, and T. Knutson, 2005: Simulation of Sahel drought in the 20th and 21st centuries. *Proc. Natl. Acad. Sci. USA*, **102**, 17 891–17 896, doi:[10.1073/pnas.0509057102](#).
- Horowitz, L. W., and Coauthors, 2003: A global simulation of tropospheric ozone and related tracers: Description and evaluation of MOZART, version 2. *J. Geophys. Res.*, **108**, 4784, doi:[10.1029/2002JD002853](#).
- Houze, R. A., and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys.*, **19**, 541–576, doi:[10.1029/RG019i004p00541](#).
- Jung, T., and Coauthors, 2012: High-resolution global climate simulations with the ECMWF model in Project Athena: Experimental design, model climate, and seasonal forecast skill. *J. Climate*, **25**, 3155–3172, doi:[10.1175/JCLI-D-11-00265.1](#).
- Kaufman, Y. J., 1987: Satellite sensing of aerosol absorption. *J. Geophys. Res.*, **92** (D4), 4307–4317, doi:[10.1029/JD092iD04p04307](#).
- , D. Tanré, O. Dubovik, A. Karnieli, and L. Remer, 2001: Absorption of sunlight by dust as inferred from satellite and ground-based remote sensing. *Geophys. Res. Lett.*, **28**, 1479–1482, doi:[10.1029/2000GL012647](#).
- Keyser, D., B. D. Schmidt, and D. G. Duffy, 1989: A technique for representing three-dimensional vertical circulations in baroclinic disturbances. *Mon. Wea. Rev.*, **117**, 2463–2494, doi:[10.1175/1520-0493\(1989\)117<2463:ATFRTD>2.0.CO;2](#).
- Koteswaram, P., 1958: The easterly jet stream in the tropics. *Tellus*, **10**, 43–57, doi:[10.1111/j.2153-3490.1958.tb01984.x](#).
- Lau, K., M. Kim, and K. Kim, 2006: Asian summer monsoon anomalies induced by aerosol direct forcing: The role of the Tibetan Plateau. *Climate Dyn.*, **26**, 855–864, doi:[10.1007/s00382-006-0114-z](#).

- , K. Kim, Y. Sud, and G. Walker, 2009: A GCM study of the response of the atmospheric water cycle of West Africa and the Atlantic to Saharan dust radiative forcing. *Ann. Geophys.*, **27**, 4023–4037, doi:[10.5194/angeo-27-4023-2009](https://doi.org/10.5194/angeo-27-4023-2009).
- Lau, N.-C., and J. J. Ploshay, 2009: Simulation of synoptic-and subsynoptic-scale phenomena associated with the East Asian summer monsoon using a high-resolution GCM. *Mon. Wea. Rev.*, **137**, 137–160, doi:[10.1175/2008MWR2511.1](https://doi.org/10.1175/2008MWR2511.1).
- Liao, H., and J. Seinfeld, 1998: Radiative forcing by mineral dust aerosols: Sensitivity to key variables. *J. Geophys. Res.*, **103** (D24), 31 637–31 645, doi:[10.1029/1998JD200036](https://doi.org/10.1029/1998JD200036).
- Lin, S.-J., 2004: A “vertically Lagrangian” finite-volume dynamical core for global models. *Mon. Wea. Rev.*, **132**, 2293–2307, doi:[10.1175/1520-0493\(2004\)132<2293:AVLFDC>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<2293:AVLFDC>2.0.CO;2).
- Marshall, J. H., P. Knippertz, N. S. Dixon, D. J. Parker, and G. Lister, 2011: The importance of the representation of deep convection for modeled dust-generating winds over West Africa during summer. *Geophys. Res. Lett.*, **38**, L16803, doi:[10.1029/2011GL048368](https://doi.org/10.1029/2011GL048368).
- Miller, R., and I. Tegen, 1998: Climate response to soil dust aerosols. *J. Climate*, **11**, 3247–3267, doi:[10.1175/1520-0442\(1998\)011<3247:CRTSDA>2.0.CO;2](https://doi.org/10.1175/1520-0442(1998)011<3247:CRTSDA>2.0.CO;2).
- , J. Perlwitz, and I. Tegen, 2004: Feedback upon dust emission by dust radiative forcing through the planetary boundary layer. *J. Geophys. Res.*, **109**, D24209, doi:[10.1029/2004JD004912](https://doi.org/10.1029/2004JD004912).
- , P. Knippertz, C. P. García-Pando, J. P. Perlwitz, and I. Tegen, 2014: Impact of dust radiative forcing upon climate. *Mineral Dust: A Key Player in the Earth System*, P. Knippertz and J.-B. W. Stuut, Eds., Springer, 327–357.
- Moulin, C., H. R. Gordon, V. F. Banzon, and R. H. Evans, 2001: Assessment of Saharan dust absorption in the visible from SeaWiFS imagery. *J. Geophys. Res.*, **106** (D16), 18 239–18 249, doi:[10.1029/2000JD900812](https://doi.org/10.1029/2000JD900812).
- Nicholson, S. E., 1980: The nature of rainfall fluctuations in subtropical West Africa. *Mon. Wea. Rev.*, **108**, 473–487, doi:[10.1175/1520-0493\(1980\)108<0473:TNORFI>2.0.CO;2](https://doi.org/10.1175/1520-0493(1980)108<0473:TNORFI>2.0.CO;2).
- , 2000: The nature of rainfall variability over Africa on time scales of decades to millennia. *Global Planet. Change*, **26**, 137–158, doi:[10.1016/S0921-8181\(00\)00040-0](https://doi.org/10.1016/S0921-8181(00)00040-0).
- , 2009: A revised picture of the structure of the “monsoon” and land ITCZ over West Africa. *Climate Dyn.*, **32**, 1155–1171, doi:[10.1007/s00382-008-0514-3](https://doi.org/10.1007/s00382-008-0514-3).
- , 2013: The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteor.*, **2013**, 453521, doi:[10.1155/2013/453521](https://doi.org/10.1155/2013/453521).
- Osborne, S., B. Johnson, J. Haywood, A. Baran, M. Harrison, and C. McConnell, 2008: Physical and optical properties of mineral dust aerosol during the dust and biomass-burning experiment. *J. Geophys. Res.*, **113** (D23), D00C03, doi:[10.1029/2007JD009551](https://doi.org/10.1029/2007JD009551).
- Otto, S., and Coauthors, 2009: Solar radiative effects of a Saharan dust plume observed during SAMUM assuming spheroidal model particles. *Tellus*, **61B**, 270–296, doi:[10.1111/j.1600-0889.2008.00389.x](https://doi.org/10.1111/j.1600-0889.2008.00389.x).
- Paeth, H., K. Born, R. Podzun, and D. Jacob, 2005: Regional dynamical downscaling over West Africa: Model evaluation and comparison of wet and dry years. *Meteor. Z.*, **14**, 349–367, doi:[10.1127/0941-2948/2005/0038](https://doi.org/10.1127/0941-2948/2005/0038).
- Pérez, C., S. Nickovic, G. Pejanovic, J. M. Baldasano, and E. Özsoy, 2006: Interactive dust-radiation modeling: A step to improve weather forecasts. *J. Geophys. Res.*, **111**, D16206, doi:[10.1029/2005JD006717](https://doi.org/10.1029/2005JD006717).
- Perlwitz, J., C. Pérez García-Pando, and R. Miller, 2015: Predicting the mineral composition of dust aerosols—Part 1: Representing key processes. *Atmos. Chem. Phys.*, **15**, 11 593–11 627, doi:[10.5194/acpd-15-3493-2015](https://doi.org/10.5194/acpd-15-3493-2015).
- Putman, W. M., and S.-J. Lin, 2007: Finite-volume transport on various cubed-sphere grids. *J. Comput. Phys.*, **227**, 55–78, doi:[10.1016/j.jcp.2007.07.022](https://doi.org/10.1016/j.jcp.2007.07.022).
- , —, and B.-W. Shen, 2005: Cross-platform performance of a portable communication module and the NASA finite volume general circulation model. *Int. J. High Perform. Comput. Appl.*, **19**, 213–223, doi:[10.1177/1094342005056101](https://doi.org/10.1177/1094342005056101).
- Ramaswamy, V., and J. Kiehl, 1985: Sensitivities of the radiative forcing due to large loadings of smoke and dust aerosols. *J. Geophys. Res.*, **90** (D3), 5597–5613, doi:[10.1029/JD090iD03p05597](https://doi.org/10.1029/JD090iD03p05597).
- Raut, J.-C., and P. Chazette, 2008: Radiative budget in the presence of multi-layered aerosol structures in the framework of AMMA SOP-0. *Atmos. Chem. Phys.*, **8**, 6839–6864, doi:[10.5194/acp-8-6839-2008](https://doi.org/10.5194/acp-8-6839-2008).
- Rayner, N., D. E. Parker, E. Horton, C. Folland, L. Alexander, D. Rowell, E. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108** (D14), 4407, doi:[10.1029/2002JD002670](https://doi.org/10.1029/2002JD002670).
- Ryder, C., and Coauthors, 2013: Optical properties of Saharan dust aerosol and contribution from the coarse mode as measured during the Fennec 2011 aircraft campaign. *Atmos. Chem. Phys.*, **13**, 303–325, doi:[10.5194/acp-13-303-2013](https://doi.org/10.5194/acp-13-303-2013).
- Schulz, M., and Coauthors, 2006: Radiative forcing by aerosols as derived from the AeroCom present-day and pre-industrial simulations. *Atmos. Chem. Phys.*, **6**, 5225–5246, doi:[10.5194/acp-6-5225-2006](https://doi.org/10.5194/acp-6-5225-2006).
- Schwendike, J., P. Govekar, M. J. Reeder, R. Wardle, G. J. Berry, and C. Jakob, 2014: Local partitioning of the overturning circulation in the tropics and the connection to the Hadley and Walker circulations. *J. Geophys. Res. Atmos.*, **119**, 1322–1339, doi:[10.1002/2013JD020742](https://doi.org/10.1002/2013JD020742).
- , G. J. Berry, M. J. Reeder, C. Jakob, P. Govekar, and R. Wardle, 2015: Trends in the local Hadley and local Walker circulations. *J. Geophys. Res. Atmos.*, **120**, 7599–7618, doi:[10.1002/2014JD022652](https://doi.org/10.1002/2014JD022652).
- Shaffrey, L. C., and Coauthors, 2009: U.K. HiGEM: The new U.K. high-resolution global environment model—Model description and basic evaluation. *J. Climate*, **22**, 1861–1896, doi:[10.1175/2008JCLI2508.1](https://doi.org/10.1175/2008JCLI2508.1).
- Slingo, A., and Coauthors, 2006: Observations of the impact of a major Saharan dust storm on the atmospheric radiation balance. *Geophys. Res. Lett.*, **33**, L24817, doi:[10.1029/2006GL027869](https://doi.org/10.1029/2006GL027869).
- Sokolik, I. N., and O. B. Toon, 1996: Direct radiative forcing by anthropogenic airborne mineral aerosols. *Nature*, **381**, 681–683, doi:[10.1038/381681a0](https://doi.org/10.1038/381681a0).
- 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](https://doi.org/10.1029/2008GL035900).
- Stier, P., J. H. Seinfeld, S. Kinne, and O. Boucher, 2007: Aerosol absorption and radiative forcing. *Atmos. Chem. Phys.*, **7**, 5237–5261, doi:[10.5194/acp-7-5237-2007](https://doi.org/10.5194/acp-7-5237-2007).
- Sylla, M., A. Gaye, and G. Jenkins, 2012: On the fine-scale topography regulating changes in atmospheric hydrological cycle and extreme rainfall over West Africa in a regional climate model projections. *Int. J. Geophys.*, **2012**, 981649, doi:[10.1155/2012/981649](https://doi.org/10.1155/2012/981649).

- Tanré, D., and Coauthors, 2001: Climatology of dust aerosol size distribution and optical properties derived from remotely sensed data in the solar spectrum. *J. Geophys. Res.*, **106**, 18 205–18 217, doi:[10.1029/2000JD900663](https://doi.org/10.1029/2000JD900663).
- Tegen, I., A. A. Lacis, and I. Fung, 1996: The influence on climate forcing of mineral aerosols from disturbed soils. *Nature*, **380**, 419–422, doi:[10.1038/380419a0](https://doi.org/10.1038/380419a0).
- Thorncroft, C., 1995: An idealized study of African easterly waves. III: More realistic basic states. *Quart. J. Roy. Meteor. Soc.*, **121**, 1589–1614, doi:[10.1002/qj.49712152706](https://doi.org/10.1002/qj.49712152706).
- , and B. Hoskins, 1994a: An idealized study of African easterly waves. I: A linear view. *Quart. J. Roy. Meteor. Soc.*, **120**, 953–982, doi:[10.1002/qj.49712051809](https://doi.org/10.1002/qj.49712051809).
- , and —, 1994b: An idealized study of African easterly waves. II: A nonlinear view. *Quart. J. Roy. Meteor. Soc.*, **120**, 983–1015, doi:[10.1002/qj.49712051810](https://doi.org/10.1002/qj.49712051810).
- , and M. Blackburn, 1999: Maintenance of the African easterly jet. *Quart. J. Roy. Meteor. Soc.*, **125**, 763–786, doi:[10.1002/qj.49712555502](https://doi.org/10.1002/qj.49712555502).
- Volz, F. E., 1973: Infrared optical constants of ammonium sulfate, Sahara dust, volcanic pumice, and flyash. *Appl. Opt.*, **12**, 564–568, doi:[10.1364/AO.12.000564](https://doi.org/10.1364/AO.12.000564).
- Williams, A. P., and C. Funk, 2011: A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. *Climate Dyn.*, **37**, 2417–2435, doi:[10.1007/s00382-010-0984-y](https://doi.org/10.1007/s00382-010-0984-y).
- Yoshioka, M., N. M. Mahowald, A. J. Conley, W. D. Collins, D. W. Fillmore, C. S. Zender, and D. B. Coleman, 2007: Impact of desert dust radiative forcing on Sahel precipitation: Relative importance of dust compared to sea surface temperature variations, vegetation changes, and greenhouse gas warming. *J. Climate*, **20**, 1445–1467, doi:[10.1175/JCLI4056.1](https://doi.org/10.1175/JCLI4056.1).
- Yue, X., H. Wang, H. Liao, and K. Fan, 2010: Direct climatic effect of dust aerosol in the NCAR Community Atmosphere Model version 3 (CAM3). *Adv. Atmos. Sci.*, **27**, 230–242, doi:[10.1007/s00376-009-8170-z](https://doi.org/10.1007/s00376-009-8170-z).
- , H. Liao, H. Wang, S. Li, and J. Tang, 2011a: Role of sea surface temperature responses in simulation of the climatic effect of mineral dust aerosol. *Atmos. Chem. Phys.*, **11**, 6049–6062, doi:[10.5194/acp-11-6049-2011](https://doi.org/10.5194/acp-11-6049-2011).
- , H. Wang, H. Liao, and D. Jiang, 2011b: Simulation of the direct radiative effect of mineral dust aerosol on the climate at the Last Glacial Maximum. *J. Climate*, **24**, 843–858, doi:[10.1175/2010JCLI3827.1](https://doi.org/10.1175/2010JCLI3827.1).
- Zhao, M., I. M. Held, S.-J. Lin, and G. A. Vecchi, 2009: Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50-km resolution GCM. *J. Climate*, **22**, 6653–6678, doi:[10.1175/2009JCLI3049.1](https://doi.org/10.1175/2009JCLI3049.1).