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Sensitivity of MENA 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 and North Africa (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, standard and inefficient absorber. Inter-comparison 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 multi-scale circulations that define the rainbelt. The maximum response and sensitivity are predicted over the northern edge of the rainbelt, geographically over 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 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.

31 **1. Introduction**

32 As a ubiquitous and arguably dominant portion of aerosols in the atmosphere, the role of dust
33 in the climate system has long been appreciated (e.g., Carlson and Benjamin 1980; Cess et al.
34 1985; Ramaswamy and Kiehl 1985; Tegen et al. 1996). It has also long been recognized that dust
35 influences earth's radiation budget directly (direct radiative effect) by scattering and absorbing
36 both solar and planetary radiation and by emitting the latter (e.g., Sokolik and Toon 1996; Liao and
37 Seinfeld 1998; Miller and Tegen 1998). However, in recent years, there has been a specific growing
38 interest in the role of dust induced atmospheric circulation changes on the strength and latitudinal
39 extent of the tropical rainbelt across the Middle East and North Africa (MENA) (Bangalath and
40 Stenchikov 2015, e.g.,). This is partly due to the rainbelt's proximity to the "dust belt" associated
41 with world's biggest deserts, and partly because of the much-discussed rainfall variability of the
42 region ("Sahel drought"). Although prior studies demonstrated various plausible mechanisms
43 involved in the dust-rainbelt interaction, especially over West Africa, significant uncertainty still
44 remains in both quantitative and qualitative conclusions among these studies. Many of the prior
45 modeling studies showed strengthening of the summer rainbelt across MENA, in response to dust
46 direct radiative effect (e.g., Bangalath and Stenchikov 2015; Lau et al. 2009; Yue et al. 2011a;
47 Miller et al. 2014), while others predict its weakening (e.g., Yoshioka et al. 2007; Yue et al. 2011b).
48 The uncertainty in the dust refractive index estimates and the consequent uncertainty in the dust
49 shortwave absorption are proposed to be a major cause of the disparity (e.g., Solomon et al. 2008;
50 Miller et al. 2004).

51 It has been shown that the values of the imaginary part of the shortwave refractive index, which
52 decides the amount of shortwave absorption, vary by an order of magnitude among various studies
53 (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 non-absorbing 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 spatio-temporal variability, various optical properties of dust, model resolution, model components and models' internal variability. Therefore, an inter-comparison 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

78 a single model with varying amounts of dust shortwave absorption, to avoid uncertainties asso-
79 ciated with inter-model differences in the sensitivity analyses. There were some specific efforts
80 along this line, which were conducted using either coarse resolution global models or regional
81 climate models. The global experiments with general circulation models (GCMs) generally focus
82 on global scale responses and they refrain from detailed regional analysis mainly due to their con-
83 ventional coarser spatial resolution (e.g., Colarco et al. 2014). On the contrary, the experiments
84 using regional climate models (RCMs) (e.g., Solomon et al. 2008) fail to incorporate the global-
85 scale circulation response to dust radiative forcing that span outside the domain of RCM, although
86 they represent regional-scale responses in detail. An original and forthright solution to overcoming
87 these issues is to use high resolution global simulation.

88 Taking into consideration the above mentioned facts, the present study investigates the sensitiv-
89 ity of the summer [June-August (JJA)] tropical rainbelt over MENA and the causative multi-scale
90 circulation responses to varying dust shortwave absorption, using a high resolution Atmospheric
91 General Circulation Model (AGCM). AMIP-style numerical simulations are conducted with the
92 High Resolution Atmospheric Model (HiRAM) at a horizontal resolution of 25 km, with three
93 different data sets of dust optical properties, representing dust as an inefficient, standard, and very
94 efficient shortwave absorber. These three sets of dust optical properties are calculated based on
95 three different refractive indices estimated by Balkanski et al. (2007), which bracket the possible
96 range of dust shortwave absorption. It should be noted that the present study specifically investi-
97 gates the sensitivity of the atmosphere-only response to dust shortwave absorption using AMIP-
98 style simulations by prescribing observed sea surface temperature (SST) as the bottom boundary
99 condition.

100 The rainbelt across MENA can primarily be seen as the ascending branch of the local Hadley
101 circulation. However, there are many distinct regional circulation features embedded within this

102 large-scale averaged circulation, such as West African monsoon (WAM), African Easterly Jet
103 (AEJ), Tropical Easterly Jet (TEJ) and West African Westerly Jet (WAWJ), which are also found
104 to be significant drivers of the rainbelt (e.g., Nicholson 2009; Cook 1999; Thorncroft and Black-
105 burn 1999). Therefore, incorporation of both global and regional circulations and the complex
106 multi-scale inter-play among these circulations are crucial for an accurate simulation of the rain-
107 belt across MENA. Recently, high resolution GCMs have emerged as an efficient way to accom-
108 plish this with the advent of petascale computing infrastructures. For instance, Bangalath and
109 Stenchikov (2015) effectively used HiRAM simulations at 25 km spatial resolution, to investigate
110 regional climate responses to globally inhomogeneous dust forcing. The high resolution (25 km)
111 simulations ensure better representation of the relatively narrow band (a few degrees of latitude) of
112 precipitation belt and the sharp gradients in the climate variables across this region, which are cru-
113 cial entities for an accurate simulation of the region's climate. Improved resolution also enables
114 better representation of orographic heterogeneity and other fine-scale forcings that are decisive
115 factors for the regional climate (e.g., Sylla et al. 2012; Paeth et al. 2005).

116 It was shown in Bangalath and Stenchikov (2015) that the dust induced off-equatorial atmo-
117 spheric heating in the MENA domain, associated with major dust source regions, alters the strength
118 and position of the local Hadley circulation and regional circulations such as WAM and AEJ.
119 These multi-scale circulation responses in turn strengthen and widen the rainbelt northward. It is
120 noteworthy that the maximum response occurs at the northern edges of the rainbelt in their ex-
121 periments. Importantly, the northern edge of the summer rainbelt is geographically over Sahel;
122 a semi-arid strip between the Sahara desert and the Sudanian Savanna that stretches between the
123 Atlantic Ocean and the Red Sea. Sahel is a unique ecoclimatic region that experienced persistent
124 drought from the 1960s to the 1980s and recovery in later years, the cause of which is an ongoing
125 debate in climate science (e.g., Nicholson 1980; Folland et al. 1986a; Held et al. 2005). The 20th

126 century evolution of Sahel rainfall, which has had severe impacts on the region's economy and life
127 of the local population, has been widely recognized as the most severe change in the hydrological
128 climate of any region in the era of instrumental records. Though this variability is mainly explained
129 by the influence of slowly varying climate components, such as SST (e.g., Folland et al. 1986a;
130 Giannini et al. 2003; Hagos and Cook 2008) and land conditions (e.g., Charney 1975), variability
131 in dust radiative forcing is also considered to be a causative mechanism (e.g., Brooks and Legrand
132 2000; Biasutti and Giannini 2006; Nicholson 2000; Yoshioka et al. 2007). At the minimum, dust
133 radiative effects could modulate the climate variability of this region as Sahara/Sahel dust emis-
134 sion has high variability from millennial to diurnal scales. Therefore, it is extremely important to
135 estimate the sensitivity of tropical rainbelt to dust shortwave absorption for a better interpretation
136 of the simulation of the historical and future climate of the MENA region in general, and of Sahel
137 in particular.

138 The rest of this article is organized as follows. Section 2 describes the model and experimental
139 design. Sensitivity of the rainbelt and the related multi-scale circulation, to the dust shortwave
140 absorption are discussed in section 3. A detailed discussion and summary follow in sections 4 and
141 5, respectively.

142 **2. Model and experiment design**

143 The global simulations at horizontal resolution of 25 km and even higher are becoming possible
144 nowadays due to improved super-computing infrastructure and highly scalable dynamical cores
145 (e.g., Zhao et al. 2009; Shaffrey et al. 2009; Lin 2004; Putman et al. 2005; Hack et al. 2006). At
146 this range of spatial resolution, models explicitly resolve important mesoscale features, weather
147 events (e.g., Zhao et al. 2009; Jung et al. 2012) and better simulate the orographically induced cir-
148 culations 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, Hi-
RAM, 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 ap-
plications 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 Hi-
RAM which has 25-km horizontal grid spacing with 360 by 360 finite-volume cells on each face
of the cube. A non-intrusive shallow convective scheme (Bretherton et al. 2004) replaces the cus-
tomary 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 ra-
diative 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) data set (Rayner et al. 2003). There-
fore, 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, 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

173 concentrations are found to be within a factor of 2 of the observed values (Ginoux et al. 2006).
174 Sources of dust are from the Goddard Chemistry Aerosol Radiation and Transport (GOCART)
175 model (Ginoux et al. 2001). Size distribution of dust aerosol is discretized into eight bins from 0.1
176 to 10 μm . Optical properties are estimated by assuming all dust particles originates from Sahara.
177 The specific extinction coefficients of dust are calculated from Mie theory using refractive indices
178 from the recent estimates of Balkanski et al. (2007), for shortwave bands, and from Volz (1973) for
179 longwave bands. Calculations assume three different cases of hematite content in dust by volume,
180 2.7%, 1.5% and 0.9%, which represent dust as a very efficient, standard and inefficient shortwave
181 absorber, respectively (Balkanski et al. 2007).

182 The general experiment design in this study is similar to that in Bangalath and Stenchikov
183 (2015), except that the current study investigates specifically the sensitivity of rainbelt and the
184 various multi-scale circulations that define the rainbelt, to dust shortwave absorption. Validation
185 of the model performance in reproducing a realistic rainbelt over MENA region was conducted in
186 Bangalath and Stenchikov (2015), by comparing with observed data. The result showed that Hi-
187 RAM simulates the rainbelt quite realistically and it captures the key features of the precipitation
188 climatology, especially the local precipitation maxima associated with the orographic features.
189 Further validation, especially that of the multi-scale circulations, is provided in the supplemen-
190 tary material of the present paper, as comparisons against ERA Interim re-analyses data. Four
191 HiRAM experiments (Table 1) are conducted for a 11 year period (1999–2009). Each of these
192 experiments comprises three ensemble members simulated from slightly different initial condi-
193 tions. One seasonal cycles (one year) is omitted from further analysis to avoid a spin-up period.
194 The “NoDUST” experiment omits dust radiative forcing in the simulations. The three other sim-
195 ulations, “DUST0.9”, “DUST1.5” and “DUST2.7” accounts for the radiative effect of dust with
196 a hematite content of 0.9%, 1.5% and 2.7% respectively. The sensitivity of atmospheric response

197 to varying dust shortwave absorption can be estimated by an inter-comparison of the anomalies of
198 climate variables in these three different simulations, compared to the NoDUST simulation.

199 **3. Results**

200 *a. Direct radiative forcing and heating rate anomalies*

201 To characterize the direct radiative effect of dust aerosols on the climate, radiative forcing and
202 heating rate anomalies are calculated. Following Bangalath and Stenchikov (2015) and other rel-
203 evant past studies (e.g., Hansen et al. 2005; Chin 2009), dust direct radiative forcing (DDRF)
204 is defined as the “*net (longwave+shortwave) radiative flux difference between a state with dust*
205 *loading and that without dust loading (downwelling minus upwelling), calculated under the same*
206 *meteorological conditions.*” In this sense, positive DDRF corresponds to warming of the system
207 and vice versa. The forcing is estimated separately at top of the atmosphere (TOA), surface and
208 within the atmosphere. The radiative fluxes with and without dust direct radiative effect are calcu-
209 lated in the simulations by calling the radiation routine twice at each radiation time step; one with
210 dust radiative effect and the other without dust influence. However, the radiation calculation with-
211 out dust influence does not feedback to the model evolution. Instead, this estimation is used only
212 to calculate the DDRF and heating rate anomalies, by comparing it with the radiation calculation
213 influenced by dust radiative effect.

214 Typically, satellite or AERONET based estimation of aerosol radiative forcing is done only
215 under clear-sky conditions, as it is not straightforward to screen out the cloud effect on radiation
216 from that of the aerosols, when they are collocated. Modeling studies generally prefer to estimate
217 forcing under all-sky conditions, mainly due to the uncertainties in cloud free scenes in the models
218 (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 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 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 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-wavelength, 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

243 averaged values lie between -0.46 W/m^2 (DUST0.9) to -0.79 W/m^2 (DUST2.7) in all-sky condi-
244 tion and between -0.63 W/m^2 (DUST0.9) to -1.02 W/m^2 (DUST2.7) in clear-sky condition. Again,
245 these forcing are much higher over MENA.

246 The DDRF within the atmosphere (difference between DDRF at TOA and at surface) can be
247 deduced as the net dust induced heating within the atmosphere, which ultimately perturbs the sta-
248 bility, cloud formation (semi-direct effect)(e.g., Hansen et al. 1997) and consequently multi-scale
249 circulations and precipitation. The DDRF within the atmosphere is always warming (positive),
250 which indicates that the shortwave heating dominates the longwave cooling (Table 2). Atmo-
251 spheric warming increases as shortwave absorption increases. The globally averaged forcing
252 ranges from $+0.27 \text{ W/m}^2$ to $+0.83 \text{ W/m}^2$ in all-sky conditions and from $+0.29 \text{ W/m}^2$ to $+0.88$
253 W/m^2 in clear-sky conditions.

254 In general, the MENA region experiences contrastingly high forcing at all levels compared to
255 the global average and the difference is almost on one order of magnitude. This is because the
256 region has high dust loading associated with major source regions and a relatively higher ratio of
257 coarse to fine mode dust particles (not shown) near to these source regions. Higher coarse mode
258 dust fraction leads to reduced SSA and increased absorption (e.g., Otto et al. 2009; Ryder et al.
259 2013). This is why the MENA region experiences reduced SSA compared to the global average
260 (see Table 2).

261 As the present study specifically focuses on climate responses during the boreal summer season,
262 the spatial pattern of summer DDRF are depicted for different experiments separately at TOA,
263 surface and within the atmosphere. Figure 1 shows global patterns of all-sky DDRF at TOA dur-
264 ing summer, for all the three experiments, assuming varying dust shortwave absorption. Overall,
265 the forcing is concentrated over the Northern Hemispheric subtropics, especially over MENA, as-
266 sociated with the major dust source regions including Sahara deserts, Sahel, Arabian desert and

267 downwind of these source regions. The most noticeable feature of the TOA forcing, in general, is
 268 the change in the sign of the forcing regionally. Over bright deserts the forcing is positive (warm-
 269 ing) and over darker ocean it is negative (cooling). This is due to the fact that the TOA aerosol
 270 forcing is highly dependent on the effective albedo of the underlying surface ("albedo effect") in
 271 addition to its dependency on the physical, chemical and optical properties of the particles (e.g.,
 272 Liao and Seinfeld 1998; Claquin et al. 1998; Stier et al. 2007; Chylek and Coakley 1974; Kauf-
 273 man 1987). In other words, if the combined aerosol-surface system reflects less solar radiation
 274 than does the surface alone, the TOA forcing becomes positive (warming the system). Over bright
 275 deserts, where surface albedo generally exceeds 0.3, the low SSA values of dust can lead to a
 276 combined dust-surface system darker than the underlying surface. Therefore, the value of dust
 277 SSA becomes a decisive factor in determining the sign of the TOA forcing over deserts. However,
 278 over dark surfaces like ocean, where surface albedo is generally less than 0.1, it is less probable to
 279 have positive forcing with the range of SSA that dust generally has. Moreover, absorbing aerosols
 280 such as dust, situated above a cloud layer, can induce positive TOA forcing in all-sky conditions,
 281 as the cloud layer can effectively act as a brighter underlying surface in this case (e.g., Schulz et al.
 282 2006; Haywood and Ramaswamy 1998).

283 In terms of the sensitivity of the TOA forcing to varying dust shortwave absorption, the positive
 284 forcing (warming) over MENA diminishes and even changes the sign as SSA increases (going
 285 from DUST2.7 to DUST0.9), especially at regions like Sahel. Similarly, the cooling over the
 286 oceanic region (negative TOA forcing) enhances as the shortwave absorption reduces. In effect
 287 there is a contrast even in the magnitude of the TOA forcing between adjacent land and ocean. As
 288 the shortwave absorption increases (from DUST0.9 to DUST2.7), positive TOA forcing over land
 289 intensifies and negative TOA forcing over ocean reduces significantly. It implies that if the dust
 290 assumes high SSA value, the major impact will be over land (deserts) rather than the downwind

291 oceanic region, in terms of TOA forcing. This differential TOA forcing over adjacent land and
292 ocean could potentially influence local circulations originating from the land-sea thermal contrast,
293 such as WAM and land-sea breezes.

294 Figure 2 depicts all-sky DDRF at surface. At surface, the DDRF is always cooling (negative) as it
295 is the combined effect of absorption and scattering in the atmosphere. Surface forcing is extremely
296 sensitive to the SSA or hematite content, as it is a strong function of the shortwave absorption
297 within the atmosphere. Therefore, as the absorption reduces (from Fig. 2a to 2c), DDRF at
298 surface also reduces. This indicates the significant role of atmospheric shortwave absorption to
299 the surface DDRF.

300 Forcing within the atmosphere can be seen as the difference between TOA and surface forcing,
301 which can induce a variety of climate effects by influencing the vertical stability, cloud forma-
302 tion (semi-direct effect or cloud burning off) and circulation patterns. Elevated Heat Pump (EHP)
303 hypotheses (Lau et al. 2009, 2006) (a regional manifestation of semi-direct effect), is a typical ex-
304 ample of how the heating within the atmosphere induced by dust will influence circulation. DDRF
305 (all-sky) within the atmosphere is estimated by subtracting forcing at TOA from that at surface
306 (Fig. 3). The forcing is always warming (positive) within the atmosphere, to which the atmo-
307 sphere primarily respond dynamically. And the magnitude of the forcing is sensitive to shortwave
308 absorption. As expected, warming reduces as shortwave absorption reduces. The heat trapped in
309 the atmosphere (warming) in DUST1.5 experiment is almost twice larger than that of DUST0.9
310 and it becomes thrice larger in DUST2.7 case.

311 The role of surface radiative forcing (reduced radiation in the present case) in the climate re-
312 sponse is through changes in surface heat fluxes, dominantly in latent heat flux over the oceanic
313 region. However, negative forcing at the ocean surface does not feedback as reduced latent heat
314 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 section 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 further 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 (20W- 60E) meridional cross section of dust induced heating rate anomalies are plotted for all three experiments (Fig. 4). Dust induced heating is confined to the subtropical lower-mid 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 DUST2.7), the heating rate increases and hence the inter-hemispheric heating gradient also strengthens. This strengthening of inter-hemispheric 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 the supplemental material of this paper, from Fig. 1 and 2). A two-tailed student's t test is performed to estimate the statistical significance of the rainbelt response. The areas where the response is sig-

nificant at 95% confidence level are marked by hatching. Figure 5 shows the responses in the mean summer precipitation for all three cases. The thick red contour bounds the area where rainfall is above $3 \text{ kg/m}^2/\text{day}$ 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 stronger a response than other regions. A comparison of the response among experiments shows that the rainbelt intensity and position of the rainbelt is sensitive to dust shortwave absorption. The rainbelt intensifies and shifts further northward, 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 part 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 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 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 (Fig. 1 to 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 sub-tropics 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 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, though it is relatively weaker. This dipole pattern of response in m_ϕ is consistent with the pattern of the rainbelt response (Fig. 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 the sign (Fig. 7a to 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 local Hadley response (Fig. 7).

Similar to the sensitivity of m_ϕ , m_λ response weakens as absorption reduces (Fig. 8a to 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 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 vital for the rainbelt dynamics. Its response is crucial for the rainbelt's strength and position, as it is the main mechanism to provide mid-tropospheric 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 (AEW) (e.g., Thorncroft and Hoskins 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, AEJ response exhibits a dipole pattern: an increase in wind speed to the north and vice versa, 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 AEJ, TEJ is also an important mechanism influencing the rainbelt by providing upper-tropospheric shear and moisture supply at that level. However, TEJ forms as a geostrophic easterly flow from the ISM anticyclone (upper troposphere) (Koteswaram 1958). Bangalath and Stenchikov (2015) showed that 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 strengthen towards 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 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

455 from the tropical Atlantic. Figure 11 shows the response in monsoon circulation depicted by the
 456 wind response at 925 hPa. The wind vectors represent the mean wind at each experiment and
 457 shaded contours are the responses. As explained in Bangalath and Stenchikov (2015), in general,
 458 WAM circulation strengthens and shifts further north in response to dust forcing. A dipole pattern
 459 of response is evident at the convergence zone where moist WAM circulation meets the dry Har-
 460 mattan wind. The wind weakens to the north of convergence (Harmattan wind) and strengthens to
 461 the south (WAM circulation) which in turn produces a north-south dipole pattern. A comparison
 462 of the response from all three experiments shows that the strength and sign of the responses are
 463 sensitive to the dust shortwave absorption. The response in wind speed weakens as absorption
 464 reduces (Fig. 10 a to c). At locations with maximum responses, such as the northern borders
 465 of Sahel, the wind anomaly reduces from around 2 m/s (DUST2.7) to almost zero (DUST0.9) re-
 466 sponse. This sensitivity is about 20% of the mean wind speed here. In DUST0.9 the wind anomaly
 467 almost vanishes in West Africa.

468 Although WAM is the major regional surface circulation in the domain, there are other local
 469 circulation features that are also important for the rainbelt and that respond strongly to dust forcing.
 470 WAWJ (Grodsky et al. 2003), a low level jet between 8°N - 11°N over the eastern Atlantic and the
 471 West African coast during summer season, is one such circulation. The jet is in nearly geostrophic
 472 balance during most of the summer and is super-geostrophic at mature stage, with a maximum
 473 speed exceeding 7 m/s at 925 hPa. The model simulates the mean wind speed and position of
 474 the jet quite well (see the Fig. 6 of supplemental material for a comparison against ERA Interim
 475 data). The jet strongly responds to dust forcing, in general. However, unlike the response over
 476 land where the dipole pattern of response occurs just at the wind convergence zone, the entire jet
 477 enhances. Similar to other circulations, WAWJ response is also very sensitive to the dust shortwave

478 absorption. Going from experiment DUST2.7 to DUST0.9, the response weakens significantly and
479 almost neutralizes in experiment assuming inefficiently absorbing case (DUST0.9).

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

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

4. Discussion

The variability in the hematite content or SSA of dust are 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, 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 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 multi-scale 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 Sahel, the semi-arid transition zone between dry Sahara

deserts to the north and humid tropical savanna (Sudanian Savanna) to the south. Precipitation response over this region varies from almost zero to $2 \text{ kg/m}^2/\text{day}$ (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 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 re-analyses do not include dust radiative effect, though 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 inter-hemispheric temperature gradient enhances and it strengthens the local Hadley circulation and other embedded regional circulations such as 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

546 Stenchikov (2015) regarding the dust-rainbelt interaction. Miller et al. (2014) conducted a similar
547 sensitivity study by utilizing various estimates of dust optical properties. The present results are
548 qualitatively in agreement with those results, especially the dependance of Sahel rainfall to dust
549 shortwave absorption. However, neither a direct quantitative comparison of the results between
550 this two studies nor the validation of the mechanistic arguments presented in Miller et al. (2014)
551 based on simplified model is possible, as the studies use different models, assumptions, dust load-
552 ing and dust optical properties. Nevertheless, the dynamic responses and the precipitation response
553 over Sahel predicted in the present study are in agreement with those arguments. For instance, the
554 enhancement of the strength of the meridional overturning circulation in response to increasing
555 dust shortwave absorption is explicitly portrayed in the present study.

556 It is also noteworthy that the response in the rainbelt (Fig. 5) and the associated circulation
557 responses, such as local Hadley and Walker circulations (Fig. 7 and 8), AEJ (Fig. 9) and surface
558 circulation (Fig. 11), have a significant east-west contrast. In general, the effects of shortwave
559 absorption are stronger over East Africa, the southern Red Sea and the south-west tip of the Ara-
560 bian Peninsula. This is an important feature and needs to be better understood. First of all, the
561 forcing itself has an east-west contrast in the present simulations with higher values in East Africa
562 (Fig. 1 to 3), which could make heightened response there. Apart from this, analyses of Walker
563 circulation (Fig. 8) demonstrate that East Africa (specifically the Ethiopian Highlands and the
564 southern Red Sea) experience significant response, unlike any other region. This differential re-
565 sponse in the Walker circulation could also contribute to the predicted east-west contrast in the
566 precipitation belt. In addition, from the surface circulation point of view (Fig. 11), West Africa
567 has more zonal component of wind associated with WAM and WAWJ, while over East Africa the
568 surface circulation is more meridional. Therefore, it is expected to predict a differential meridional
569 circulation response over East Africa, provided that the large scale forcing is primarily meridion-

ally oriented (Fig. 4). Furthermore, East Africa has many "hot spots" in the climatological mean summer precipitation associated with orographic features such as the Ethiopian High Lands and Asir escarpment mountains in the southwest tip of the Arabian Peninsula, and areas with high local surface winds such as Tokar gap jet. These hot spots in the climatological mean precipitation and surface wind are well captured in our simulations (Fig. 1 of supplemental material) 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. 1986b; 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 being 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 multi-scale circulations that are crucial for the rainbelt maintenance and dynamics, global high resolution simulations has 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 is 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 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 inter-hemispheric temperature gradient act as the basic driving force for the rainbelt response. The inter-hemispheric heating gradient induced by dust intensifies the local Hadley circulation and moves it farther northward. 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 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, overturning circulation as well as the embedded regional circulations contribute positively to rainbelt enhancement and its pole-ward shift in response to dust shortwave absorption. It all indicates that the sensitivity of the rainbelt stems from the sensitivity of these multi-scale circu-

lations 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 decide 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 spatio-temporal distribution. Simulations with fully interactive dust might give different amount of dust loading and responses, since the perturbed precipitation can feedback 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 are 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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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.

TABLE 2. Annual DDRF

<i>Experiment</i>	<i>Domain</i>	<i>DDRF TOA AllSky</i>			<i>DDRF Surface AllSky</i>			<i>DDRF ATM AllSky</i>	<i>DDRF TOA ClearSky</i>			<i>DDRF Surface ClearSky</i>			<i>DDRF ATM ClearSky</i>	<i>Average SSA (at 550 nm)</i>
		SW	LW	NET	SW	LW	NET	NET	SW	LW	NET	SW	LW	NET	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	0.94
	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	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	0.90
	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	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	0.86
	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	0.84

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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 Figure 1a outlines the borders of MENA region.

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.

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FIG. 5. Precipitation response ($\text{kg}/\text{m}^2/\text{day}$) 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 $3 \text{ kg}/\text{m}^2/\text{day}$, to depict the position of the rainbelt.

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.

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.

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.

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 AEJ.

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.

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 WAM and WAWJ. Mean wind vectors in each experiment is overlaid.