

1 **Fine and Coarse Dust Effects on Radiative Forcing,**
2 **Mass Deposition, and Solar Devices over the Middle**
3 **East**

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8 **Key Points:**

- 9 • Models and reanalysis products underestimate coarse dust emission and dust de-
10 position by 2-3 times
11 • Fine dust affects radiation, but coarse dust dominates mass deposition rates
12 • Atmospheric dust dims solar radiation, and coarse dust causes soiling of solar pan-
13 els

14 **Key Words:** Emission, Air quality, Arabian Peninsula, PV, Soiling, WRF-Chem

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Abstract

In desert regions like the Middle East (ME), dust has a profound impact on the environment, climate, air quality, and human health. In addition, dust affects the efficiency of solar energy devices by reducing the downward solar flux and settling on their optically active surfaces. The size of dust particles determines the extent of these effects. Our size-segregated dust deposition (DD) measurements show that coarse dust particles with geometric radius $r > 10 \mu\text{m}$ comprise the majority of the deposited mass, but these particles are not represented in the current models that are tuned to fit the observed aerosol visible optical depth (AOD) but not dust emission (DE) or DD. As a result, the current models and reanalysis products severely underestimate DD and DE. This is the first study to constrain the dust simulations by both AOD and DD measurements to quantify the effect of coarse and fine dust on radiative fluxes and DD/DE rates using the WRF-Chem model. We found that, on average, coarse dust contributes less than 10% to dust shortwave (SW) radiative forcing (RF) at the surface but comprises more than 70% of DE. Coarse dust warms the atmosphere more effectively than fine dust in longwave (LW), comprising 30% of LW RF at the surface, although the LW effect is 2-3 times smaller than the SW effect. Aerosol annual mean net radiative cooling at the surface over the Arabian Peninsula and regional seas locally reaches 25 W m^{-2} . Airborne fine dust particles with radii $r < 3 \mu\text{m}$ are mainly responsible for the significant dimming (5-10%) of solar radiation, cooling the surface and hampering solar energy production. However, dust mass deposition is primarily linked to coarse particles, causing accumulation of soiling losses at the rate of 2-5% per day. Therefore, incorporating coarse dust in model simulations and data assimilation would improve the overall description of the dust mass balance and its impact on environmental systems and solar devices.

1 Introduction

Mineral dust is a critical player in the earth system, with a broad impact on the environment and different aspects of weather, climate, planetary radiative budget, cloud microphysics, and atmospheric chemistry (Knippertz & Stuut, 2014; Anisimov et al., 2018; Z. Meng & Lu, 2007; Prospero et al., 2008; Ukhov et al., 2020; Parajuli et al., 2022). Dust fertilizes oceans by providing nutrients to surface waters and, ultimately, the seabed (Talbot et al., 1986; Watson et al., 2000; Swap et al., 1996; Zhu et al., 1997). The total annual dust deposition in the Red Sea reaches 8.6 Mt (Shevchenko et al., 2021), and major dust storms are estimated to contribute 6 Mt to this total (Jish Prakash et al., 2015). Dust can negatively impact infrastructure and technology by attenuating the solar radiation reaching the earth's surface due to dust scattering and absorption, therefore reducing the output of photovoltaic (PV) systems. Furthermore, dust deposition on solar panels diminishes their efficacy (Mani & Pillai, 2010a; Rao et al., 2014; Sulaiman et al., 2014; Valerino et al., 2020).

With its large deserts, the Middle East (ME) is one of the most significant mineral dust sources on Earth (Zender et al., 2004; Knippertz & Stuut, 2014; Ukhov et al., 2020). The region is characterized by hot, dry summers and mild winters with intermittent rains (Climate.com, 2018; Mostamandi et al., 2022). In summer, northern wind (Shamal) dominates (Yu et al., 2016; Hamidi et al., 2013; Anisimov et al., 2018); whereas in winter, southern wind, related to monsoon circulation, prevails. Column dust loading (DL) is controlled by dust emission (DE), dust transport (DT), and dust deposition (DD) (Knippertz & Stuut, 2014). DE is difficult to measure in situ and also to calculate in meteorological and climate models coupled with aerosol chemical transport models (Zender et al., 2004; Uno et al., 2006; Todd et al., 2008; Ginoux et al., 2012). The main mechanisms of dust generation in the ME are cold fronts, haboobs, and gust winds, but they are not all well represented in the up-to-date atmospheric chemical transport models. To resolve haboobs, for example, a grid spacing of at least 3-km is required to allow resolving deep convection (Anisimov et al., 2018; Kalenderski & Stenchikov, 2016). Unfortunately, cal-

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In addition to absorbing and scattering radiation, dust affects clouds, acting as cloud condensation nuclei (CCN) and ice nuclei (IN), and causes indirect radiation forcing (RF) (DeMott et al., 2010; Parajuli et al., 2022). Deposited dust alters surface albedo and harms vegetation (Chadwick et al., 1999). DL and dust optical depth (DOD) over the ME are higher than in other parts of the world (Jish Prakash et al., 2015; Kalenderski et al., 2013). Osipov et al. (2015) and Kalenderski and Stenchikov (2016) showed that mineral dust over the ME contributes more than 80% to AOD. Non-dust aerosols like sulfate (SO_4), sea salt (SS), black carbon (BC), organic carbon (OC), and volatile organic compounds (VOCs) comprise, on average, about 20% of AOD. We assume that the optical depth of non-dust aerosols is $NOD=AOD-DOD$. Osipov et al. (2022) indicated an even larger fractional contribution (about 30%) of anthropogenic fine particulates with geometric diameter less than $1 \mu m$ to AOD. In this study, we characterize particles by their geometric radii instead of using aerodynamic radii; for dust, aerodynamic radii are almost 50% smaller than geometric radii (Adebiyi et al., 2023).

Dust impacts regional radiative balance, thus affecting climate (Forster et al., 2007; Zhao et al., 2014; Ukhov et al., 2020). Kalenderski et al. (2013) simulated reduction of solar radiation at the earth's surface during a dust storm reaching $100 W m^{-2}$. Osipov and Stenchikov (2018) calculated that the dust radiative effect has a profound thermal and dynamic impact on the Red Sea. Over the last two decades, the dust effects on the environment have been extensively studied (Marticorena & Bergametti, 1995; Ginoux et al., 2001; Shao, 2001; Zender et al., 2003; Darmenova et al., 2009; Shao et al., 2010; Zhao et al., 2010; Solomos et al., 2011; Mahowald et al., 2011; Cakmur et al., 2006; Kok et al., 2021; Adebiyi et al., 2023; Adebiyi & Kok, 2020). Although up-to-date models capture many features of dust generation and transport, the spatial distribution of dust and its RF remains uncertain (Zhao et al., 2013). For example, the simulated global DE in AeroCom models varies from $500 Mt year^{-1}$ to $5000 Mt year^{-1}$ (Textor et al., 2006; Huneus et al., 2011; Kalenderski & Stenchikov, 2016).

The discrepancies in simulated dust emissions can be attributed to the fact that models are tuned to fit the observed visible AOD, and DE is a tuning parameter. Among different models, varying dust sources, particle size distribution (PSD), optical properties, and chemical composition are the major factors that exacerbate differences in the emissions (Ginoux et al., 2012; Tegen et al., 2002; Zender et al., 2003; Balkanski et al., 2007; Darmenova et al., 2009; McConnell et al., 2010; Kok, 2011; Zhao et al., 2010, 2011).

Dust size distribution and composition are key factors that control dust optical properties and the rate of gravitational sedimentation (Mallet et al., 2009; Bergametti & Forêt, 2014; Zhao et al., 2013; Mahowald et al., 2011; Kok et al., 2021; Adebiyi & Kok, 2020). However, the dust microphysical modules often do not consider giant ($r > 10 \mu m$) dust particles, which could be radiatively significant (Ryder et al., 2019; Kok et al., 2021; Adebiyi et al., 2023). The amount and size distribution of emitted dust depends on the surface wind, soil morphology, and moisture content. Kok (2011) analyzed six sets of size-resolved dust emission measurements and found that the size distribution of emitted fine dust with $r < 5 \mu m$ is independent of wind speed (Kok, 2011; Kok et al., 2017). Adebiyi et al. (2023) suggested that the up-to-date models significantly underestimate coarse DL in the atmosphere because the models deposit coarse dust too rapidly.

Reducing the efficacy of solar energy devices is another aspect of dust impacts on human activities. Deserts receive a record amount of solar radiation, but a high concen-

119 tration of dust in the atmosphere attenuates solar radiation at the Earth’s surface. Dust
 120 deposited on PV panel surfaces causes soiling losses that accumulate at a rate of 0.1 to
 121 1% per day (Ilse, Figgis, Naumann, et al., 2018; Valerino et al., 2020). Ilse, Figgis, Werner,
 122 et al. (2018) analyzed soiling and cementation processes on PV panels in Qatar, find-
 123 ing that dust deposition on PV surface causes energy losses exceeding 1% per day. Boyle
 124 et al. (2013, 2015) showed that 1 g m^{-2} of dust deposited on a PV panel reduces power
 125 output by 4-6%. Ilse, Figgis, Naumann, et al. (2018) detected that the highest soiling
 126 rate is in the ME (0.95 % per day), and the lowest is in South America. Bergin et al.
 127 (2017) combined field measurements and global modeling to estimate the effect of aerosols
 128 on solar electricity generation, showing that about 17 to 25% of solar energy could be
 129 lost due to soiling in regions with abundant dust and anthropogenic aerosols. It was sug-
 130 gested that soiling losses associated with fine dust particles are larger than those caused
 131 by coarse particles (El-Shobokshy & Hussein, 1993; Sayyah et al., 2014; El-Shobokshy
 132 & Hussein, 1993; Ilse, Figgis, Werner, et al., 2018). Baras et al. (2016) conducted three
 133 years of soiling measurements in Rumah, Saudi Arabia, and proposed an 8-day clean-
 134 ing cycle to increase the efficiency of PV panels. Mani and Pillai (2010b) found that weekly
 135 cleaning is necessary for the dry subtropics ($15 - 25^\circ\text{N}$), which experience rare rainfall;
 136 in low latitudes with frequent rainfall, natural cleaning is usually sufficient. However,
 137 while heavy rains clean solar panels, light rains can increase surface contamination (Valerino
 138 et al., 2020; Ilse, Figgis, Naumann, et al., 2018). In regions with an arid and semi-arid
 139 climate, for example, dew can cause particle cementation on PV panel surfaces (Ilse, Fig-
 140 gis, Naumann, et al., 2018). Valerino et al. (2020) showed that high relative humidity
 141 almost doubles the soiling rate.

142 Thus both AOD and DD play an important role in shaping the dust impact on cli-
 143 mate and solar devices. To achieve an agreement with observations, DE is usually tuned
 144 to fit the observed AOD in visible wavelengths in models. Because giant dust particles
 145 with $r > 10 \mu\text{m}$ are often not considered in the models, the emission of dust particles
 146 with $r < 10 \mu\text{m}$ is artificially increased to fit visible AOD, while the longwave (LW) ef-
 147 fect of giant particles is underestimated (Zhao et al., 2014; Ukhov et al., 2020; Kalen-
 148 derski et al., 2013; Adebisi & Kok, 2020). At the same time, the simulated DD (and con-
 149 sequently DE) rates are much lower than observed (Engelbrecht et al., 2017; Shevchenko
 150 et al., 2021). DOD characterizes the amount of dust suspended in the atmosphere, and
 151 it alone is insufficient to constrain the dust mass balance because it is defined by DT,
 152 DD, and DE.

153 In this study, we combine model simulations, data assimilation products, and DD
 154 and AOD observations to quantify the dust impact in the ME. For the first time, we con-
 155 strain the model dust simulations with both AOD and DD measurements. Considering
 156 the dust impact on solar devices, we account for both attenuation of incoming solar ra-
 157 diation by dust suspended in the atmosphere and soiling caused by DD, discriminating
 158 the effects of fine and coarse dust particles. Along with AOD observations, we utilize size-
 159 segregated DD measurements conducted at King Abdullah University of Science and Tech-
 160 nology (KAUST, Saudi Arabia) (Jish Prakash et al., 2016; Engelbrecht et al., 2017; Shevchenko
 161 et al., 2021). We quantify the contributions of different dust sizes to RF and DD rate,
 162 aiming to answer the following questions:

- 163 1. What is the temporal and spatial distribution of dust mass deposition over the
- 164 ME land areas and regional seas?
- 165 2. What are the comparative contributions of fine and coarse dust to radiative forc-
- 166 ing and mass deposition rates over the ME?
- 167 3. What is the comparative impact of fine and coarse dust suspended in the atmo-
- 168 sphere and deposited on surfaces on solar energy devices?

169 **2 Methodology**

170 First, we analyzed the model output obtained using the up-to-date model constrained
 171 only by AOD observations to reveal the deficiencies in the current models and reanal-
 172 ysis products. The size-segregated DD measurements, which we collected at the Red Sea
 173 coastal plain, allowed us to improve the model DE and calculate the effects of coarse and
 174 fine dust on DL, DD, RF, and the efficacy of solar devices. Below, in this section, we briefly
 175 discuss the data sets and the model used in this study.

176 **2.1 Observations and Data Assimilation Products**

177 The CIMEL robotic sun-photometer at the KAUST Campus has collected obser-
 178 vations since the start of 2012. This instrument is part of the National Aeronautics and
 179 Space Administration (NASA) AEROSOL ROBOTIC NETWORK (AERONET, <http://aeronet.gsfc.nasa.gov>). The sun-photometer measures in clear-sky conditions direct sun and sky radiances at eight wavelengths (340, 380, 440, 500, 550, 670, 870, 940, and 1020 nm) every 15 min during daylight, providing spectral AODs and aerosol column integrated size distribution (Dubovik & King, 2000). AERONET data are available from https://aeronet.gsfc.nasa.gov/cgi-bin/data_display_aod_v3?. In addition to the KAUST site, this study uses AERONET observations from sites at Sede Boker and Mezaira (Fig. 1).
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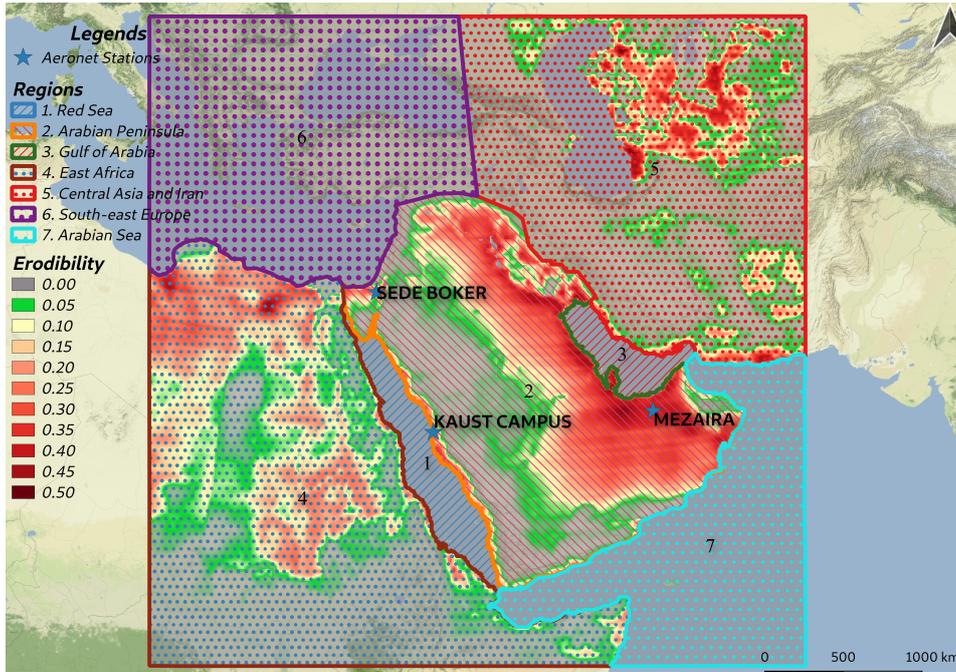


Figure 1: The square area depicts the simulation domain. Shading shows dust source function S . Contours show selected regions: 1 - The Red Sea, $0.46 \times 10^6 \text{ km}^2$; 2 - Arabian Peninsula, $3.63 \times 10^6 \text{ km}^2$; 3 - Arabian Gulf, $0.24 \times 10^6 \text{ km}^2$; 4 - East Africa, $5.10 \times 10^6 \text{ km}^2$; 5 - Central Asia and Iran, $4.51 \times 10^6 \text{ km}^2$; 6 - South-East Europe, $3.37 \times 10^6 \text{ km}^2$; and 7 - Arabian Sea, $2.09 \times 10^6 \text{ km}^2$. Blue stars indicate the locations of AERONET stations used in the current study.

187 We used satellite observations to estimate the spatial-temporal distribution of mod-
 188 eled AOD. The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments

189 are aboard the NASA EOS (Earth Observing System) Terra and Aqua satellites. MODIS
 190 provides AOD over the global continents and oceans with a spatial resolution of $10 \times$
 191 10 km^2 (Remer et al., 2005; Abdou et al., 2005). We used AOD retrieval obtained us-
 192 ing a "deep-blue" algorithm that is capable of providing aerosol optical thickness over
 193 bright land areas, such as most deserts (Levy et al., 2015).

194 To measure the amount of deposited dust, we used passive dust samplers, which
 195 collect settling dust in a sponge layer over a "frisbee plate" on a monthly basis. The dust
 196 was washed down from the frisbee and sponge with distilled water. After lyophilization,
 197 the samples were weighed and then subjected to XRD analysis to obtain their miner-
 198 alogical composition. We measured particle size distribution in the samples using a Malvern
 199 Mastersizer 3000 Laser Diffraction Particle Size Analyzer (LPSA). The installation de-
 200 tails, geographical coordinates of the deposition samplers, and observational data from
 201 December 2014-December 2019 can be found in (Shevchenko et al., 2021).

202 We also used reanalysis and data assimilation products as a data source. MERRA-
 203 2 reanalysis (<https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2>) provides meteorolo-
 204 gical and atmospheric composition fields on a $0.625^\circ \times 0.5^\circ$ latitude-longitude grid and
 205 72 terrain-following hybrid σ - p model levels (Randles et al., 2017; Buchard et al., 2017).
 206 MERRA-2 uses the Goddard Earth Observing System, version 5 (GEOS-5) atmospheric
 207 model (Rienecker et al., 2008), which is interactively coupled with the GOCART aerosol
 208 model (Chin et al., 2002, 2000). Anthropogenic emissions in MERRA-2 are based on the
 209 EDGAR-4.2 emission inventory (Janssens-Maenhout et al., 2013). MERRA-2 assimilates
 210 AERONET AODs and MODIS radiances (Randles et al., 2017). The European Center
 211 for Medium-Range Weather Forecast (ECMWF) Copernicus Atmosphere Monitoring Ser-
 212 vice (CAMS) provides operational daily analysis and forecast of AOD for aerosol species
 213 using an Integrated Forecast System (IFS) (Bozzo et al., 2017). The aerosol model im-
 214 plemented in CAMS is based on the modified version of the Laboratoire d'Optique At-
 215 mospherique (LMD) model (Boucher et al., 2002; Morcrette et al., 2009).

216 2.2 Model

217 In this study, we used a free-running regional meteorological and chemical trans-
 218 port model, WRF-Chem-3.7.1 (Skamarock et al., 2005; Grell et al., 2005), which has been
 219 configured for the ME. The model settings and the domain are similar to those we pre-
 220 viously used in (Ukhov et al., 2020). The model domain (Fig. 1) covers the ME, Ara-
 221 bian Peninsula, Eastern Mediterranean, and parts of Central Asia with a $10 \times 10 \text{ km}^2$
 222 horizontal grid and 50 hybrid vertical levels (See Figure 1). We employed the Yonsei Uni-
 223 versity planetary boundary layer Scheme (YSU) (Hong et al., 2003). To account for at-
 224 mospheric convection, we used the Grell 3D ensemble convective parameterization scheme
 225 (Grell & Dévényi, 2002).

226 To calculate atmospheric chemistry, we used the Regional Atmospheric Chemistry
 227 Mechanism (RACM) (Stockwell et al., 1997). The photolysis rates were calculated on-
 228 line according to (Madronich, 1987). Dust microphysics was calculated within the GO-
 229 CART (Chin et al., 2000, 2002, 2014) model, which approximates the dust size distri-
 230 butions into five bins (Table 1).

231 The Rapid Radiative Transfer Model (RRTMG) for both SW and LW radiation
 232 is used for radiative transfer calculations (Iacono et al., 2008; E. Mlawer & Clough, 1998;
 233 E. J. Mlawer et al., 1997). In the course of this study, we found that WRF-Chem with
 234 GOCART microphysics erroneously disregards the radiative effect of dust particles with
 235 $r > 5 \mu\text{m}$. However, GOCART considers particles with $0.1 \mu\text{m} < r < 10 \mu\text{m}$. We mod-
 236 ified the code to rectify this error. It had a marginal effect in our previous simulations
 237 as bin 5 was poorly populated. However, it had a much stronger effect in the current study,
 238 as we significantly increased DE in bin 5 to account for the effect of giant dust particles
 239 (see below).

240 The dust emission scheme we employed in our simulations (Ginoux et al., 2001)
 241 assumes that dust emission mass flux, F_p ($\mu\text{g m}^{-2} \text{s}^{-1}$) in each dust-bin $p=1,2,\dots,5$ is
 242 defined by the relation:

$$243 \quad F_p = \begin{cases} CSs_p u_{10m}^2 (u_{10m} - u_t), & u_{10m} > u_t \\ 0, & u_{10m} < u_t \end{cases} \quad (1)$$

244 where C has the dimension of [$\mu\text{g s}^2 \text{m}^{-5}$] and is a spatially uniform factor that
 245 controls the magnitude of dust emission flux; S is the dimensionless spatially varying dust
 246 source function (Ginoux et al., 2001) that characterizes the spatial distribution of dust
 247 emission sources ($0 < S < 1$); u_{10m} is the horizontal wind speed at 10 m above ground
 248 level; u_t is the threshold velocity, which depends on particle size and surface wetness;
 249 s_p is a fraction of dust mass emitted into dust-bin p , and $\sum s_p = 1$. s_p ($p=1,2,3,4,5$)
 250 defines the size distribution of emitted dust.

251 2.3 Model Tuning Using AERONET AOD and PSD

252 In (Ukhov et al., 2020), following the common practice (Kalenderski & Stenchikov,
 253 2016; Jish Prakash et al., 2015; Zhao et al., 2010), we tuned dust emissions to fit the AOD
 254 from the AERONET stations located within the domain. For this purpose, the factor
 255 C from Eq. (1) was adjusted to obtain the best agreement between simulated and ob-
 256 served AOD at the KAUST Campus, the Mezaira, and Sede Boker AERONET sites (C
 257 = 0.525). We also tuned s_p from (1) to better reproduce the Aerosol Volume Size Dis-
 258 tribution (PSD) provided by the AERONET inversion algorithm (Ukhov et al., 2020,
 259 2021) (see Table 1).

Table 1: Dust Bins and Dust Emission Size Distribution Parameters

Dust Bins					
Bin Numbers	1	2	3	4	5
Radii (μm)	0.1 - 1.0	1.0 - 1.8	1.8 - 3.0	3.0 - 6.0	6.0 - 10.0
Sp (Ukhov et al., 2020)	0.15	0.1	0.25	0.4	0.1
Sp (This Study)	0.05	0.03	0.07	0.12	0.73

260 The aerosol number-density or volume PSD defines the aerosol lifetime with respect
 261 to gravitational sedimentation and largely controls their radiative effect (Shevchenko et
 262 al., 2021; Osipov et al., 2015; Miller & Tegen, 1998; Highwood & Ryder, 2014; Scheuvens
 263 & Kandler, 2014; Maghami et al., 2016).

264 Figure 2 compares the annual average column integrated PSD from WRF-Chem
 265 simulations in (Ukhov et al., 2020) with PSD from the AERONET retrievals (Dubovik
 266 & King, 2000) for the KAUST Campus, Mezaira, and Sede Boker AERONET sites. The
 267 solid green line depicts AERONET PSD, the blue bars show PSD from (Ukhov et al.,
 268 2020), and the red bars show PSD obtained in this study (discussed below; Table 1). For
 269 all locations, the model in (Ukhov et al., 2020) reproduces the observed AERONET PSDs.
 270 The PSDs have a fine mode and coarse mode, peaking at $r=0.2 \mu\text{m}$ and $r=2.5 \mu\text{m}$ re-
 271 spectively. The AERONET retrievals and the model do not include particles with $r >$
 272 $10 \mu\text{m}$. They are not approximated in the model (see Table 1) and AERONET is weakly
 273 sensitive to particles with $r > 10 \mu\text{m}$, which are much larger than the AERONET sun-
 274 photometer maximum operating wavelength of $1.02 \mu\text{m}$. Further below we refer to the

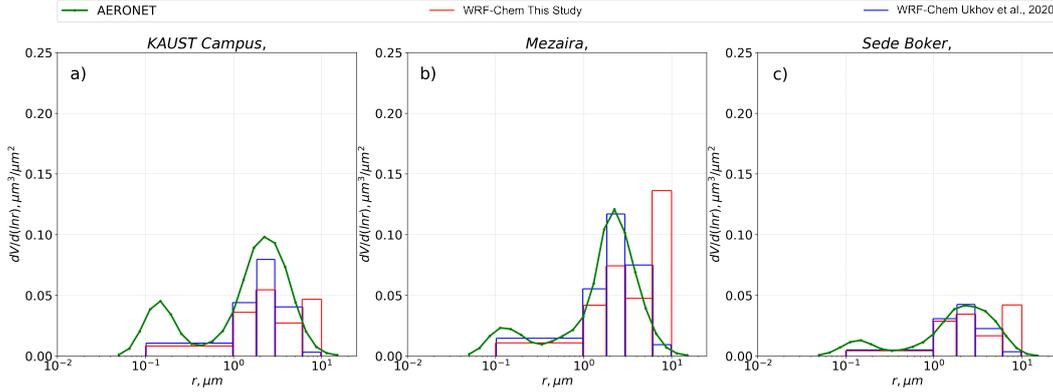


Figure 2: Annual average volume PSDs $\mu\text{m}^3\mu\text{m}^{-2}$ calculated within WRF-Chem (bars), and obtained by AERONET inversion algorithm (green solid line) for 2016 at a) KAUST Campus, b) Mezaira and c) Sede Boker. The blue bars are from the WRF-Chem run without the DD constraints, and the red bars are from the current study with the DD constraints.

275 particles in the first three bins with $r < 3 \mu\text{m}$ as fine dust; the particles in bins 4 and
 276 5 with $3 \mu\text{m} < r < 10 \mu\text{m}$ as coarse dust; and the particles with $r > 10 \mu\text{m}$, that are not
 277 approximated in most models (but are present in the dust deposition samples), as gi-
 278 ant dust particles.

279 **2.4 Test of AOD Fitted Model against DD Observations**

280 Before discussing the new model setup, the deficiencies of the previous free-running
 281 model simulations and data assimilation products constrained by only AERONET ob-
 282 servations and tested against satellite AODs should be analyzed. To achieve this, we first
 283 compared the DD calculated in MERRA-2, CAMS, and the free-running WRF-Chem
 284 tuned using AERONET AOD as in (Ukhov et al., 2020) with the DD observations at
 285 the KAUST site. The data assimilation products, like MERRA-2 and CAMS, are often
 286 used as a proxy for observations, but none of the available assimilation systems are con-
 287 strained by DD or DE measurements. Therefore, for these products, DD is based on their
 288 physical parameterizations, as in free-running WRF-Chem, and must be similarly tested
 289 against observations.

290 For this test, we used the DD measurements that have been conducted at the KAUST
 291 site since 2015 (Figure 3). To make a meaningful comparison of the observed and sim-
 292 ulated DD, we measured PSD in all deposited samples (Engelbrecht et al., 2017; Shevchenko
 293 et al., 2021). The simulated (in WRF-Chem, MERRA-2, and CAMS) and observed monthly
 294 DD rates at the KAUST site throughout 2016 are shown in Figure 3, revealing a strik-
 295 ing difference between the observed and simulated DD. The observed DD rates are more
 296 than three times higher than the simulated rates. This issue was discussed in (Engelbrecht
 297 et al., 2017; Shevchenko et al., 2021); the discrepancy occurs because we collect parti-
 298 cles with radii up to $30 \mu\text{m}$ for observations, but in the models, we consider only parti-
 299 cles with $r < 10 \mu\text{m}$. At the same time, the DD of particles with $r < 5 \mu\text{m}$ in the mod-
 300 els and reanalysis products compare well with observations. Figure 4a shows the 2016
 301 annual average normalized (to 100%) volume PSD of deposited dust at the KAUST site
 302 (Shevchenko et al., 2021). Table 2 compares the DD rates at the KAUST campus cal-
 303 culated within WRF-Chem with the settings from (Ukhov et al., 2020), MERRA-2, and
 304 CAMS with 2016 observations (Shevchenko et al., 2021). The correlation coefficient (R),
 305 root mean square error (RMSE), and bias were calculated with respect to observations

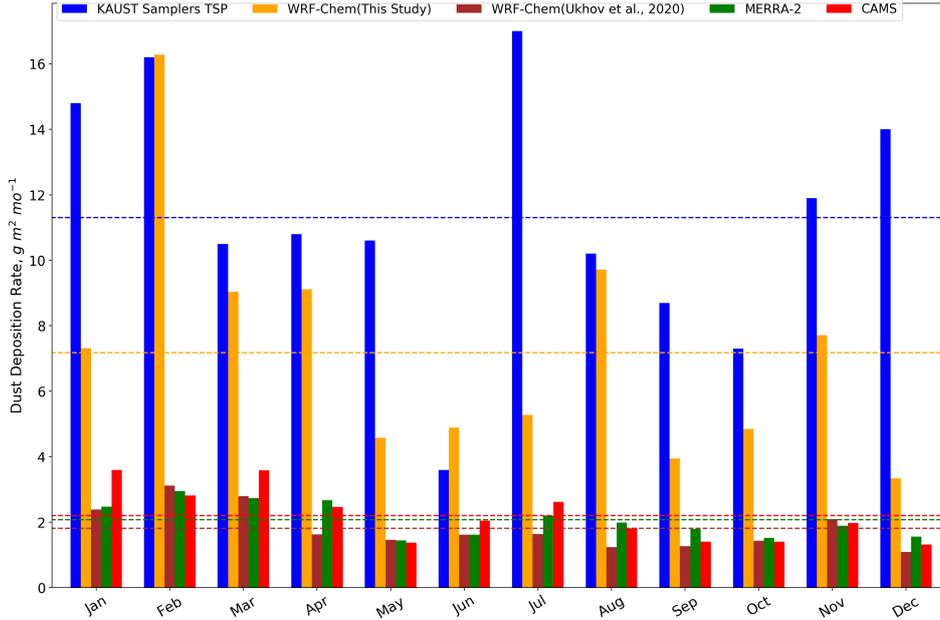


Figure 3: Monthly dust deposition rates ($g\ m^{-2}\ mo^{-1}$) averaged for six KAUST deposition sites (blue), simulated in WRF-Chem without the DD constraints (brown) and in the current study with DD constraints (light brown), calculated in MERRA-2 (green), and CAMS (red) at KAUST campus for 2016. Dashed lines show annual mean deposition rates for corresponding observations.

306 using monthly data. For WRF-Chem, $R=0.70$, while for MERRA-2 and CAMS $R=0.25$
 307 and 0.36 , respectively. The WRF-Chem DD annual bias = $-9.48\ g\ m^{-2}\ mo^{-1}$. At the
 308 same time, WRF-Chem, MERRA-2, and CAMS reproduce the DD rate of particles with
 309 $r < 5\ \mu m$ much better (see Table S1 in the supplement information). Thus, AERONET
 310 tuning helps to simulate the dust fraction with $r < 5\ \mu m$ relatively well, but coarse (5
 311 $< r < 10$) and giant ($r > 10$) dust is simulated poorly.

312 Figure 4b presents the annual mean normalized (to 100%) volume PSD (shown in
 313 bins) of emitted and deposited dust calculated in the model (Ukhov et al., 2020), as well
 314 as dust suspended in the atmosphere at the KAUST site. Dust suspended in the atmo-
 315 sphere comprises a larger fraction of fine particles in bins 1, 2, and 3 than in dust emis-
 316 sions because these particles have a longer lifetime in the atmosphere than coarse par-
 317 ticles in bins 4 and 5. Compared to emissions, the deposited dust has a larger fraction
 318 of the coarsest bins 4 and 5 because coarse particles deposit quickly. The fraction of coarse
 319 particles suspended in the atmosphere is 2-3 times smaller than in deposited dust. Thus,
 320 atmospheric dust loadings are less sensitive to coarse dust emission than DD. Compar-
 321 ing the size distributions of deposited dust in Figures 4a and b, we conclude that the WRF-
 322 Chem model with the settings from (Ukhov et al., 2020), in addition to the missing par-
 323 ticles with $r > 10\ \mu m$, underestimates the emission of coarse particles with $6\ \mu m < r <$
 324 $10\ \mu m$ in bin 5, as the observed size distribution reaches a maximum for $r > 10\ \mu m$ but
 325 in simulation bin 4 ($3-6\ \mu m$) is the most abundant. This indicates that even within the
 326 approximated dust sizes $r < 10\ \mu m$, the model underestimates the emission of coarse dust.
 327 In the new model setup developed in this study, we aim to fix this discrepancy and ac-
 328 count for the effect of giant dust particles with $r > 10\ \mu m$ by fitting AOD and DD si-
 329 multaneously.

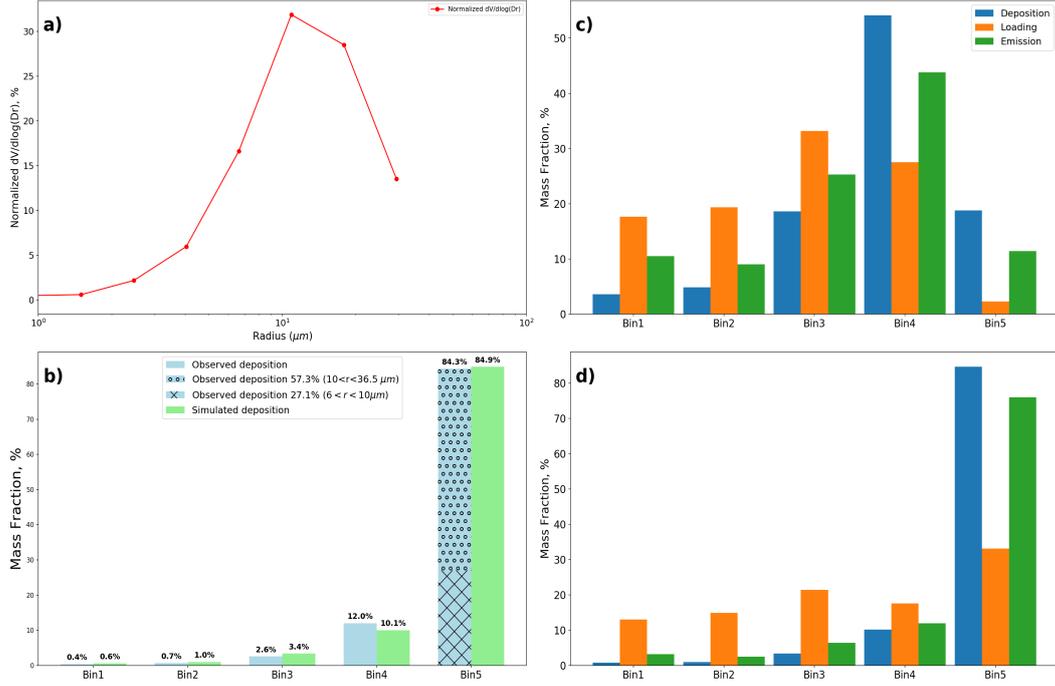


Figure 4: Annual mean normalized (to 100%) volume PSD for 2016: a) Measured in deposited samples at KAUST Campus; b) Simulated in bins in the run without DD constraints: DD (blue), DE (green), and DL (orange); c) DD simulated in bins in the run with DD constraints (blue) and integrated in bins using observed PSD in panel a; d) same as b), but in the run with the DD constraints.

Table 2: Statistical scores (R, RMSE, and Bias) of DD simulated within WRF-Chem, MERRA2, and CAMS compared to observations for 2016.

	R	RMSE	Bias
WRF-Chem (Ukhov et al., 2020)	0.70	10.10	-9.48
WRF-Chem (This Study)	0.79	5.75	-4.12
MERRA-2	0.25	9.85	-9.22
CAMS	0.36	9.19	-8.54

330 **3 RESULTS**

331 In this section, we first describe the new model setup constrained by AERONET
 332 AOD at three AERONET stations and DD observations at the KAUST site. We test
 333 the model results against observations and further discuss the geographical distributions
 334 of simulated SW and LW dust RF at the Earth’s surface and DD over the Arabian Penin-
 335 sula and the regional seas. We also develop a theoretical model to calculate the effect
 336 of DD and dust suspended in the atmosphere on the efficacy of PV panels.

337 **3.1 Test of Model Setup with Simultaneous Fitting of AOD and DD**

338 To simultaneously fit both AOD and DD in WRF-Chem simulations, we modified
 339 the DE size distribution, assuming that bin 5 incorporates a mass of dust particles with

340 $r > 6 \mu m$ including giant particles with $r > 10 \mu m$. The relative distribution of emit-
 341 ted mass in bins 1-4, which were constrained by AERONET PSD, remained intact. The
 342 new s_p settings are shown in Table 1. To fit the observed DD, we increased the emis-
 343 sion in the largest bin 5 to 73% of the total mass. To fit the observed AOD, we chose
 344 $C=1$. It is suggested that the deposition rate for giant dust particles is overestimated
 345 in the models due to unaccounted asphericity of dust particles or turbulence effects (Adebiyi
 346 & Kok, 2020; Adebiyi et al., 2023). To overcome this deficiency, J. Meng et al. (2022),
 347 Adebiyi et al. (2023) decreased the density of giant particles. In our study, approxim-
 348 ating the giant particles in bin 5 ($6 \mu m < r < 10 \mu m$) would effectively lower the sedimen-
 349 tation velocity for giant dust particles. The radiative effect of giant particles will be slightly
 350 overestimated both in SW and LW in our case, as particles in bin 5 are more optically
 351 effective per unit mass than giant dust particles both in SW and LW (this effect is quan-
 352 tified in section 3.2.3).

353 We ran the WRF-Chem-3.7.1 model for the entire year 2016. The lateral bound-
 354 ary and initial conditions for meteorological fields, aerosols, and chemical species were
 355 calculated using MERRA-2 reanalysis (Ukhov & Stenchikov, 2020). This provides the
 356 most consistent boundary conditions that allow us to use a moderate-size spatial domain
 357 and reduce computation time. Simulations were conducted for all months in parallel, with
 358 one week spin-up time for each month. The integration time step was 60 s.

359 In the chosen domain, there are three main dust emission areas (Figure 1). In Cen-
 360 tral Asia, dust is emitted predominantly between the Aral and Caspian Seas. In the Ara-
 361 bian Peninsula, the main dust sources are in the eastern region and a narrow zone along
 362 the west coast. In Africa, dust is generated in the Sahara and Somalian Peninsula. To
 363 represent climatology and spatial distribution of dust deposition, we divided our sim-
 364 ulation domain into seven regions (Figure 1) based on the spatial patterns of the source
 365 function S .

366 To demonstrate how the model reproduces the DD and AOD, we test simulated
 367 both with observations. The bias of DD in the current simulations decreased at least two
 368 times compared with runs without DD tuning, and the correlation coefficient reached
 369 0.79 (see Table 2). Figure 3 shows a subsequent better fit of DD and observations. Fig-
 370 ure 5 demonstrates that the simulated AOD fits the AERONET observations at the KAUST,
 371 Mezaira, and Sede Boker sites well (see Figure 1). Table 3 compares the WRF-Chem,
 372 CAMS, and MERRA-2 daily averaged AODs with the AERONET observations at the
 373 KAUST Campus, Mezaira, and Sede Boker. Because of the finer spatial resolution, the
 374 free-running WRF-Chem outperforms the assimilation products. Table 4 summarizes the
 375 statistical scores for the simulated annual and seasonal mean AODs with respect to MODIS.
 376 WRF-Chem has the smallest RMSE and bias with respect to the MODIS AOD compared
 377 with MERRA-2 and CAMS data assimilation products. The spatial correlation of WRF-
 378 Chem AOD is close to that produced by both data-assimilation products.

Table 3: Statistical Scores (R and Bias) of daily mean AODs from CAMS, MERRA-2, and WRF-Chem with DD constraints with respect to AERONET AOD observations for 2016

	CAMS		MERRA-2		WRF-Chem	
	<i>R</i>	<i>bias</i>	<i>R</i>	<i>bias</i>	<i>R</i>	<i>bias</i>
KAUST Campus	0.71	0.01	0.85	-0.05	0.74	-0.04
Mezaira	0.62	0.12	0.83	0.04	0.73	0.07
Sede Boker	0.83	0.07	0.72	0.02	0.43	-0.01

Table 4: Statistical Scores (R , $RMSE$, and $Bias$) of annual and seasonal mean AODs for 2016 from CAMS, MERRA-2, and WRF-Chem with DD constraints with respect to MODIS observations

	CAMS			MERRA-2			WRF-Chem		
	R	$RMSE$	$bias$	R	$RMSE$	$bias$	R	$RMSE$	$bias$
Winter (DJF)	0.59	0.08	0.02	0.57	0.09	-0.03	0.47	0.08	-0.01
Spring (MAM)	0.70	0.13	0.05	0.72	0.13	-0.05	0.62	0.12	-0.01
Summer (JJA)	0.70	0.15	0.07	0.74	0.13	-0.05	0.68	0.17	0.000
Autumn (SON)	0.56	0.11	0.03	0.60	0.11	-0.03	0.43	0.11	-0.02
Annual mean	0.65	0.12	0.04	0.66	0.12	-0.04	0.61	0.12	-0.01

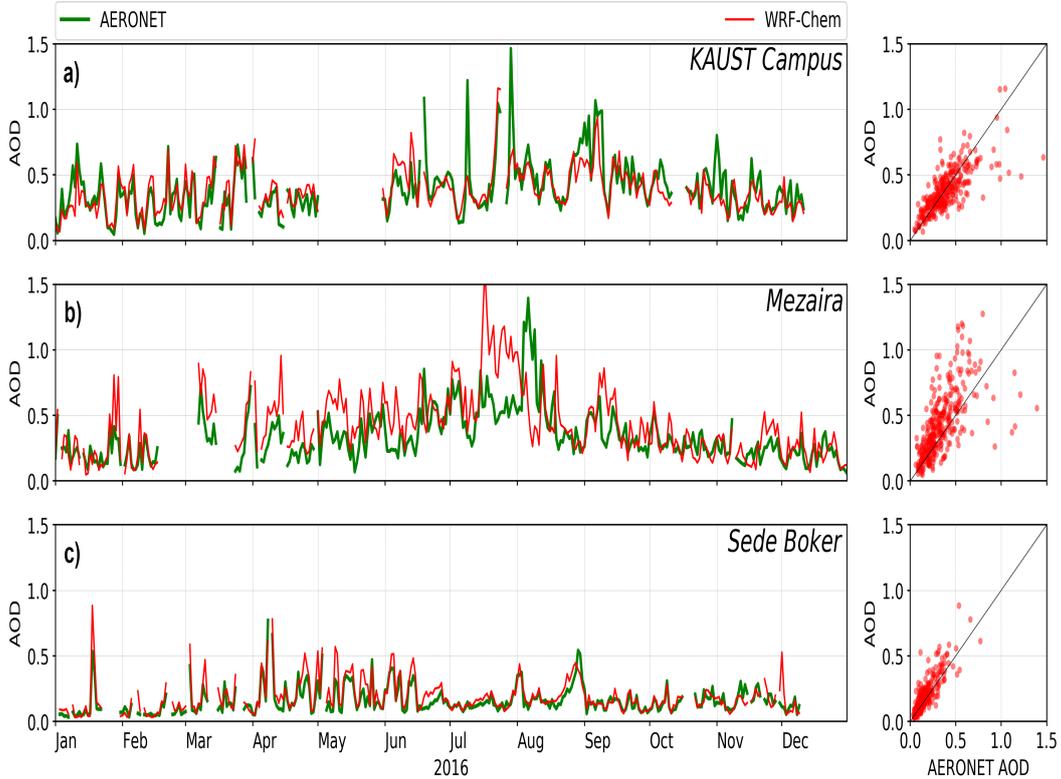


Figure 5: Observed AERONET and simulated WRF-Chem daily mean aerosol optical depth in 2016 for: a) KAUST Campus, b) Mezaira, and c) Sede Boker. The green curve shows AERONET AOD at $0.550 \mu\text{m}$ and the red curve shows model AOD at $0.6 \mu\text{m}$. Scatter diagrams are shown on the right.

379 Figure 4c demonstrates that the simulated annual average volume PSD of DD (at
 380 at the KAUST Campus), approximated by five bins, closely reflects that calculated using
 381 the observed PSD in Figure 4a. The coarse dust particles with $6 \mu\text{m} < r < 10 \mu\text{m}$ and
 382 giant dust particles with $r > 10 \mu\text{m}$ contribute 27% and 57 % to observed DD, respec-
 383 tively. Figure 4d shows annual mean normalized (to 100%) volume PSDs of emitted dust,
 384 suspended in the atmosphere dust, and deposited dust simulated in this study. With the
 385 new settings, bin 5 contributes 73% to DE, 80% to DD, and 30% to dust atmospheric

loading. The red bars in Figure 2 show the PSD of dust suspended in the atmosphere simulated in the current study when the model was simultaneously constrained by DD and AERONET AOD. With new settings, bin 5 (which also accounts for giant dust) is more pronounced, reflecting the large-radii tail of PSD that is not captured by AERONET retrieval (Figure 2). Overall, we conclude that the performance of the WRF-Chem tuned simultaneously by AOD and DD improved in comparison with our previous simulations, and it adequately represents the AOD and DD observations. Below, we use our model output to analyze the geographically distributed effects of dust in the ME in terms of its radiative impact on climate, DD rates, and deterioration of the efficacy of solar devices.

3.2 Radiative Effects of Coarse and Fine Dust

The radiative effects of dust particles suspended in the atmosphere are calculated using Mie theory because particles are sparse and distances between them are much larger than their sizes. Therefore, they do not interact optically, and their collective optical effect is a linear superposition of the effect of all individual particles. The optical properties of the individual particles are defined by their size, shape, and complex refractive index. The particles are most optically effective for the wavelengths comparable to their size. The complex part of the refractive index characterizes light absorption. Dust particles could effectively scatter and absorb solar radiation, which complicates the calculation and interpretation of their radiative effect.

3.2.1 AODs

Aerosol RF remains one of the largest uncertainties in future climate projections (Gliß et al., 2020). Dust RF depends on dust abundance, composition, and size distribution and is modulated by surface albedo (Osipov et al., 2015). In dust source regions like the ME, dust is particularly essential because of its widespread abundance. Evaluating the radiative effect of dust, we stepped ahead of the conventional approach in the analysis of AODs and RF by discriminating the effects of dust particles of different sizes. Coarse and fine dust particles have a different lifetime in the atmosphere, which controls how far from an emission source they can be transported by atmospheric airflow. In SW, finer dust particles are generally more optically active per unit mass compared to coarser particles.

In WRF-Chem, we calculated the contributions of each of the five aerosol bins (see Table 1) to optical depth and instantaneous RF. We specifically focused on the surface RF, as we were interested in the impact of dust on ground-based solar devices. We also compared the radiative effects of dust and non-dust aerosols. Figure 6 shows the visible ($0.6 \mu\text{m}$) optical depth produced by each dust bin and the total DOD. The finest dust bin 1 ($0.1\text{-}1 \mu\text{m}$), which comprises a relatively small mass, produces 45% of DOD, and bins 2 and 3 ($1\text{-}3 \mu\text{m}$) combined contribute about 42%. The optical depth of coarse dust in bin 5, which comprises the most dust mass (Figure 2), is 6% of total visible DOD.

Figure 7a shows the visible optical depth of non-dust aerosols that comprise the effects of sea salt over marine areas, biomass burning BC and OC mostly transported from Africa, and anthropogenic sulfate over the eastern Red Sea, Arabian Gulf, and Yemeni coastal areas and Oman. The high air pollution over the Arabian Sea originates from India and comprises a mixture of BC, OC, and sulfates/nitrates. The non-dust AOD is comparable with the DOD in coastal areas, but is much smaller than the DOD in the interior of the Arabian Peninsula.

Our results show a stronger dust contribution to AOD over the Arabian Sea and the Red Sea compared with previous studies (Myhre et al., 2013; Osipov et al., 2022). However, the aerosol effects are spatially variable and their contributions depend on the

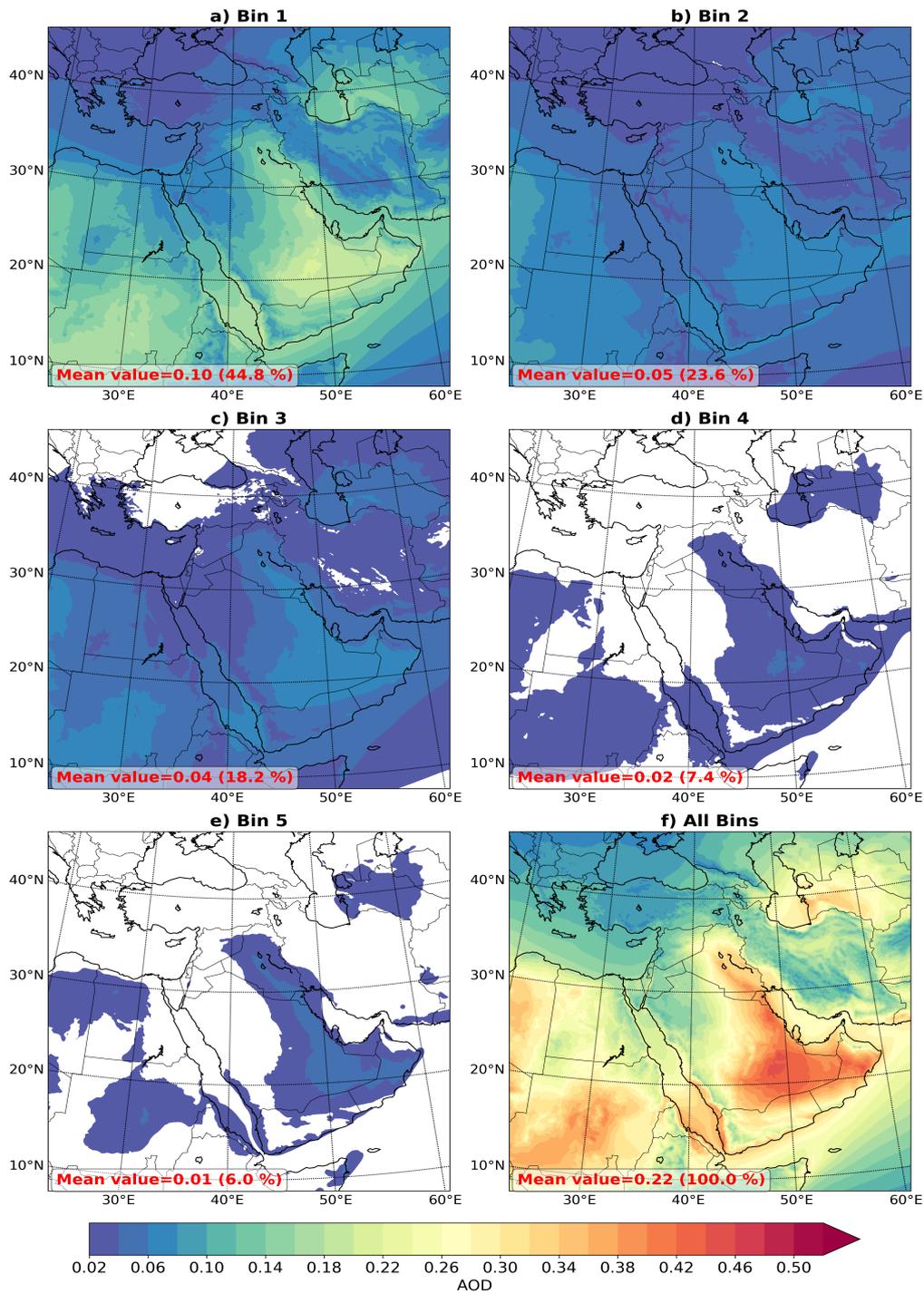


Figure 6: Annual mean visible DOD ($0.6 \mu\text{m}$) caused by individual bins and the total simulated in WRF-Chem with the DD constraints for 2016: a) Bin 1, b) Bin 2, c) Bin 3, d) Bin 4, e) Bin 5, and f) all Bins. The area average DODs and their relative contributions to each bin are shown at the bottom of each panel.

435 distribution of aerosol sources. For example, we observed that dust produces more than

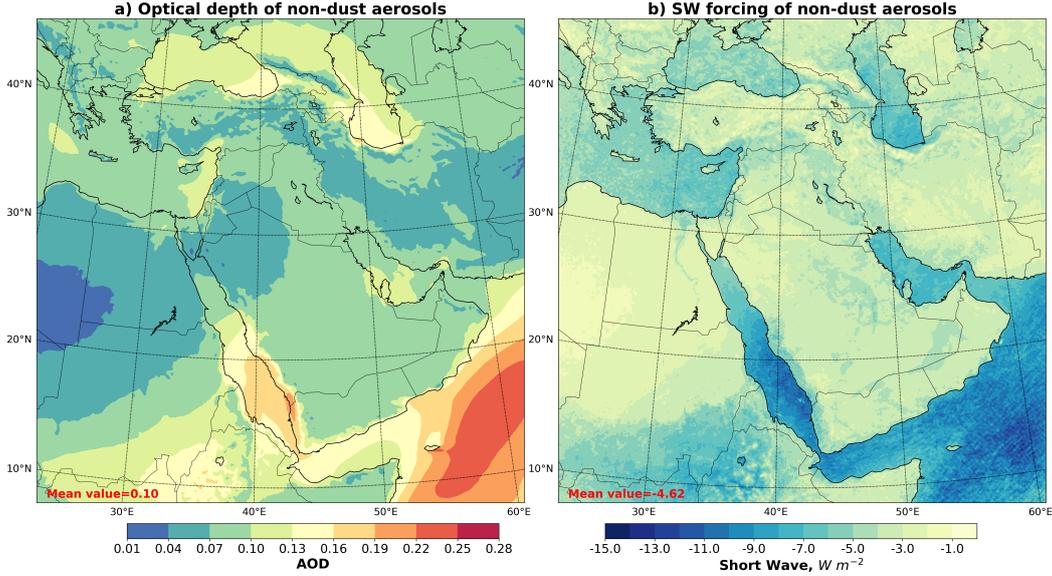


Figure 7: a) Annual mean non-dust visible optical depth, NOD at $0.6 \mu\text{m}$ calculated in WRF-Chem with the DD constraints for 2016; b) SW clear-sky radiative forcing ($W m^{-2}$) of non-dust aerosols at the surface calculated in WRF-Chem with the DD constraints for 2016. The area average NOD and RF are shown at the bottom of each panel.

436 80% of visible AOD in the interior regions of the Arabian Peninsula, where anthropogenic
 437 aerosol sources are weak compared to natural sources.

438 **3.2.2 Aerosol Radiative Forcing**

439 Fig. 8 presents the annual mean clear-sky direct instantaneous dust SW RF at the
 440 surface produced by each dust bin and the total. The radiative fluxes were obtained by
 441 double calls of radiative routine with and without the corresponding dust component.
 442 The radiative transfer calculations were conducted on the same meteorological fields (tem-
 443 perature and humidity). The RF was obtained as the difference between the net SW down-
 444 ward flux ($SW_{\downarrow} - SW_{\uparrow}$) in the calls with and without the corresponding dust bin. The
 445 dust total SW RF at the surface is negative, as dust absorbs and scatters SW radiation,
 446 thereby reducing solar radiation flux reaching the surface. The finest three bins with r
 447 $< 3 \mu\text{m}$ contribute almost all of the RF. The contribution of the coarsest dust particles
 448 with $r > 6 \mu\text{m}$ (represented by bin 5) in the total SW surface RF is about 7-8%, so
 449 the coarse dust SW radiative effect is relatively small, although it is not negligible. The
 450 total annual mean SW RF reaches $-30 W m^{-2}$ over the southern Red Sea. This area ex-
 451periences one of the largest climatological forcings in the world (Osipov & Stenchikov,
 452 2018). We also observe that the continental dust outflow generates high RF over the south-
 453 ern coast of the Arabian Peninsula and the Arabian Sea, reaching $-20 W m^{-2}$. Over land,
 454 the RF peaks in the dust source areas, including Rub' al-Khali, the deserts in the east-
 455 ern Arabian Peninsula, and the Red Sea coastal plain.

456 Fig. 9 shows clear-sky direct instantaneous dust LW RF at the surface for each bin
 457 and all bins. The LW RF, similar to the SW RF, is calculated using double calls of ra-
 458 diation routines. It is calculated as the difference between ($LW_{\downarrow} - LW_{\uparrow}$) flux with
 459 and without the corresponding dust component. Dust thermal radiation warms the surface,
 460 but the average magnitude over the domain LW warming is four times smaller compared

461 to SW cooling. The largest LW effect is over land areas, caused predominantly by coarse
 462 dust, and the coarsest bin 5 contributes 26% of the LW radiative heating at the surface.
 463 However, the average over the domain LW surface heating is only 3.26 Wm^{-2} .

464 The instantaneous net (SW + LW) RF is shown in Fig. 10. This RF defines the
 465 effect of dust on the regional climate and reflects the spatial pattern of the SW RF. Fine
 466 bins are the major contributors. Averaged over the domain, the annual mean radiative
 467 cooling reaches 5.72 Wm^{-2} , but over the southern Red Sea it exceeds 20 Wm^{-2} . Dust
 468 bin 5 is the only bin that actually warms the surface. The SW and LW radiative effects
 469 of the coarsest bin almost cancel each other resulting in a 3.5% contribution to the net
 470 RF at the surface.

471 The non-dust aerosols mostly contribute to the SW RF (see Figure 7b), as their
 472 LW RF in the ME is negligible. Averaged over the domain, the SW RF of non-dust aerosols
 473 is twice as small (but still significant) compared to dust SW RF. The contribution of non-
 474 dust aerosols becomes more significant in the cities, the areas affected by industrial sul-
 475 fur emissions, and over regional seas where the dust effect diminishes.

476 *3.2.3 Test of the Radiative Effects of Coarse and Giant Dust Using Ob-* 477 *servated PSD*

478 Following the approach used in (Adebiyi et al., 2023; Adebiyi & Kok, 2020), we used
 479 the PSD observed in the central part of the Arabian Peninsula (Pósfai et al., 2013) to
 480 calculate the contribution of coarse and giant dust particles in aerosol optical proper-
 481 ties and RF and to test our model results discussed in the previous section. For this, we
 482 used a 1D standalone column model that employs Line-by-Line radiative transfer cal-
 483 culations (Mok et al., 2016; Osipov et al., 2020). A standalone modeling framework per-
 484 mits greater flexibility and higher accuracy of radiative transfer calculations than broad-
 485 band radiative codes embedded in unwieldy and complex Global Circulation Models (GCMs).
 486 We employ a realistic PSD (Figure 11), which spans $0.05 \mu\text{m} < r < 30 \mu\text{m}$. The size dis-
 487 tribution was sampled in Riyadh on 9 April, 2007 during the Kingdom of Saudi Arabia
 488 Assessment of Rainfall Augmentation research program (Pósfai et al., 2013; Anisimov
 489 et al., 2018) after a typical mesoscale haboob dust storm event in the region (referred
 490 to hereafter as Riyadh PSD). It comprises a longer large-particle tail compared to other
 491 size distributions sampled in fair weather conditions (see Figure 16 in (Anisimov et al.,
 492 2018) and corresponding explanations). The instrument counts aerosol particles at the
 493 immediate entrance of the inlet, so the loss of large particles should be low (Pósfai et al.,
 494 2013). During the campaign, the research aircraft followed a spiral trajectory, sampling
 495 the entire dust profile in the troposphere. We took advantage of the vertical sampling
 496 to derive and employ the column-integrated PSD.

497 Compared with the recent airborne campaigns in the Sahara (see Figure 4 in (Adebiyi
 498 et al., 2023)), the Riyadh PSD falls within the envelope of dust size distributions obtained
 499 in SAMUM1 and SAMUM2 campaigns and is similar to AER-D size distribution with
 500 the maximum at $7 \mu\text{m}$. The Riyadh PSD, similar to the bulk of Saharan size distribu-
 501 tions, has a less pronounced relative contribution of the super-coarse particles ($10 \mu\text{m}$
 502 $< r < 30 \mu\text{m}$) than the Fennec PSD (Ryder et al., 2019). The dust particles with $r >$
 503 $30 \mu\text{m}$ were not measured during the Riyadh campaign.

504 The RF of dust, including its sensitivity to various parameters, has been studied
 505 extensively using 1D models (e.g., Figure 16 in (Osipov et al., 2015)). Instead, here we
 506 quantify the relative contribution of dust particles of various sizes to the optical depth
 507 τ and RF (defined as a difference ΔF of surface radiative fluxes calculated with and with-
 508 out dust effect) via diagnostics similar to the cumulative distribution function (CDF):

$$\tau_{CDF}(r^*) = \frac{\tau(r^*)}{\tau} \quad (2)$$

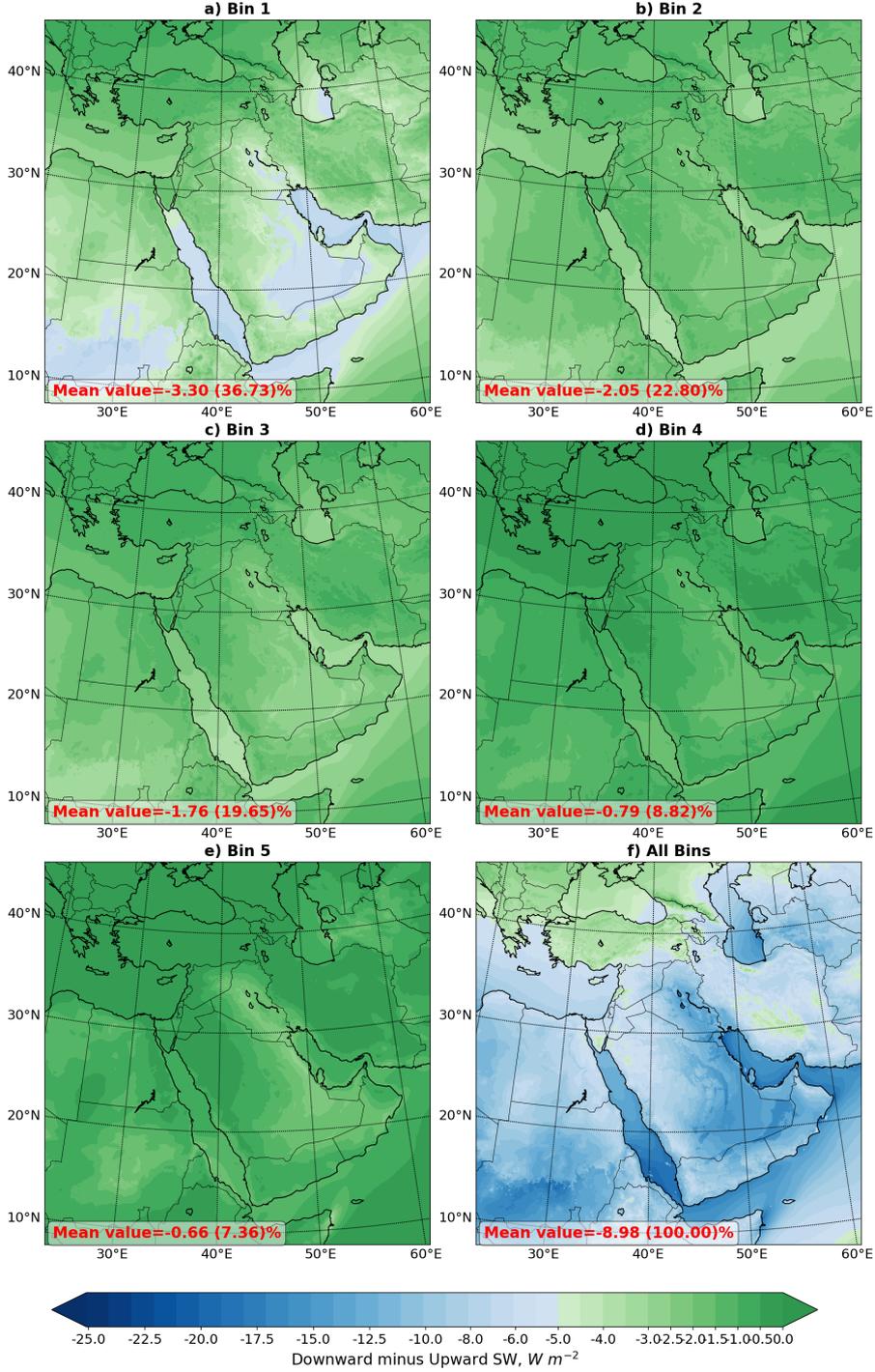


Figure 8: Annual mean clear-sky SW dust radiative forcing ($W m^{-2}$) at the surface caused by the individual bins and total calculated in WRF-Chem with the DD constraints for 2016: a) Bin 1, b) Bin 2, c) Bin 3, d) Bin 4, e) Bin 5, and f) all Bins. The area average forcing and relative contributions of each bin are shown at the bottom of each panel.

$$\Delta F_{CDF}(r^*) = \frac{\Delta F(r^*)}{\Delta F} \quad (3)$$

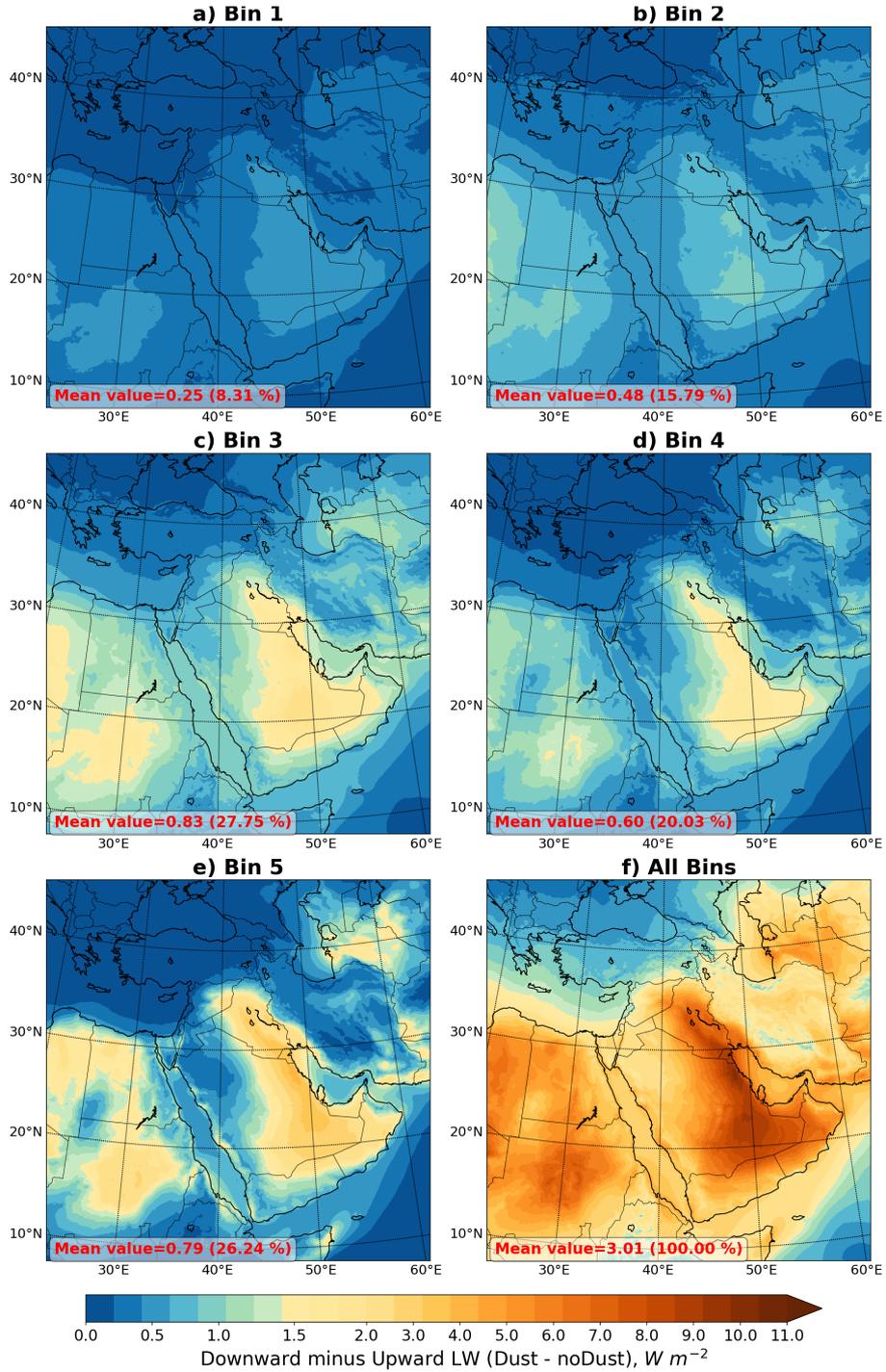


Figure 9: Annual mean clear-sky LW dust radiative forcing ($W m^{-2}$) at the surface caused by the individual bins and calculated in WRF-Chem with the DD constraints for 2016: a) Bin 1, b) Bin 2, c) Bin 3, d) Bin 4, e) Bin 5, and f) all Bins. The area average forcing and relative contributions of each bin are shown at the bottom of each panel.

509 where $\tau(r^*)$ and $\Delta F(r^*)$ are the SW or LW optical depth and RF generated by dust
 510 particles with $r < r^*$, respectively. In equation (2), the partial RF in the numerator (which

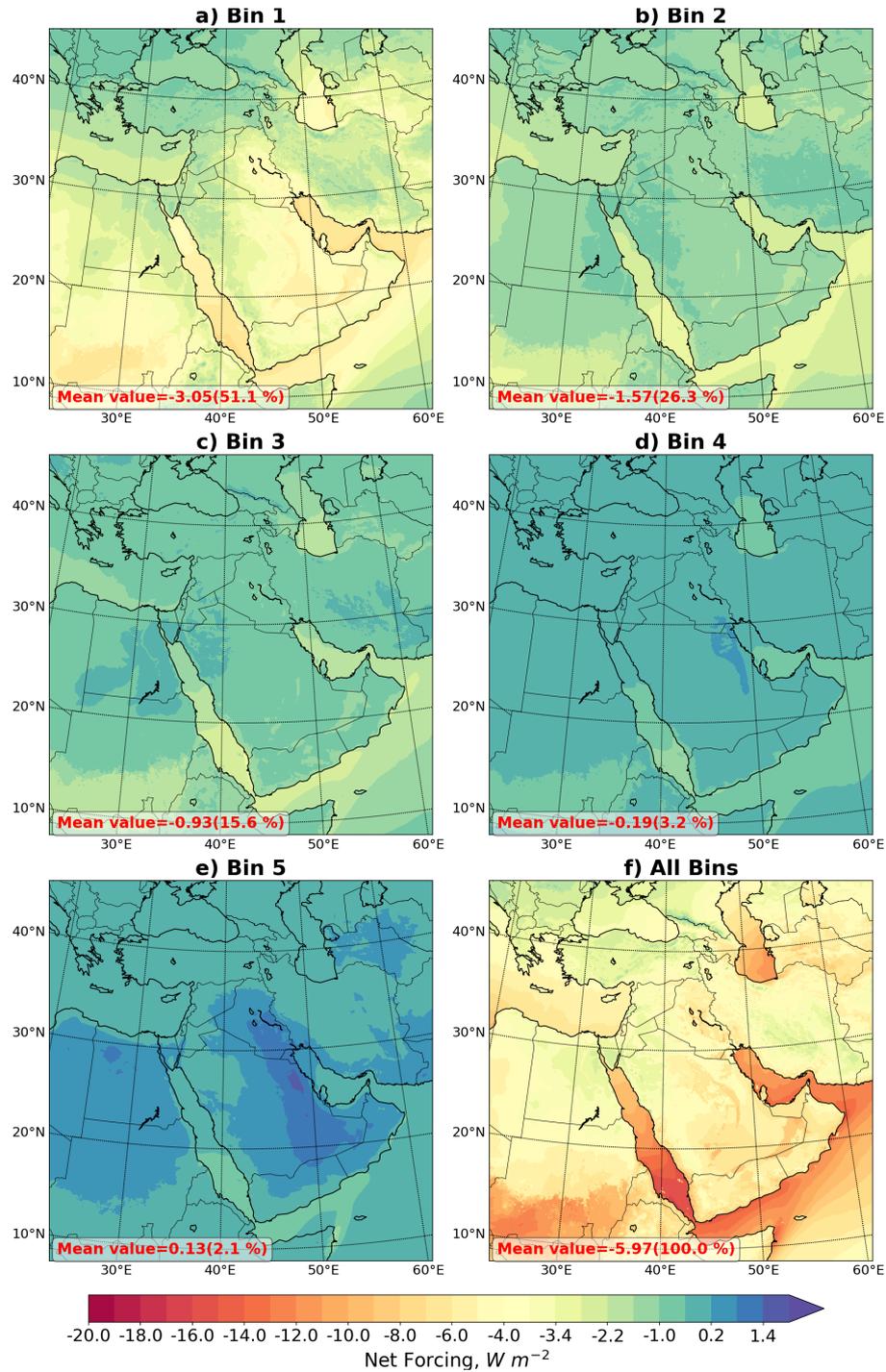


Figure 10: Annual mean clear-sky net (SW+LW) dust radiative forcing ($W m^{-2}$) at the surface caused by the individual bins and total calculated in WRF-Chem with the DD constraints for 2016: a) Bin 1, b) Bin 2, c) Bin 3, d) Bin 4, e) Bin 5, and f) all Bins. The area average RF and relative contributions of each bin are shown at the bottom of each panel.

511 accounts only for a fraction of dust particles with $r < r^*$) is normalized by the total RF

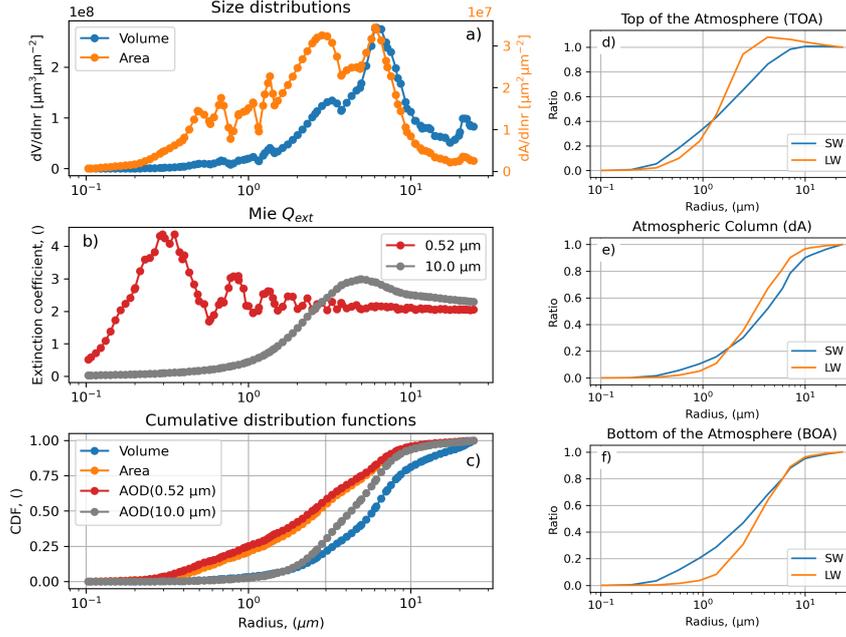


Figure 11: Size-resolved microphysical and optical properties of dust, and the RF. The left column shows: a) dust volume size distribution and surface area; b) SW and LW extinction cross-sections; and c) cumulative distribution functions of the dust total volume, surface area, and AOD (bottom). The cumulative distribution functions of volume, surface area, and AOD are normalized (to their maximum value) to show the relative contribution of all the particles in the size distribution up to the radius r . The right column shows the relative contribution of dust particles up to radius r to dust SW and LW RFs (i.e., ΔF_{CDF} in equation 2) at the d) top of the atmosphere (TOA), f) the bottom of the atmosphere (BOA) and e) dust absorption within the atmospheric column (dA).

512 (integrated over the entire radii range), which results in a relative contribution of dust
 513 particles up to a size r^* (normalized CDF). Similarly, we define the CDFs of the aerosol
 514 optical properties: extinction coefficients ϵ , ϵ_{CDF} , scattering coefficient ϵ_S , single scatter-
 515 ing albedo ω_{CDF} :

$$\epsilon(r^*) = \int_0^{r^*} Q(r) \frac{dN}{dr} dr \quad (4)$$

$$\epsilon_S(r^*) = \int_0^{r^*} Q_S(r) \frac{dN}{dr} dr \quad (5)$$

$$\tau(r^*) = \int_0^\infty \epsilon(r^*) dz \quad (6)$$

$$\omega_{CDF}(r^*) = \epsilon_S(r^*) / \epsilon(r^*) \quad (7)$$

$$\epsilon_{CDF}(r^*) = \frac{\int_0^{r^*} Q(r) \frac{dN}{dr} dr}{\int_0^\infty Q(r) \frac{dN}{dr} dr} \quad (8)$$

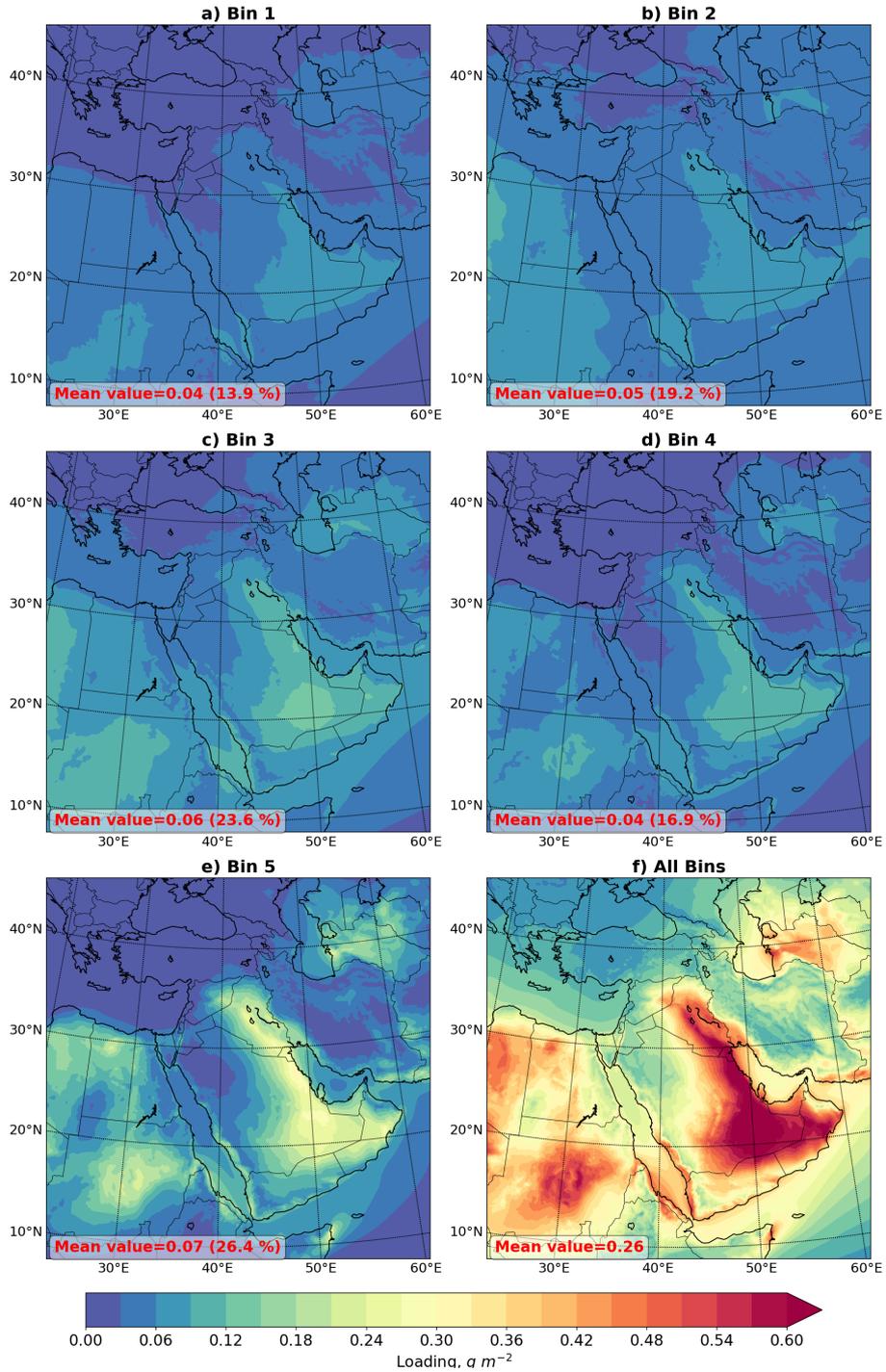


Figure 12: Annual mean column integrated dust concentration, DL ($g m^{-2}$) of the individual dust bins and total calculated in WRF-Chem with the DD constraints for 2016: a) Bin 1, b) Bin 2, c) Bin 3, d) Bin 4, e) Bin 5, and f) all Bins. The area average values for each bin and their relative contributions are shown at the bottom of each panel.

516
517

where $Q(r)$ and $Q_S(r)$ are the extinction and scattering cross-sections for individual particles with radius r . dN/dr is number-density dust PSD. The spectral dust op-

518 tical properties (Figure S1) and corresponding CDFs (Figure S2) are available in the Sup-
519plementary section.

520 The standalone 1D analysis (Figure 11a-c) corroborates the conclusions of the WRF-
521 Chem modeling. We resolve the contributions of dust particles of various sizes to the phys-
522 ical, optical, and radiative properties of atmospheric dust. In particular, we found that
523 fine dust with $r < 3\mu m$ constitutes 20% of the total mass but more than 50% of the
524 total cross-section and surface area (i.e., the properties that modulate the radiative trans-
525 fer and heterogeneous chemistry on the surface of the particles), 60% of the visible DOD,
526 and 25% of DOD in LW. Dust with $r < 10\mu m$ explains 75% of the dust loading in the
527 column and $> 90\%$ of the $0.52\mu m$ and $10\mu m$ AODs. Furthermore, the particles with
528 $r > 3\mu m$ explain 75% of DOD in longwave.

529 Figure 11d-f confirms that giant dust particles with $r > 10\mu m$ contribute less than
530 10% in the SW and LW ΔF_{CDF} either at the top of the atmosphere (TOA), the bot-
531 tom of the atmosphere (BOA), or atmospheric absorption (dA). Dust particles with $6\mu m < r < 10\mu m$,
532 for which the radiative effect was virtually absent previously due to
533 model error, account for 10% of the surface SW and LW RFs, relevant for the impact
534 on solar panels, and 5-7% of SW and LW dA, relevant for the climate and circulation
535 effects. Large particles with $r > 6\mu m$, that are now represented in bin 5, account for
536 at least 40% of total dust mass suspended in the atmosphere, which is consistent with
537 our results (see Figure 4d) showing that bin 5 accounts for about 30% of dust mass sus-
538 pended in the atmosphere (at the KAUST Campus). The dust SW and LW RFs tend
539 to cancel each other out at the surface, but SW and LW dust absorption in the atmo-
540 sphere enhances each other, thus producing stronger atmospheric warming.

541 3.3 Effect of Fine and Coarse Dust on DE, DD, and DL

542 Dust is generated across almost the entire Arabian Peninsula, where the source func-
543 tion $S > 0$ (see Figure 1). The most intensive dust generation occurs in the eastern and
544 south-eastern parts of the Arabian Peninsula, where S reaches its maximum value of 0.45.
545 In the absence of rain, dry deposition and gravitational sedimentation are the primary
546 mechanisms of dust deposition in desert regions (Mahowald et al., 2011; Adebisi et al.,
547 2023).

548 Fig. 12 shows column-integrated atmospheric DL for each bin and all bins. The
549 distribution of all-bin loading is similar to that of DOD. The larger total loadings up to
550 $0.6 g m^{-2}$ are observed in the eastern Arabian Peninsula, the Rub Al Khali desert, and
551 the southern Red Sea. The domain average annual mean loading in different bins varies
552 from $0.04 g m^{-2}$ (in bin 1) to $0.07 g m^{-2}$ in bin 5. Bin 5, representing coarse and giant
553 dust with $r > 6\mu m$, incorporates 26% of total DL (consistent with (J. Meng et al., 2022;
554 Kok et al., 2021; Adebisi & Kok, 2020; Adebisi et al., 2023)), although it receives 73%
555 of total DE. The gravitational settling of coarse dust particles in bin 5 is so rapid that
556 few remain suspended in the atmosphere even over the regions where they are generated
557 in large quantities (eastern Arabian Peninsula, Rub Al Khali desert), confirming that
558 DL is less sensitive to the emission of coarse and giant particles than, for example, DD.

559 The mean seasonal dust emission rates averaged over the dust source regions (i.e.,
560 Arabian Peninsula, Central Asia and Iran, and East Africa, excluding the seas) is shown
561 in Figure 13. The largest DE is in Spring and Summer. The Arabian Peninsula and East
562 Africa emit twice as much dust compared to the Central Asia and Iran regions. In Sum-
563 mer, the Arabian Peninsula emits more dust than other sub-regions within the domain
564 because the northwesterly winds, Shamal, that blow over the Arabian Peninsula cause
565 frequent dust outbreaks (Rashki et al., 2019; Yu et al., 2016; Patlakas et al., 2019). The
566 Central Asia and Iran sub-region exhibits the maximum emission rate in summer (28.8
567 $Mt mo^{-1}$) and minimum in winter ($20.5 Mt mo^{-1}$). The annual dust emission from the

568 entire domain tripled in our current simulations in comparison with those not account-
 569 ing for the generation of giant dust particles.

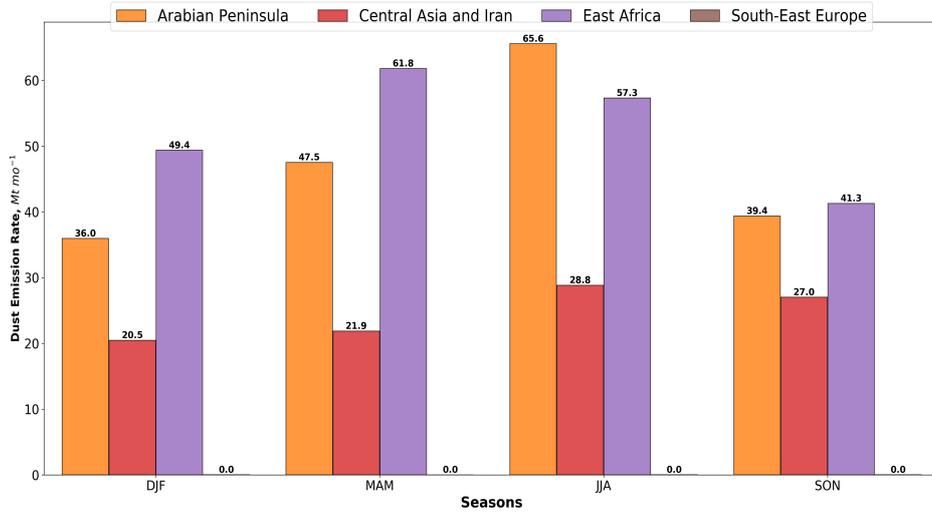


Figure 13: Seasonal mean dust emission rates ($Mt mo^{-1}$) calculated in WRF-Chem with the DD constraints for 2016 for four seasons (DJF, MAM, JJA, SON) integrated over the selected sub-regions: Arabian Peninsula (light brown), central Asia and Iran (red), east Africa (violet), and south-east Europe (dark brown bar is too small to be visible).

570 Figure S3 (see the supplementary information) shows the spatial distribution of dust
 571 deposition over the Arabian Peninsula for four seasons. Consistent with the seasonal pat-
 572 tern of DE, the largest seasonally integrated DD occurs in summer and spring. Over-
 573 all, dust deposition rates in the eastern Arabian Peninsula are much higher than in the
 574 western Arabian Peninsula. The largest simulated deposition rates are observed in Oman,
 575 exceeding $20 g m^{-2} mo^{-1}$, which is at least three times higher than in the Red Sea coastal
 576 plain.

577 Figure 14 shows the spatial distribution of the annual mean deposition over the Ara-
 578 bian Peninsula produced by dust from different bins. Annually, 446 Mt of dust is deposited
 579 in the Arabian Peninsula, with bin 5 being a major contributor (377 Mt). Fine parti-
 580 cles in bins 1 and 2 ($r < 1.8 \mu m$) are deposited almost uniformly over the entire region.
 581 Most of the coarse particles in bin 5, however, deposit close to the source regions where
 582 they were emitted, resembling the spatial patterns of the source function S (see Fig. 1).
 583 However, we also observe significant deposition of coarse and giant particles in the re-
 584 gional seas.

585 Dust deposition plays a key role in the geochemical cycles in the oceans and seas
 586 (Fan et al., 2006; Martin, 1990; Sunda & Huntsman, 1997; Watson et al., 2000; Mahowald
 587 et al., 2011). The dust released into the ocean feeds marine ecosystems and increases their
 588 productivity. The chemicals brought by dust deposition are particularly important in
 589 seas with little perennial freshwater discharge, such as the Red Sea (Jish Prakash et al.,
 590 2015).

591 Figure S4 (see the supplementary information) shows the seasonal spatial distri-
 592 bution of dust deposited in the Red Sea. The maximum deposition rate ($5-6 g m^{-2} mo^{-1}$)
 593 occurred within 10 km of the coastline due to proximity to dust sources. Away from the
 594 coast, except during summer in the southern Red Sea, the rate of dust deposition de-

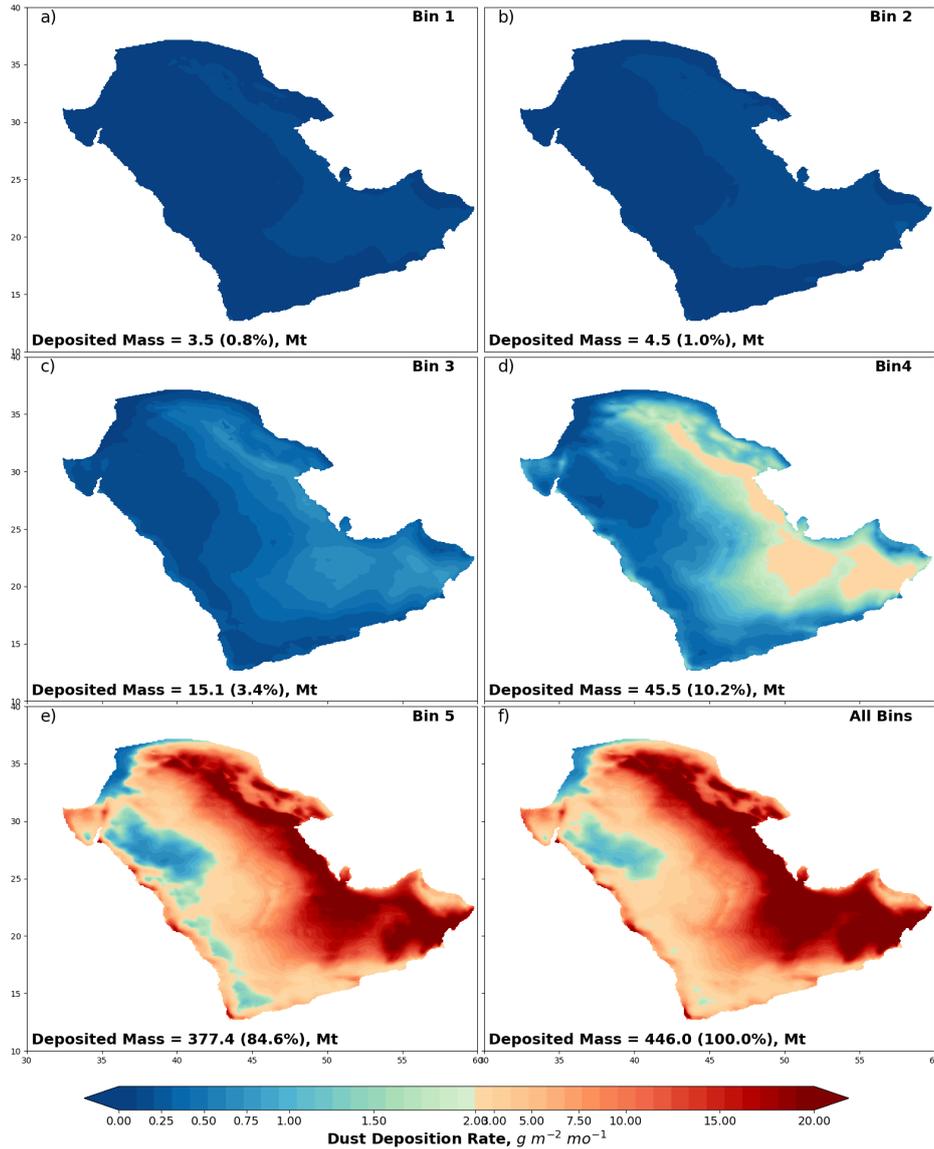


Figure 14: Annual mean dust deposition rate $g\ m^{-2}\ mo^{-1}$ calculated in WRF-Chem with the DD constraints for 2016 over the Arabian Peninsula caused by the individual and total: a) Bin 1; b) Bin 2; c) Bin 3; d) Bin 4; e) Bin 5; and f) all Bins. The spatially integrated mass of deposited dust for each bin and its relative contribution are shown in each panel at the bottom.

595 creases. The maximum dust deposition in the Red Sea (7.9 Mt) occurs in the months
 596 June-August (JJA; see Figure S4c) when the north African monsoonal circulation trans-
 597 ports dust from Africa's Bodele Depression through the Tokar Mountain Gap (Kalenderski
 598 & Stenchikov, 2016). The Northerly winds, prevailing in Summer, push dust to the south-
 599 ern Red Sea where it is trapped by high coastal mountain ranges so that AOD reaches
 600 1 (Osipov & Stenchikov, 2018). The minimum DD over the Red Sea is observed in Fall
 601 (SON), when it decreases to 3.2 Mt.

602 The annual average DD rates in the Red Sea for the individual bins and total are
 603 shown in Figure 15. The total annual DD in the Red Sea is 19.8 Mt, predominantly pro-
 604 duced by dust in bin 5 (15.3 Mt). The deposition rate of coarse particles is 3-4 times smaller
 605 in central sea compared to the near-shore areas. The fine particles in bins 1 and 2 con-
 606 tribute 4% of deposited mass, which is uniformly distributed over the Red Sea area. The
 607 total DD rate varies from $7 \text{ g m}^{-2} \text{ mo}^{-1}$ near the coasts to $1 \text{ g m}^{-2} \text{ mo}^{-1}$ in the cen-
 608 tral Red Sea, which is hardly reachable by coarse dust. Overall, giant dust deposition
 609 in the Red Sea is 2.5 times higher when compared with simulations without DD tuning
 610 (Shevchenko et al., 2021).

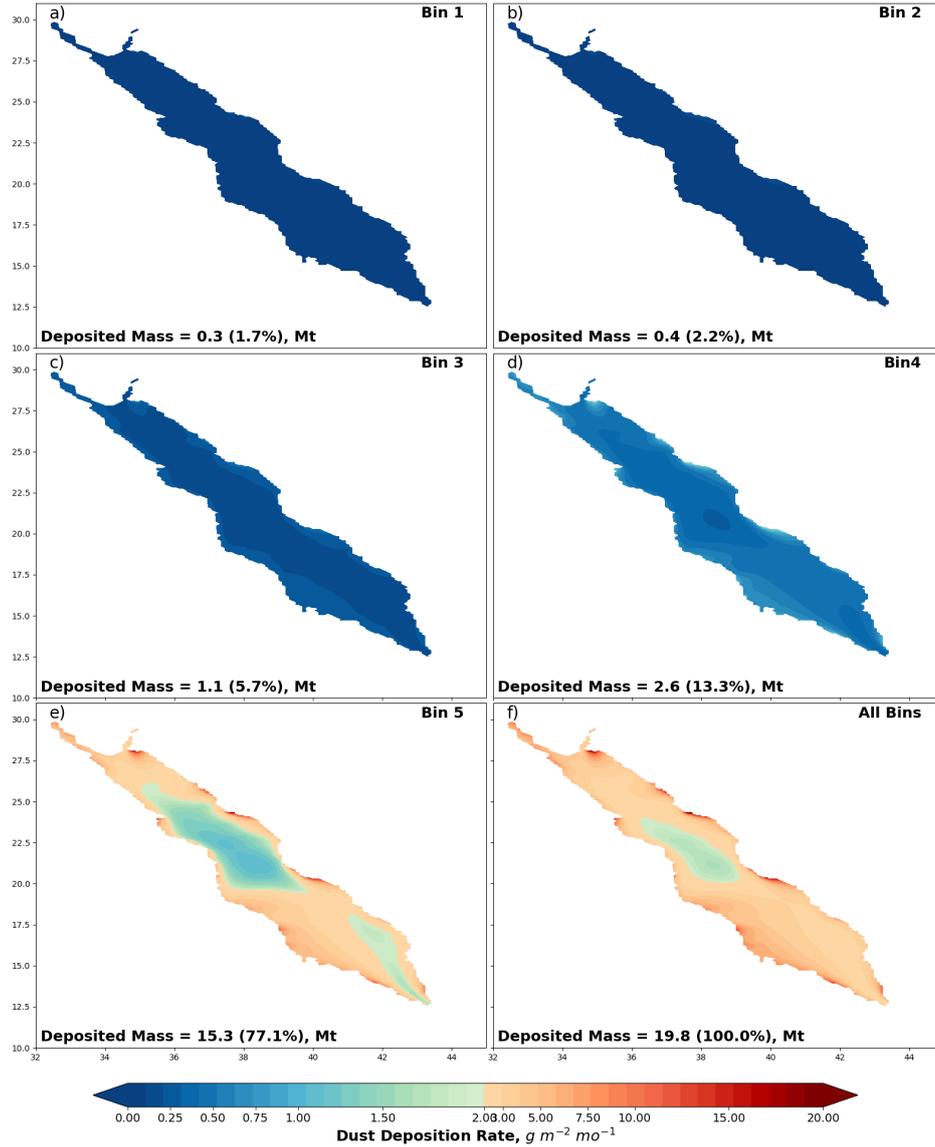


Figure 15: Annual mean dust deposition rate ($\text{g m}^{-2} \text{ mo}^{-1}$) in the Red Sea calculated in WRF-Chem with the DD constraints for 2016 caused by the individual dust bins and total: a) Bin 1; b) Bin 2; c) Bin 3; d) Bin 4; e) Bin 5; and f) all Bins. The spatially integrated mass of deposited dust for each bin and its relative contribution is shown in each panel at the bottom.

611 The seasonal spatial deposition rate over the Arabian Gulf is shown in Figure S5
 612 (see the supplementary information). The maximum deposition is observed in summer
 613 (JJA - Figure S5c), reaching 5.5 Mt. Deposition reduces to a minimum of 2.1 Mt in win-
 614 ter (DJF - Figure. S5a). The maximum dust deposition rates, similar to the Red Sea,
 615 are along the coastlines in the vicinity of the primary dust sources. The Arabian Gulf
 616 receives dust from the eastern Arabian Peninsula, Iraq, the Omani coast, and the west-
 617 ern part of Iran.

618 Figure 16 shows the spatial distribution of annual dust deposition over the Ara-
 619 bian Gulf contributed by the different bins and total, which is 14.1 Mt. The total an-
 620 nual average deposition rate varies from $10 \text{ g m}^{-2} \text{ mo}^{-1}$ in the north-western and west-
 621 ern coastal areas to $1.0 \text{ g m}^{-2} \text{ mo}^{-1}$ in the central Arabian Gulf (Figure 16f). This de-
 622 position rate is about 25% higher than in the Red Sea. Similarly to the Red Sea, the coarse
 623 dust particles in bin 5 contribute 76.1% to the dust deposition, and the finest bins 1 and
 624 2 contribute only 3.5%.

625 Annual deposition over the Arabian Sea within our computational domain is about
 626 14 Mt, with an average rate of $4.9 \text{ g m}^{-2} \text{ mo}^{-1}$. However, in summer, there are areas
 627 with a dust deposition rate above $34.2 \text{ g m}^{-2} \text{ mo}^{-1}$ located in the northwestern Ara-
 628 bian Sea and along its northern coastline caused by the seasonal intensification of local
 629 north-westerly winds and Indian Monsoon circulation. In addition, the Somali jet asso-
 630 ciated with the southwestern Indian monsoon transports dust from Somalia's deserts to
 631 the Arabian Sea in summer (Tindale & Pease, 1999).

632 Figure 17 shows seasonal deposition rates averaged over the selected regions indi-
 633 cating contributions of coarse dust. In all seasons over land (excluding the southeast Eu-
 634 rope region), coarse and giant dust comprises more than 90% of the total deposited dust
 635 mass. Over the regional seas, however, fine dust contribution is more than 20%. Thus,
 636 the relative contribution of fine dust to DD is twice as large over the seas as the land ar-
 637 eas because coarse dust particles predominantly deposit in the coastal areas.

638 4 Impact of Coarse and Fine Dust on Solar Devices

639 The Middle East receives a huge amount of solar radiation. For example, the $500 \times$
 640 500 km^2 area in the Saudi desert receives enough solar energy to cover the entire global
 641 energy consumption. Dust, however, could significantly hamper the efficiency of solar
 642 devices and must be accounted for.

643 Dust and other aerosols have two main impacts on solar devices. Firstly, aerosols
 644 suspended in the atmosphere attenuate solar radiation reducing the downward solar flux
 645 at the surface by 12 W m^{-2} on average (see Fig. 18). Secondly, dust and other aerosols
 646 deposit on the optically active surfaces of solar devices, causing power loss due to soil-
 647 ing (Ilse, Figgis, Werner, et al., 2018; Ilse et al., 2016; Ilse, Figgis, Naumann, et al., 2018;
 648 Figgis et al., 2017; Baras et al., 2016; Boyle et al., 2013; Sayyah et al., 2014)

649 We define the effect of dust as the relative energy loss due to dust deposited on the
 650 surfaces of a solar device, e.g., solar PV panels, or because dust attenuates the incom-
 651 ing solar flux when suspended in the atmosphere. Considering the solar devices with a
 652 constant radiation-to-electricity conversion coefficient, we can formulate the losses as a
 653 relative decrease of incoming solar radiation caused by dust. Thus soiling losses (SL) and
 654 attenuation losses (AL) could be calculated in the following way:

$$SL = \frac{E_0 - E_s}{E_0} \times 100\% = \frac{\Delta E_s}{E_0} \times 100\% \quad (9)$$

$$AL = \frac{E_0 - E_a}{E_0} \times 100\% = \frac{\Delta E_a}{E_0} \times 100\% \quad (10)$$

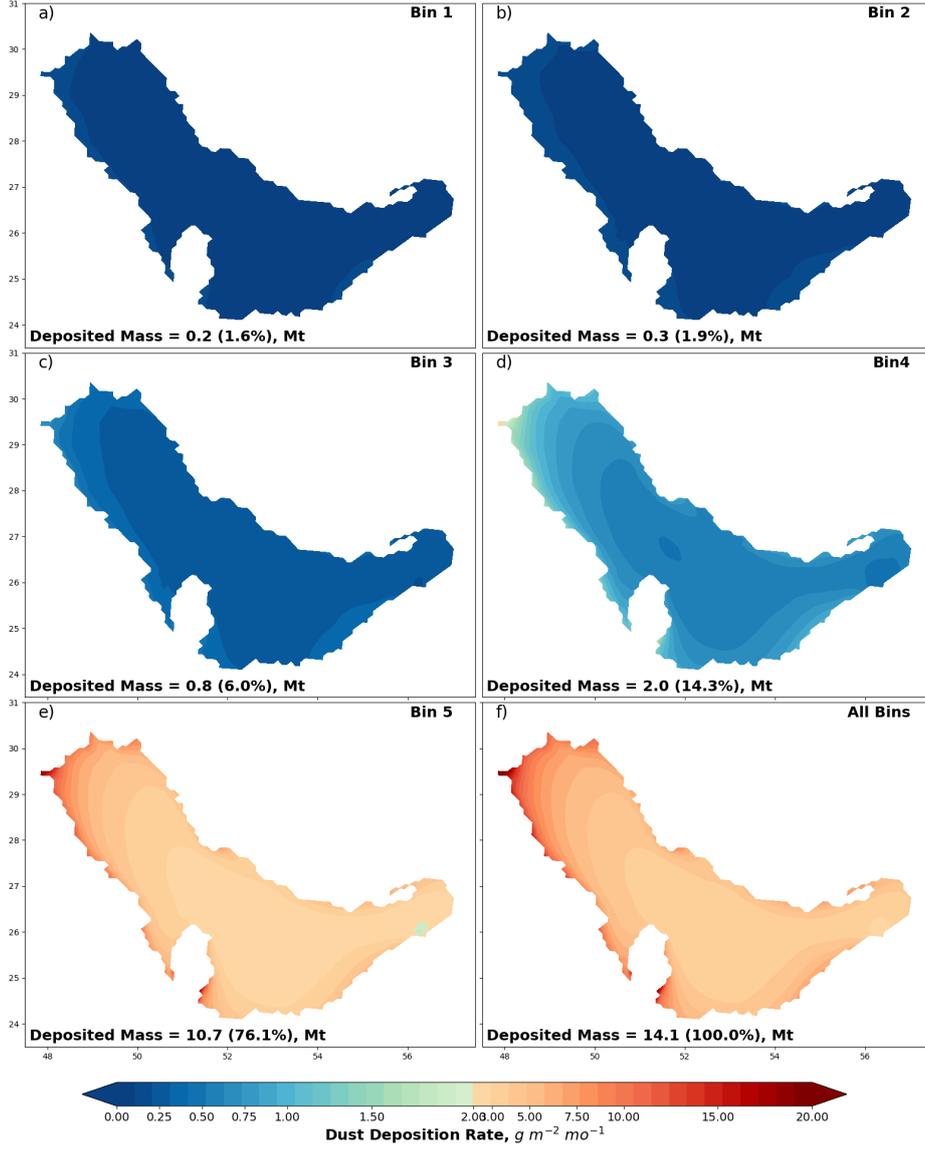


Figure 16: Annual mean dust deposition rate ($g m^{-2} mo^{-1}$) in the Arabian Gulf calculated in WRF-Chem with the DD constraints for 2016 caused by the individual dust bins and total: a) Bin 1; b) Bin 2; c) Bin 3; d) Bin 4; e) Bin 5; and f) all Bins. The spatially integrated mass of deposited dust for each bin and its relative contribution is shown in each panel at the bottom.

655 where E_0 , E_s , and E_a are, respectively, daily solar energy received by a clean de-
 656 vice in a clean atmosphere, the soiled device in a clean atmosphere, and a clean device
 657 in a dusty atmosphere. ΔE_s and ΔE_a are, respectively, the solar energy loss due to soil-
 658 ing and attenuation.

659 The total loss (TL) can be calculated as the sum of soiling and attenuation losses:

$$TL = SL + AL \quad (11)$$

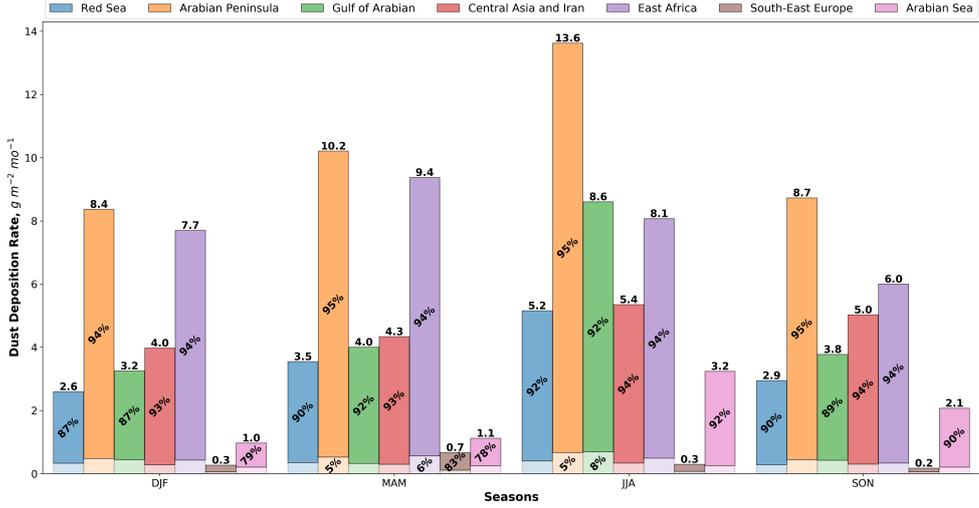


Figure 17: Seasonal mean dust deposition rate ($g m^{-2} mo^{-1}$) in the seven selected regions calculated in WRF-Chem with the DD constraints for 2016. From bottom to top, the color grading shows the contribution of fine (sum of bins 1-3) and coarse (sum of bins 4-5) dust particles (see Table 1).

660 Here, we use the assessments of dust radiative effect and DD rates obtained in this
 661 study to estimate SL and AL. Figure 18 demonstrates the effect of dust on the down-
 662 ward solar flux at the surface. The average change of solar radiation over the domain
 663 is $12.13 W m^{-2}$, but locally it reaches $30 W m^{-2}$. The finest three bins with $r < 3 \mu m$
 664 produce about 90% of this effect. Thus, the average daily attenuation loss in the cho-
 665 sen domain $AL = 4.75\%$ but locally exceeds 11 %. Specifically, for the KAUST site in
 666 summer, this is $AL = 5\%$ (see Figure 18a).

667 Soiling losses depend on the amount of deposited dust. Our analysis shows that
 668 coarse dust comprises most of the deposited mass. Valerino et al. (2020) conducted a com-
 669 prehensive analysis, measuring soiling loss per unit deposited mass. According to their
 670 measurements conducted in Gandhinagar (Gujarat, India), soiling loss is 5-6% per $1 g m^{-2}$
 671 of material deposited on the PV surfaces. This is a useful way to assess soiling, allow-
 672 ing us to scale the soiling loss against corresponding deposition rates.

673 To interpret their results, Valerino et al. (2020) assumed that the radiative effect
 674 of aerosols deposited on the surface of a PV panel would be the same as if they were sus-
 675 pended in the atmosphere. This assumption led to the conclusion that fine particles pro-
 676 duce the greatest soiling effect. However, deposited particles are densely packed on the
 677 surface of a PV panel, and the Mie theory assumptions (large distances between parti-
 678 cles preventing their optical interactions), assumed by Valerino et al. (2020), cannot be
 679 satisfied. Here, we suggest a different physical model, assuming that deposited particles
 680 make a uniform layer over a solar panel surface. Knowing the refractive index of deposited
 681 material, we can calculate the SL per unit deposited mass of $1 g m^{-2}$.

682 In our simulations, the main deposited material is dust with density $d = 2500 kg m^{-3}$,
 683 and refractive index.

$$R_i = n + i \times \chi \quad (12)$$

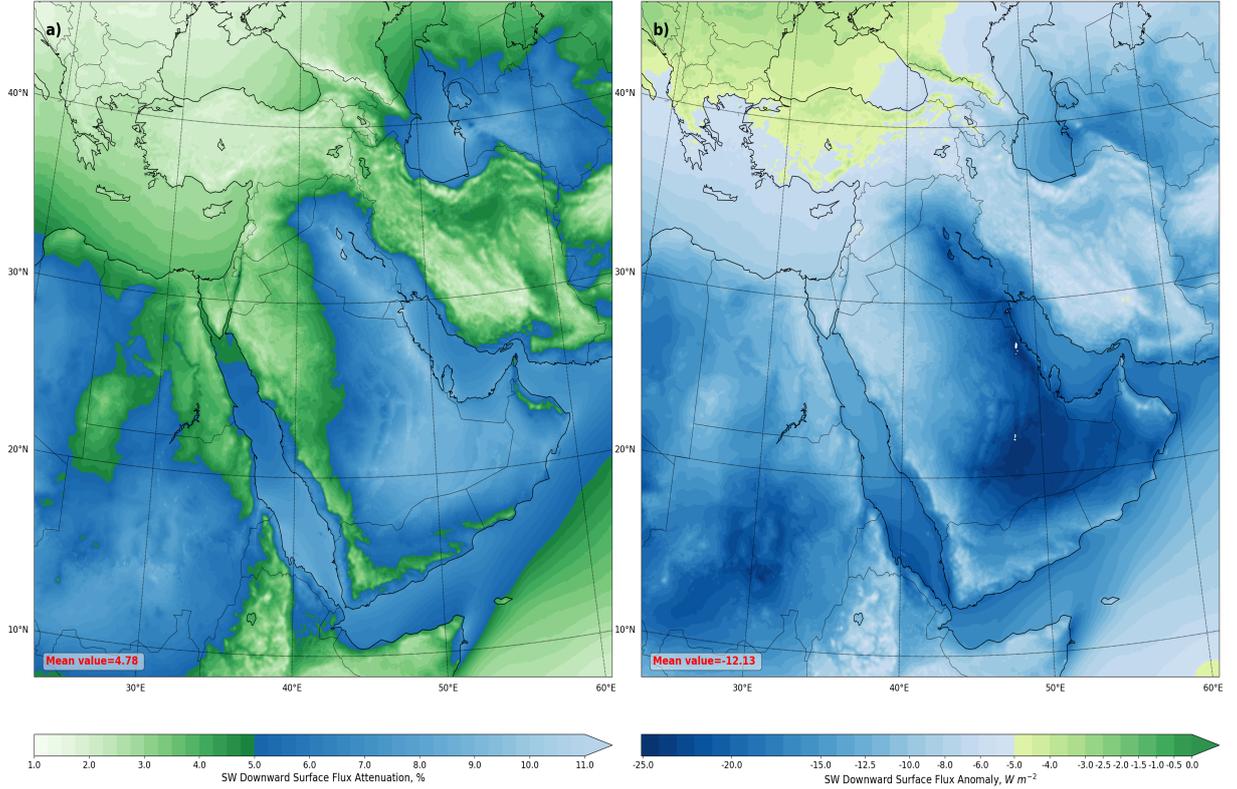


Figure 18: Annual mean dust-caused downward SW radiative flux anomaly at surface calculated in WRF-Chem with the AOD and DD constraints for 2016. a) Normalized to its annual mean value (%); b) Absolute value ($W m^{-2}$) The spatially averaged value is shown at the bottom of the panel.

684 Where the real part of the refractive index is $n = 1.55$, and the imaginary part
 685 is $\chi = 0.003$. The depth of the deposited layer with a mass of $1 g m^{-2} h = 0.4 \mu m$,
 686 the following relation gives us the soiling loss (Landau et al., 2013):

$$SL = \frac{4\pi n \chi h}{\lambda} \times 100\% \quad (13)$$

687 where λ is a characteristic wavelength of solar light. Assuming $\lambda = 0.55 \mu m$ for
 688 the most energetic visible light, we obtain $SL = 4.25\%$, consistent with the measure-
 689 ments conducted by Valerino et al. (2020). However, in this case, we have to conclude
 690 that the largest contribution to soiling is from large particles that comprise most of the
 691 deposited mass.

692 The deposition of dust particles on the surface of a PV panel is a complex process
 693 that depends on meteorological conditions (Ilse, Figgis, Naumann, et al., 2018), the tilt
 694 of a panel (Boyle et al., 2013), dust mineralogy (Engelbrecht et al., 2017), the presence
 695 of water, and adhesion forces between a panel and dust particles (Ilse, Figgis, Naumann,
 696 et al., 2018). The detailed analysis of these processes is beyond the scope of this paper,
 697 but we can estimate the upper limit of the soiling effect. We assume that a PV panel
 698 is oriented horizontally and all deposited material is retained on its surface. The aver-

699 age deposition, e.g., at the KAUST site, is about $3 \text{ gm}^{-2}\text{week}^{-1}$ (Shevchenko et al., 2021).
 700 Therefore, the average soiling loss $SL = 12.75\%$ for a weekly cleaning schedule assumes
 701 linear dependence of SL on the deposited mass and temporarily uniform accumulation
 702 of material on PV surfaces. Accounting for the attenuation losses $AL = 5\%$, we can
 703 expect that the total loss of efficiency of the solar panels on the west coast of Saudi Ara-
 704 bia (on a weekly cleaning schedule) would be $TL = 17 - 18\%$ for the areas similar to
 705 the KAUST campus. According to our simulations, the deposition rates on the east coast
 706 of the Arabian Peninsula are at least three times higher than on the west coast. There-
 707 fore, for those areas, the dust-related losses could be projected to $TL=45\%$ (assuming
 708 a weekly cleaning schedule).

709 5 Conclusions

710 In desert regions like the ME, dust is an important climate factor as it significantly
 711 attenuates solar radiation at the surface and heats the atmospheric column (Osipov et
 712 al., 2015). We evaluated the radiative dust effect and deposition rates in the ME using
 713 the free-running WRF-Chem model.

714 Observations show that large particles with $r > 10 \mu\text{m}$ contribute the most mass
 715 in dust deposition. However, the deposited dust mass was underestimated by 2-3 times
 716 because the up-to-date models (free-running and used in data assimilation) underrep-
 717 resented the content of coarse and giant dust in the atmosphere. Therefore, we approx-
 718 imate the effect of giant dust with $r > 10 \mu\text{m}$ by increasing the emission of coarse par-
 719 ticles in bin 5 with $6 \mu\text{m} < r < 10 \mu\text{m}$. This approach compensates for the suspected
 720 model overestimation of the giant dust deposition rate. For the first time, we simulta-
 721 neously constrained the model simulations by DD and AERONET AOD observations
 722 by using dust deposition observations collected on the Red Sea coast with passive dust
 723 deposition samplers (Shevchenko et al., 2021). We specifically quantified the effect of dust
 724 particles of different sizes on dust RF and mass deposition.

725 The annual mean area average reduction of SW surface flux reaches 9 W m^{-2} , but
 726 regionally solar surface cooling exceeds 30 W m^{-2} . Dust-induced LW warming partly
 727 compensates for SW cooling so that domain averaged dust annual mean net RF is re-
 728 duced to -5.72 W m^{-2} , but regionally net radiative cooling reaches 20 W m^{-2} . Annu-
 729 ally, non-dust aerosols contribute, on average, about 20% to AOD and RF over land. In
 730 the urban centers and areas affected by sulfur emissions and sea salt intrusions, however,
 731 the non-dust aerosols' contribution to solar flux reduction increases to $> 30\%$. Fine dust
 732 particles with radii $r < 3 \mu\text{m}$ produce about 90% of the net clear-sky SW RF at the sur-
 733 face, while the SW contribution of the coarsest particles with $r > 6 \mu\text{m}$ is $< 10\%$. Con-
 734 versely, giant and coarse particles dominate the effect on DD and DE. Accounting for
 735 giant dust particles and simultaneously fitting the DD and visible AOD observations led
 736 to a tripling of DE compared to the simulations without the DD constraints; consequently,
 737 DD increases over land 3 times and over regional seas 2.5 times. The fine dust deposi-
 738 tion fraction (compared to the coarse dust fraction) in the seas is twice as large than over
 739 land because most of the coarse dust particles deposit within the narrow coastal area.

740 Dust suspended in the atmosphere significantly affects the functioning of solar de-
 741 vices by reducing the downward solar flux and efficacy of solar panels by an average of
 742 5% over the domain. Dust deposition on solar devices is another factor that affects their
 743 functionality. Based on the annual average dust deposition rate, the soiling losses could
 744 reach 12% per week on the west coast and could be up to three times higher on the East
 745 Coast. Fine dust is predominantly responsible for solar light attenuation, but coarse dust
 746 particles play a major role in deposition and soiling.

747 Fitting visible AOD helps to constrain the emission of fine dust, whereas fitting DD
 748 constrains the emission of coarse dust. Approximating the giant dust with coarse dust

749 leads to marginally stronger cooling in SW and a slight overestimation of warming in LW
750 (see Figure 11). The SW and LW effects of giant dust almost cancel each other out at
751 the surface, but their SW and LW absorption in the atmosphere enhance their heating
752 of the atmospheric column. Overall, our results are consistent with recent studies (J. Meng
753 et al., 2022; Kok et al., 2017; Adebiyi et al., 2023) and highlight that coarse dust par-
754 ticles underrepresented in the up-to-date models contribute to atmospheric loading by
755 about 25%. At the same time, we found that DD and DE triple in the experiments con-
756 strained by AOD and DD, while the radiative effect of giant dust does not exceed 10%.
757 Accounting for giant dust, as suggested in this study, allows us to reach an agreement
758 between the model results and the available observations. Dust deposition data appear
759 to be a valuable asset that, together with AOD, allows model performance to be recti-
760 fied. Expansion of the network of dust deposition observations is necessary to improve
761 dust modeling and forecasting further.

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