Modeling East Asian Dust and Its Radiative Feedbacks in CAM4-BAM

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Abstract
East Asian dust and its radiative feedbacks are analyzed by the use of the fourth version of the Community Atmosphere Model (CAM4) with a bulk aerosol model parameterization (BAM) for the dust size distribution. Two numerical experiments are conducted and intercompared: one with (Active) and one without (Passive) the radiative effects of dust aerosols. CAM4-BAM captures the main spatial distribution of the dust aerosol optical depth (AOD) and the dust surface concentrations over East Asia, with positive correlations with the local observational data on annual and seasonal means. A comparative analysis of the Active and Passive experiments reveals that consideration of the dust-radiation interaction can significantly reduce dust emissions, loading, transport, and dry and wet depositions over East Asia, which is opposite to enhanced dust cycle over North Africa. Further analysis of the contrasting dust-radiation feedbacks between North Africa and East Asia shows that over North Africa, the dust radiative forcing significantly increases the surface temperature and 10 m wind speed, whereas it decreases the surface temperature and the surface wind speeds over East Asia. These contrasting radiative effects, in turn, result in distinct dust cycle changes over these two regions. Mechanistic analysis reveals that the radiative contrasts between East Asia and North Africa are mainly due to the differences in their regional surface albedo, dust vertical distribution, and size distribution.

1. Introduction
East Asia is one of the main sources of atmospheric mineral dust, mainly from the Taklamakan and Gobi Deserts, where approximately 800 Tg of mineral dusts are annually injected into the atmosphere and carried over the widespread downwind areas (e.g., the Pacific Ocean and the eastern China) through westerly winds (Zhang et al., 1997, 2006). Over this region, especially in northwestern and northern China, the dust surface concentration is 80–85 μg/m³, contributing to 33%–60% of the total aerosol mass concentration, shown in Zhang et al. (2012). Hence, it is of fundamental importance to investigate the dust cycle and its climatic effects over East Asia.

Mineral dust, as an important component of aerosols, is acknowledged as having a significant impact on the regional and global climates (Huang et al., 2014, Mahowald et al., 2014; Shao et al., 2011). Dust aerosols can both scatter and absorb solar radiation and thermal radiation directly (labeled as dust direct radiative forcing (DRF)), and the importance of DRF has been extensively recognized in general circulation models for several decades (Miller & Tegen, 1998; Tegen & Lacis, 1996; Yue et al., 2009; Zhang et al., 2010). The estimate of the annual mean DRF of dust aerosols is given by −0.4 W/m² from −0.30 to −0.6 W/m² on the global scale, estimated by AeroCOM models (Huneeus et al., 2011). Kok et al. (2017) recently noted that this value of DRF is underestimated due to less coarser dusts in the current global climate models, resulting in a larger DRF (−0.2 W/m² between −0.48 and +0.20 W/m²). For the regional mean DRF over East Asia, the corresponding values are much larger than at the global scale (several times larger) and have much uncertainty, which may significantly affect the East Asian climate (Gu et al., 2016; Guo & Yin, 2015; Han et al., 2012; Sun et al., 2012, 2017; Zhang et al., 2009). Zhang et al. (2009) claimed that the DRF decreases the net surface radiative fluxes and cools the surface locally up to −1°C, which can increase local stability. Furthermore, dust and anthropogenic...
aerosols can affect the East Asian summer monsoon circulation and the associated precipitation by changing the atmospheric thermal structures due to aerosol radiative forcing (Guo & Yin, 2015; Sun et al., 2012, 2017; Xie, Wang, et al., 2016; Xie, Liu, et al., 2016).

Different versions of the Community Atmosphere Model (i.e., version 3, CAM3 and version 4, CAM4) have been used to simulate the dust cycle and its radiative forcing in previous years (Liu et al., 2012; Mahowald, Muhs, et al., 2006; Mahowald, Yoshioka, et al., 2006; Shi et al., 2011). The CAM4 with a bulk aerosol model parameterization (BAM) for the dust size distribution (CAM4-BAM) is described by Neale et al. (2010) with four size bins including 0.1–1.0 μm (Bin1), 1.0–2.5 μm (Bin2), 2.5–5.0 μm (Bin3), and 5.0–10.0 μm (Bin4) in diameter (Mahowald, Muhs, et al., 2006). The released version of the CAM4-BAM has had some problems in simulating the dust cycle and dust radiative forcing at global and regional scales (Albani et al., 2014). Hence, Albani et al. (2014) revised the CAM4-BAM model to improve its representation of mineral dust and its ability to assess the effects of the improvements of dust direct effects on the atmospheric radiation balance, which mainly includes three aspects: new dust emission size distributions, new tuning soil erodibility, and updated dust shortwave and longwave optical properties. This updated CAM4-BAM model enhances the ability of the model to represent the global dust cycle, mainly due to more accurate dust size distributions.

Mineral dust can affect regional atmospheric temperature structures through DRF and then affect the regional climate, and thus, it feedbacks on the dust cycles, including dust emissions, loading, transport, and deposition. Perlwitz et al. (2001) were the first to describe this feedback, and they found that DRF reduced dust emissions. The mechanisms of this reduction were described by an interaction between DRF and the planetary boundary layer (PBL), whereby the surface negative net DRF reduces the sensible heat flux from the ground into the atmosphere (Heinold et al., 2007; Miller et al., 2004a; Perez et al., 2006). Colarco et al. (2014) found a positive feedback through the same mechanism, resulting from the surface positive net DRF owing to the existence of larger particles than in other studies. Additionally, an alternative mechanism has been proposed (Ahn et al., 2007; Heinold et al., 2008), where DRF creates anomalies in surface pressure and wind speed, especially on the edge of the dust layer, where the circulation responds to a gradient of DRF. A similar mechanism was described by Rémy et al. (2015). The above mentioned studies are mainly focused on dust cycle changes induced by dust radiative forcing over North Africa. Nevertheless, little attention has been paid to the feedbacks of dust-radiation over East Asia perhaps due to the complexity of aerosol-radiation-climate feedbacks over this region. In this paper, we use the improved CAM4-BAM (Albani et al., 2014) to address two questions. (1) Is the dust cycle enhanced or reduced by the DRF over East Asia? (2) Is the feedback of the dust cycle over East Asia the same as that over North Africa?

The structure of the paper is as follows. We describe the improved CAM4-BAM and the experiment design in section 2. Section 3 shows the observational evaluation of the improved CAM4-BAM. The main results and further discussion are shown in sections 4 and 5, respectively. Summary and conclusions are finally shown in section 6.

2. Model Description and Numerical Experiment Design

The CAM4 is the atmospheric component of the fourth version of the Community Climate System Model, which is more fully documented in Neale et al. (2010). The CAM4-BAM adopts a subbin fixed size distribution of externally mixed aerosols including dust, black carbon, organic carbon, sea salt, and sulfate (Tie et al., 2005). The released version of the CAM4-BAM (Neale et al., 2010) has had some problems in simulating the dust cycle and dust radiative forcing at global and regional scales (Albani et al., 2014). The CAM4-BAM has been improved in terms of three major aspects by Albani et al. (2014): (1) optimized soil erodibility maps through generating the specific scale factors to the macroareas, (2) updated dust optical properties based on more realistic absorption coefficients (Yoshioka et al., 2007), and (3) an improved size distribution for use in dust emissions provided by Kok (2011). These three aspects further show that the improved CAM4-BAM better represents the dust cycle, especially in terms of the improved dust size distribution. Note that in the CAM4-BAM, the total vertical dust flux $F_d$ (unit: kg m$^{-2}$ s$^{-1}$) from the soil during saltation is calculated as

$$F_d = C_{MB} h_{bare} \frac{g}{\rho} \left(1 - \frac{U^2}{u^2_*}ight) \left(1 + \frac{U^2}{u^2_*}ight) \left(1 - \frac{U^2}{u^2_*}ight) \left(1 + \frac{U^2}{u^2_*}ight) \left(1 - \frac{U^2}{u^2_*}ight), (u_* \geq u_{st}),$$

$$F_d = 0, (u_* < u_{st}),$$

(1)
Figure 1. (a) Spatial distributions of the annually averaged surface dust mass concentrations ($\mu g m^{-3}$) derived from the Active numerical experiment. The crosses mark the locations of the 14 CAWNET observational sites. (b) Comparison of the annually averaged dust surface concentrations between the observations and the model over East Asia.

where $\rho_a$ is the air density, $C_{MB}$ is a dimensionless proportionality constant, $\eta$ is the sand blasting efficiency, and $g$ is the gravitational acceleration. It is noted that $u_*$ is the friction velocity related to the atmospheric stability and the 10 m wind speed, and $u_{*t}$ represents the threshold friction velocity. More atmospheric instability and larger 10 m wind speed can both enhance the dust emission flux by increasing $u_*$.

In our study, the improved CAM4-BAM uses the finite volume dynamical core for the high horizontal resolution ($0.9^\circ \times 1.25^\circ$) and 26 vertical levels. It is noted that the model used here for the current climate is the same as that in Albani et al. (2014), except for the fixed surface sea temperature (SST). Due to the dust-induced SST change (categorized by a slow response) from the coupled atmosphere-ocean model (Miller et al., 2004b; Solmon et al., 2012; Yue et al., 2011), the slow response can also affect the regional climate and dust cycles. In our manuscript, we concentrate on the dust fast responses (the aerosol direct effect on land surface, clouds and radiation (rapid adjustments)) and ignore the dust slow responses. Hence, we use the improved CAM4-BAM (Albani et al., 2014) except for a fixed SST for the current climate. To examine the dust-radiation interaction and its climatic effects, two sets of numerical experiments with 21 years (1 year spin-up) are performed: without (Passive) and with (Active) the dust radiative effects. The dust direct radiative forcing was derived from the effective radiative forcing (net radiative fluxes at the TOA (the top of atmosphere) to perturbations with rapid adjustments), not instantaneous radiative forcing, following the Intergovernmental Panel on Climate Change (2013). It is noteworthy that only dust aerosols are considered in our study; the radiative effects of the other types of aerosols (black carbon, organic carbon, sulfate, and salt) are always passive in both experiments. Additionally, mineral dust and black carbon in the snow over the Tibetan Plateau can influence the snow albedo and exert a significant positive radiative forcing, affecting the East Asian climate and hydrological cycle (Qian et al., 2011). Such radiative forcing of dust-in-snow is also ignored to isolate the direct radiative forcing of dust over East Asia. Hence, the dust-snow interactions are always turned off in these two simulations including the Passive and Active experiments.

3. Observational Evaluation of the Improved CAM4-BAM

The improved CAM4-BAM was evaluated against measurements such as dust surface concentration, dust aerosol optical depth (AOD), and dust deposition at the global scale, especially over North Africa (Albani et al., 2014). However, the evaluations over East Asia were not sufficient due to the lack of local measurements in this region. Hence, this section first evaluates the improved CAM4-BAM by comparing the simulated dust surface concentration and dust AOD in the annual and seasonal means for MAM (March-April-May), JJA (June-July-August), SON (September-October-November), and DJF (December-January-February) with the East Asian observational stations from the CAWNET (14 stations) and the CARSNET (7 stations) detailed in section 3.1.

3.1. Observational Data

Monthly means of surface mass concentrations including mineral dust, ammonium, nitrate, elemental carbon, organic carbon, and sulfate aerosols are obtained from the observed data of the CAWNET (the China
Figure 2. Same as Figure 1 but for four different seasons.
Figure 3. (a) Spatial distributions of the annually averaged dust AOD derived from the Active numerical experiment. The crosses mark the locations of the seven CARSNET observational sites. (b) Comparison of the annually averaged surface dust mass concentrations over East Asia between the observations and the model.

Meteorological Administration Atmosphere Watch Network), which was shown in Zhang et al. (2012). The surface mass concentrations of aerosols were collected every 3 days from the 24 h aerosol filter samples from 2006 to 2007 at the CAWNET stations. To compare with the model, the observed data of the dust surface mass concentrations are used from 14 CAWNET stations that cover the area of the entire China, including Chengdu, Dalian, Dunhuang, Gaolanshan, Gucheng, Jinsha, Lhasa, LinAn, Longfengshan, Nanjing, Panyu, Tianyangshan, Xi’an, and Zhengzhou.

The monthly mean AOD at the stations over the desert region in the northwestern China is derived from the measurements of the CARSNET (the China Aerosol Remote Sensing Network), which was shown in Che et al. (2009) and Che et al. (2015). This region has 10 CARSNET stations, including Tazhong, Hontan, Hami, Urumqi, Ejina, Dunhuang, Minqin, Jiuquan, Lanzhou, and Yinchuan. In this evaluation, we use only the data from seven CARSNET stations (Tazhong, Hontan, Hami, Ejina, Dunhuang, Minqin, and Jiuquan) located in arid and semiarid regions over northwestern China where aerosols are dominated by dust particles. The three stations (Urumqi, Lanzhou, and Yinchuan) located in the city centers, where aerosols mainly come from fine particle pollution (Yu et al., 2015) are excluded. The measured CARSNET AOD at the central wavelength in the visible spectrum (550 nm) is obtained from the observed data at 675 nm and 440 nm following the Ångström law.

3.2. Evaluation

Figure 1a displays the spatial distribution of annually averaged dust surface mass concentrations derived from the model in the Active experiment. Higher dust concentration centers are mainly located over the dust source regions including the Taklamakan and the Gobi Deserts, where the corresponding concentration can reach a value more than 200 μg m⁻³. Large amounts of mineral dusts over the dust source region was transported to the wide downwind areas, including the Pacific Ocean and the eastern China through the middle latitude westerly winds, and the dust surface concentration is reduced significantly from northwestern China to the Pacific Ocean, as shown in Figure 1a. Figure 1b compares the annually averaged dust surface concentrations between the CAWNET observations and the CAM4-BAM over East Asia. The improved CAM4-BAM shows a positive correlation (coefficient $R^2$ of 0.46) with the observations of the dust surface mass concentrations. However, the model underestimates the dust mass concentrations, more likely due to the absence of anthropogenic dust aerosols in the current models (Tegen et al., 2004) and the low resolution of the model. Additionally, Figure 2a shows a similar spatial pattern of dust surface concentrations in seasonal means, including MAM, JJA, SON, and DJF, showing that dust aerosols are markedly reduced from Northwestern China to the Pacific Ocean. The maximum values of dust concentrations are simulated in MAM, in line with the observed higher dust storm frequency in this season. The model also shows a positive correlation between the observations on the dust surface concentrations in the four seasons (coefficients $R^2$ of 0.14 in MAM, 0.38 in JJA, 0.12 in SON, and 0.19 in DJF).

Figure 3a shows the spatial distribution of annually averaged dust AOD derived from the model (Active experiment). The dust AOD has a maximum value above 0.1 over Northwestern China, which decreases from this region to the widespread downwind areas. The spatial pattern of dust AOD is virtually identical to that of the
Figure 4. Same as Figure 3 but for four different seasons.
Figure 5. Differences in (a) dust emission (g/m²/yr), (b) dust loading (mg/m²), (c) dust transport (g m⁻¹ s⁻¹), (d) dust dry deposition (g/m²/yr), and (e) dust wet deposition (g/m²/yr) between the Active and Passive experiments in the annual means over East Asia (75°E–120°E and 35°N–48°N) and over North Africa (20°W–35°E and 10°N–30°N). The green dots represent the grid points with statistical significance above the 95% level.
Figure 6. Vertical profile of the differences in (a) annual and (b) MAM dust concentrations (μg/kg) for Active (solid) and Passive (dotted) experiments over East Asia (blue) and over North Africa (red).

the main spatial patterns about the dust surface concentrations and dust AOD, for example, the significant decrease from the dust source regions to the Pacific Ocean, lending confidence to the model in simulating the dust cycle.

4. Effects of Dust Radiative Forcing

4.1. Changes in Key Processes of the Dust Cycle Induced by Dust Radiative Forcing

It is well known that dust aerosols can affect atmospheric temperature structures and surface winds through their radiative effects, in turn influencing the dust cycle (Colarco et al., 2014; Heinold et al., 2008; Miller et al., 2004a; Perlwitz et al., 2001; Woodage et al., 2010; Zhang et al., 2009). This subsection investigates the key processes of dust cycle changes induced by dust radiative forcing (Active-Passive experiments), including dust emissions, loading, transport, and dry and wet depositions over East Asia. Comparisons are made with that over North Africa as well.

Figure 5 compares annual differences in the dust cycle induced by the dust radiative forcing (Active-Passive experiments) over East Asia and over North Africa. This figure shows that the dust emissions (Figure 5a), dust loading (Figure 5b), dust transport (Figure 5c, defined as the vertically integrated dust flux, which is similar to water vapor transport), and dry (Figure 5d) and wet depositions (Figure 5e) can all significantly increase due to dust radiative forcing over North Africa. The result is quite consistent with those of recent studies (Colarco et al., 2014; Woodage et al., 2010). Over East Asia, the changes in the dust cycle induced by dust radiative forcing are opposite to those over North Africa. These dust emissions, dust loading, dust transport, and dust dry and wet depositions are markedly decreased in this region by dust radiative forcing, as shown in Figure 5.

Figure 6 compares the vertical profiles of the annual dust concentrations, showing the contrasting behaviors over North Africa (strengthening) and over East Asia (weakening), up to 300 mb. For the annual vertical dust concentrations, they also increased over North Africa and decreased over East Asia (Figure 6a). Considering a comparison of the four seasons including MAM, JJA, SON, and DJF, the maximum changes in the dust cycles in the MAM are shown over these two regions (Tables 1 and 2). Additionally, we present the MAM difference
Table 2

Dust Budget for MAM, JJA, SON, DJF, and ANN for Dust Source Regions Over North Africa for Active-Passive Experiments

<table>
<thead>
<tr>
<th></th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
<th>ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission (Tg/season or Tg/yr)</td>
<td>23.87</td>
<td>18.50</td>
<td>10.39</td>
<td>-0.21</td>
<td>52.54</td>
</tr>
<tr>
<td>Dust loading (Tg)</td>
<td>0.17</td>
<td>0.08</td>
<td>0.09</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>Transport (g/m/s)</td>
<td>0.11</td>
<td>0.07</td>
<td>0.06</td>
<td>0.00</td>
<td>0.06</td>
</tr>
<tr>
<td>Dry deposition (Tg/season or Tg/yr)</td>
<td>18.69</td>
<td>10.38</td>
<td>6.83</td>
<td>1.65</td>
<td>37.56</td>
</tr>
<tr>
<td>Wet deposition (Tg/season or Tg/yr)</td>
<td>1.78</td>
<td>4.20</td>
<td>-0.81</td>
<td>-0.21</td>
<td>4.97</td>
</tr>
</tbody>
</table>

Figure 7. Differences in (a) dust emissions (g/m²/season), (b) dust loading (mg/m²), (c) dust transport (g m⁻¹ s⁻¹), (d) dust dry deposition (g/m²/season), and (e) dust wet deposition (g/m²/season) between the Active and Passive experiments in the MAM over East Asia (75°E–120°E and 35°N–48°N) and over North Africa (20°W–35°E and 10°N–30°N). The green dots represent the grid points with statistical significance above the 95% level.
Table 3
Dust Budget and AOD for MAM, JJA, SON, DJF, and ANN for Dust Source Regions Over East Asia for the Active Experiment

<table>
<thead>
<tr>
<th></th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
<th>ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission (Tg/season or Tg/yr)</td>
<td>115.37</td>
<td>62.48</td>
<td>49.04</td>
<td>37.60</td>
<td>264.49</td>
</tr>
<tr>
<td>Dust loading (Tg)</td>
<td>1.44</td>
<td>1.16</td>
<td>0.69</td>
<td>0.42</td>
<td>0.93</td>
</tr>
<tr>
<td>Transport (g/m/s)</td>
<td>1.45</td>
<td>0.57</td>
<td>0.59</td>
<td>0.53</td>
<td>0.79</td>
</tr>
<tr>
<td>Dry deposition (Tg/season or Tg/yr)</td>
<td>61.58</td>
<td>29.61</td>
<td>29.99</td>
<td>24.47</td>
<td>45.65</td>
</tr>
<tr>
<td>Wet deposition (Tg/season or Tg/yr)</td>
<td>28.46</td>
<td>21.09</td>
<td>10.63</td>
<td>5.13</td>
<td>65.29</td>
</tr>
<tr>
<td>Lifetime (days)</td>
<td>1.86</td>
<td>2.53</td>
<td>1.95</td>
<td>2.07</td>
<td>1.94</td>
</tr>
<tr>
<td>AOD at 550 nm</td>
<td>0.103</td>
<td>0.080</td>
<td>0.051</td>
<td>0.031</td>
<td>0.066</td>
</tr>
</tbody>
</table>

Table 4
Dust Budget and AOD for MAM, JJA, SON, DJF, and ANN for Dust Source Regions Over North Africa for the Active Experiment

<table>
<thead>
<tr>
<th></th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
<th>ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission (Tg/season or Tg/yr)</td>
<td>292.21</td>
<td>266.74</td>
<td>208.55</td>
<td>303.25</td>
<td>1,070.75</td>
</tr>
<tr>
<td>Dust loading (Tg)</td>
<td>6.12</td>
<td>5.40</td>
<td>4.09</td>
<td>3.74</td>
<td>4.84</td>
</tr>
<tr>
<td>Transport (g/m/s)</td>
<td>2.69</td>
<td>2.47</td>
<td>2.28</td>
<td>3.17</td>
<td>2.65</td>
</tr>
<tr>
<td>Dry deposition (Tg/season or Tg/yr)</td>
<td>187.23</td>
<td>128.40</td>
<td>126.38</td>
<td>214.57</td>
<td>656.59</td>
</tr>
<tr>
<td>Wet deposition (Tg/season or Tg/yr)</td>
<td>16.51</td>
<td>71.54</td>
<td>20.71</td>
<td>1.62</td>
<td>110.39</td>
</tr>
<tr>
<td>Lifetime (Day)</td>
<td>3.64</td>
<td>3.36</td>
<td>3.26</td>
<td>2.42</td>
<td>3.06</td>
</tr>
<tr>
<td>AOD at 550 nm</td>
<td>0.313</td>
<td>0.266</td>
<td>0.202</td>
<td>0.180</td>
<td>0.240</td>
</tr>
</tbody>
</table>

in the dust cycles over North Africa and over East Asia, which shows a similar pattern in Figure 7 compared to that in Figure 5. Furthermore, Figure 6b shows that the vertical dust concentrations increased over North Africa and decreased over East Asia in MAM, which are both more significant than that in the annual means.

Table 3 shows the dust budgets and AOD (Active experiment) for the seasonal and annual means for dust source regions over East Asia (75°E–120°E and 35°N–48°N) in Figure 5. In our model’s results, there are larger seasonal differences in dust emissions, loading, transport, and dry and wet depositions, showing that these corresponding maximum values are found in MAM. The lifetime of dust aerosols is approximately 2 days for all the seasonal and annual means. The 550 nm dust AOD also has the largest value (0.103) in MAM over East Asia. For a comparison, Table 4 provides the dust cycles and AOD for the seasonal and annual means for the dust source regions in North Africa (20°W–10°E and 10°N–30°N). Compared to East Asia, the dust emissions, loading, transport, and dry and wet depositions are much larger, except for wet deposition in the seasonal and annual means over North Africa, and there are no significant seasonal differences. The lifetime of dust aerosols is markedly longer (3 days) over North Africa than over East Asia, more likely due to the weaker wet deposition accounting for less rain over North Africa. The regional dust AODs (0.180–0.313) are also significantly larger than those (0.031–0.103) over East Asia in the annual and seasonal means. For the regional mean values of dust cycles over these two regions, annual differences are similar with Figure 5, showing that dust emissions, dust loading, dust transport, and dry and wet depositions increase over North Africa (Table 2), and they decrease over East Asia (Table 1), induced by dust radiative forcing. Note that their maximum changes are found in the MAM compared to other seasons.

Hence, in the following subsection, we will concentrate on the analysis about the radiative forcing of dusts and its climatic feedbacks in the MAM over East Asia and North Africa, which induces distinct effects on dust cycle changes over the two regions.

4.2. Dust Radiative Forcing and Dust Radiative Feedbacks

Figures 8 and 9 show the spatial distributions about the MAM dust radiative anomalies between the Active and Passive numerical experiments including shortwave, longwave, and the net (shortwave + longwave) components (at the surface, at the TOA, and in the atmosphere), respectively, for clear-sky and all-sky radiative forcing. It is noted that the difference in these radiative forcings are significant almost everywhere over these two regions (not shown in the figures). The corresponding mean radiative values over East Asia and North Africa are shown in Table 5. For the clear-sky, the dust-induced surface shortwave radiative forcing (Figure 8a)
Dust radiative anomaly for clear-sky forcing between the Active and Passive experiments (a, d, and g) at the surface, (b, e, and h) at the TOA, and (c, f, and i) in the atmosphere. Shown are net values with shortwave (SW, Figures 8a–8c), longwave (LW, Figures 8d–8f), and shortwave + longwave (NET, Figures 8g–8i) components in the MAM over East Asia (75°E–120°E and 35°N–48°N) and over North Africa (20°W–35°E and 10°N–30°N). Units are W/m².

is negative owing to absorption and scattering of solar radiation induced by dust aerosols, and it is stronger over North Africa (−16.97 W m⁻²) than over East Asia (−11.62 W m⁻²) because North Africa has larger dust atmospheric loadings (Table 4). The TOA shortwave dust forcing (Figure 8b) is negative (−7.31 W m⁻²) over East Asia, but slightly positive (0.03 W m⁻²) over North Africa. The positive TOA shortwave forcing over North Africa is likely due to a higher surface albedo (Takemura et al., 2009). Figure 8c shows the atmospheric column heating due to dust absorption of incoming shortwave radiation over these two regions, derived from the difference between the radiative forcing between, at the surface, and at the TOA. Evidently, North Africa exhibits a much larger heating (17.00 W m⁻²) than East Asia (4.30 W m⁻²).

In contrast to dust shortwave radiative effects, dust aerosols trap the outgoing longwave radiation over these two regions, leading to positive longwave radiative forcings at both the TOA and surface, particularly over North Africa (Figures 8d and 8e), and to atmospheric column cooling (Figure 8f). It is interesting to note that the net radiative forcings exhibit strikingly different behaviors over East Asia and North Africa. The net radiative forcings are negative over East Asia at both the surface and TOA (−4.59 and −1.71 W m⁻²) in Figures 9g and 9h. In contrast, the net radiative forcings are almost positive over North Africa at the surface and at the TOA (1.66 and 5.11 W m⁻²). Additionally, the net radiative forcing by dust aerosols in the atmosphere are positive over these two regions and it has a larger value (3.45 W m⁻²) over North Africa because the dust longwave
Figure 9. Same as Figure 8 but for the all-sky forcing.

cooling is outweighed by the dust shortwave warming in Figure 8i. Furthermore, Figure 9 shows a similar spatial distribution of all-sky radiative forcings compared to the clear-sky values (Figure 8). The values of the all-sky radiative forcings at the surface, at the TOA, and in the atmosphere are different from those in the clear-sky in Table 5 because of the perturbations of cloud radiative forcing induced by dust radiative feedbacks.

Figure 10 shows the corresponding changes in the surface temperature at 2 m, the surface sensible heat flux, the 10 m wind speed, and the surface precipitation induced by dust radiative forcing in the MAM. The surface temperature is effectively decreased over East Asia (Figure 10a) mainly due to the negative dust net radiative forcing at the surface (Figure 9g) and at the TOA (Figure 9h), also shown in Table 5 (−2.75 and −4.23 W/m², respectively). The surface negative net radiative forcing (Figure 9g) causes a reduction in the sensible heat flux from the ground into the atmosphere (Figure 10b), and the reduction would reduce vertical mixing within the PBL. This reduced mixing would cause less acceleration at the surface, consistent with the negative wind anomaly (Figure 10c). Hence, the decreased 10 m wind speed can reduce the emission flux of dust aerosols according to equation (2), leading to the weakened dust cycle (Figure 5). This PBL mechanism associated with the dust emission feedback has been proposed by Miller et al. (2004a), Perez et al. (2006), and Heinold et al. (2007). Additionally, the surface precipitation changes induced by dust aerosols are insignificant over East Asia, as shown in Figure 10d.
Table 5

Dust Radiative Anomaly (W/m²) in MAM for Clear-Sky and All-Sky Forcings at the Surface, at the TOA, and in the Atmosphere Over East Asia and Over North Africa for Active-Passive Experiments

<table>
<thead>
<tr>
<th>Clear-sky forcing</th>
<th>All-sky forcing</th>
<th>Clear-sky forcing</th>
<th>All-sky forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>over East Asia</td>
<td></td>
<td>over North Africa</td>
</tr>
<tr>
<td>Surface LW</td>
<td>7.02</td>
<td>6.39</td>
<td>18.63</td>
</tr>
<tr>
<td>Surface NET</td>
<td>−4.59</td>
<td>−4.23</td>
<td>1.66</td>
</tr>
<tr>
<td>TOA SW</td>
<td>−7.31</td>
<td>−6.67</td>
<td>0.03</td>
</tr>
<tr>
<td>TOA LW</td>
<td>5.60</td>
<td>3.91</td>
<td>5.08</td>
</tr>
<tr>
<td>TOA NET</td>
<td>−1.71</td>
<td>−2.75</td>
<td>5.11</td>
</tr>
<tr>
<td>ATMOS SW</td>
<td>4.30</td>
<td>3.95</td>
<td>17.00</td>
</tr>
<tr>
<td>ATMOS LW</td>
<td>−1.42</td>
<td>−2.47</td>
<td>−13.55</td>
</tr>
<tr>
<td>ATMOS NET</td>
<td>2.88</td>
<td>1.48</td>
<td>3.45</td>
</tr>
</tbody>
</table>

However, it is noted that the climatic feedbacks (the surface temperature, the 10 m wind speed, and surface precipitation) over North Africa are opposite to that over East Asia (Figure 10). We believe that the enhanced dust cycle can be attributed to two factors occurring over North Africa. The first factor is that the isolated regions of positive surface DRF (Figure 9g) display a positive surface sensible flux (Figure 10b) and increase the local 10 m wind speed (Figure 10c) by the PBL mechanism (Heinold et al., 2007; Miller et al., 2004a; Perez et al., 2006). The other factor is described by the strengthened large-scale circulation over North Africa. Figure 10a

![Figure 10](image-url)

**Figure 10.** Differences in (a) the surface temperature (°C), (b) the surface sensible heat flux (W/m²), (c) the 10 m wind speed (m/s), and (d) the surface precipitation (mm/d) between the Active and Passive experiments in the MAM over East Asia (75°E–120°E and 35°N–48°N) and over North Africa (20°W–35°E and 10°N–30°N). The green dots represent the grid points with statistical significance above the 95% level.
shows a significant increase in the surface temperature over North Africa mainly owing to the positive net radiative forcing at the TOA (Figure 9h) for the averaged value of 6.45 W/m², which is because the surface temperature anomaly is more strongly related to the forcing at TOA (Miller, 2012). The surface temperature is slightly decreased by the DRF over the northern region of North Africa and the ocean region to its west. The spatial patterns in the surface temperature changes increase the meridional pressure gradient (Figure 11b) over North Africa, enhancing the regional large-scale circulation (Figure 11c) and the surface wind speeds (Figure 10c). These two factors increase the surface wind speeds, which enhance dust emissions and then increase dust loading, transport, and dry and wet depositions over this region (Figure 5). Surface precipitation can be enhanced by dust aerosols due to the strengthened large-scale circulation, which may suppress the dust emissions and partly offset the enhanced dust cycles due to increased surface wind speeds.

![Figure 11](image1.png)

**Figure 11.** Spatial distribution of (a) sea level pressure (hPa) and (c) 850 hPa wind field (m/s) for the Active experiment in MAM. The corresponding differences in (b) sea level pressure (hPa) and (d) 850 hPa wind field (m/s) between the Active and Passive experiments.

![Figure 12](image2.png)

**Figure 12.** Spatial distribution of (a) annual and (b) MAM surface albedo for the Active experiment.
5. Further Discussions

The different climatic feedbacks of the DRF over these two regions are mainly due to the distinct dust radiative forcing. These distinct dust radiative forcings mainly result from different regional surface albedo, dust layer height, and dust optical properties over these two regions. Figure 12 shows a higher surface albedo over North Africa compared to that over East Asia for annual and MAM means, except that it is the highest surface albedo due to larger snow cover fraction over the Tibetan Plateau (Xu et al., 2009). It is noted that dust aerosols at higher surface albedo can lead to a positive DRF by decreasing the reflection of sunlight, and a negative DRF can be found at lower surface albedo (Takemura et al., 2009). Hence, different surface albedos mainly result in different dust radiative forcings over these two regions. Additionally, Liu et al. (2008) claimed that the dust aerosol layers over East Asia can be found higher than that over North Africa using the CALIPSO lidar measurements. Our simulated results also show that East Asia has a higher dust aerosol layer in annual (Figure 13a) and MAM means (Figure 13b). The position of the dust aerosol layer over these two regions can also affect the dust radiative forcing at the surface and TOA. Furthermore, our results show that dust particles exhibit different distributions over East Asia and North Africa (Figure 14). The average ratio of dusts with large size (Bin3 + Bin4) to all dust is approximately 70% over East Asia, whereas the average is 75% over North Africa. Hence, East Asian dust has weaker absorption of radiation due to its smaller size, while North African dust has stronger absorption, which has also been shown in AERONET retrievals (Su & Toon, 2011).
6. Summary and Conclusions

In this paper, the improved CAM4-BAM by Albani et al. (2014) is used to evaluate the East Asian dust, including surface dust concentrations and the AOD, based on local observational sites from CAWNET (Zhang et al., 2012) and CARSNET (Che et al., 2015). The two numerical experiments are completed and intercompared, one without and one with the dust direct radiative effects. Their differences are used to study the radiative feedbacks of dust aerosols over East Asia, compared with those over North Africa.

Our results showed that the improved CAM4-BAM mainly captures the spatial features of the observed dust surface concentration and the AOD over East Asia and showed a positive correlation with the observations from CAWNET and CARSNET stations in terms of annual and seasonal means. The simulated values for dust surface concentrations and AOD are lower than the observed results. According to the differences between the Active and Passive experiments, the dust emissions, loading, and dry and wet depositions over North Africa can be enhanced significantly with dust radiative forcing. However, the changes in the dust cycle over East Asia are opposite to those over North Africa, yielding a significant decrease with dust radiative forcing. Over North Africa, dust radiative forcing increases surface temperature mainly owing to the dust positive TOA radiative forcing and enhances the 10 m wind speed significantly affected by the PBL mechanism and the strengthened large-scale circulation over North Africa, while it decreases surface temperature due to dust negative TOA and negative surface forcing and decrease the 10 m wind speed through the PBL mechanism over East Asia, which can lead to distinct dust cycle changes over these two regions. Further mechanistic analysis reveals that the contrast of the dust-radiation effects between East Asia and North Africa likely stems from their differences in regional surface albedo, vertical dust distribution, and particle size distributions.

It is noteworthy that the direct radiative forcing of dust aerosols is strongly dependent on the input dust optical parameters including particle shape (e.g., sphericity and nonsphericity) and refractive index, which will affect atmosphere shortwave and longwave forcing (Perlwitz et al., 2001; Wang et al., 2013; Yang et al., 2007; Yi et al., 2011). Furthermore, Colarco et al. (2014) noted that the sensitivity of dust optical parameters can affect dust emissions and transport, which may have an influence on our results in terms of the changes in dust cycles. The absorbing aerosols including dust and black carbon in snow have a significant radiative forcing at global scale, especially over the Tibetan Plateau (Flanner et al., 2009; Qian et al., 2011). The radiative forcing in dust-in-snow over the Tibetan Plateau increases the surface air temperature and further affects the monsoon climate and the Asian hydrological cycle (Qian et al., 2011), which will influence the dust cycle over East Asia. We plan to further address these points in future. Additionally, the dust semidirect effect can evaporate the clouds to exert a positive radiative forcing over arid and semiarid regions (e.g., Huang et al., 2014). Our simulated results also show that dust aerosols decrease the cloud liquid and ice path to exert a significant positive forcing mainly owing to the semidirect effect over East Asia, whereas the cloud amount increased and led to a negative radiative forcing owing to the strengthened large-scale circulation over North Africa (figures not shown).

References


