Mineral dust impacts on regional precipitation and summer circulation in East Asia using a regional coupled climate system model

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Abstract The climatic impacts of dust on East Asian precipitation, summer monsoon, and sea surface temperature (SST) were investigated by a regional coupled atmosphere-ocean-land model. The regional and annual mean dust clear-sky (all-sky) direct radiative forcings were predicted to be $-6.65 \,\text{W m}^{-2}$ ($-1.78 \,\text{W m}^{-2}$) at the surface and $3.79 \,\text{W m}^{-2}$ ($8.65 \,\text{W m}^{-2}$) at the top of atmosphere. The climatic effects of dust include a cooling effect below 700 hPa and a warming effect above, leading to more stabilized lower troposphere and anomalously cyclonic wind over Japan and surrounding oceans. Sensitivity tests show that the "surface cooling" effect by dust could reduce evaporation over land and enhance stability of the lower atmosphere, leading to reduced vapor content and precipitation in China in the spring. However, the upward movements by the "elevated heat pump" effect of dust over northern China or by the atmospheric convergence over southern China, and the downward movement by the secondary circulation over central China, along with the enhanced evaporation and the weakened lapse rate over Chinese continent, lead to increased precipitation in downwind areas of dust source regions and southern China and to decreased precipitation in central China in summer. Results from this simulation also show that dust aerosol tends to weaken the East Asian summer monsoon by reducing the land-sea-temperature contrast. In addition, dust could also perturb SST by the local net heat flux rebalance as well as the northward heat transport from surrounding oceans. The anomalous northward surface wind contributes even larger on SST in June, July, and August.

1. Introduction

East Asia is a major source of mineral dust. It was estimated that more than half of the total aerosol burden and aerosol optical depth (AOD) were contributed by dust [Chin et al., 2002]. The uplifted dust particles could be transported thousands of kilometers away from its surface source regions across the Pacific Ocean, even to the North America continent, along about 40°N [Zhang et al., 1997; Zhao et al., 2006]. Furthermore, the transported Asian dust aerosol might rebuild the Earth system energy balance [Lau et al., 2006; Sun et al., 2012]. By scattering and absorption of solar radiation and by absorption of infrared radiation, the regional mean direct radiative forcing (DRF) by dust was estimated to range from $-6.85$ to $0.94 \,\text{W m}^{-2}$ at the top of the atmosphere (TOA) and $-10.61$ to $-1.50 \,\text{W m}^{-2}$ at the terrestrial surface over East Asia [Miller et al., 2004; Wu et al., 2005, 2010; Han et al., 2012; Zhang et al., 2013]. As a result of the radiative effects of surface cooling and atmospheric heating by dust, the East Asian temperature and precipitation could also be modified.

Several general circulation model [Miller and Tegen, 1998; Miller et al., 2004], regional climate model (RCM) [Zhang et al., 2009; Sun et al., 2012], and cloud model [Yin et al., 2002; Yin and Chen, 2007] studies have suggested a reasonable assessment of the potential processes associated with the radiative effects by dust. Miller and Tegen [1998] found that the dust could enhance or weaken precipitation in different regions depending on the presence of deep convection. Increased occurrence of convection induced by a lofted dust layer heating could strengthen the East Asian summer monsoon circulation and result in a local increase in precipitation [Miller et al., 2004; Stephens et al., 2004]. Miller et al. [2004] also found that the precipitation could be enhanced over desert areas, yet as a result of surface cooling effect by dust, the global mean precipitation was assumed to be reduced. Recently, the "elevated heat pump" (EHP) mechanism which was induced by atmospheric heating effect of a lifted dust (or black carbon) layer was found over northern India [Lau et al., 2006] and western Africa [Salomon et al., 2008; Lau et al., 2009], which could enhance precipitation in these
regions in specific months of a year. All these aforementioned results suggested that two components induced by dust determine the changes in precipitation patterns. The presence of atmospheric heating effect by dust could enhance local precipitation, while the surface cooling component might pose an opposite effect. While some studies indicated a south wetting and north drying trend in China [Menon et al., 2002; Ye et al., 2013], dust aerosol was considered to offset this tendency and produce an increase in precipitation over the dusty regions in northern China [Lau et al., 2006; Zhang et al., 2009; Wu et al., 2010; Sun et al., 2012].

Similar to precipitation changes produced by absorbing aerosols, i.e., dust and black carbon in western Africa [Solmon et al., 2008; Lau et al., 2009] and South Asia [Ramanathan et al., 2005; Lau et al., 2006], we assumed that similar mechanisms on precipitation might also exist over East Asia during transport of dust layer from northwestern China to the northwestern Pacific Ocean around 40°N. However, the possible mechanisms on dust-induced changes in precipitation over East Asia are still unclear. Thus, it is meaningful to explore the dust climatic impacts on precipitation in East Asia.

On the other hand, dust aerosol also affects the ground temperature over continent and surrounding oceans. Ramanathan et al. [2005] showed that as a result of forcings by black carbon and dust, the changes in meridional sea surface temperature (SST) gradient and land-sea temperature contrast (LSTC) could weaken the strengths of the South Asian monsoon circulation and the amount of precipitation over India during summer. Similarly, changes in surface thermal contrast between the Eurasian continent and the surrounding oceans by aerosols could also modify atmospheric circulation and precipitation over East Asia [Yue et al., 2011]. The changes in East Asian summer circulation induced by black carbon and sulfate have been well documented in literature [Xu, 2001; Liu et al., 2009]; however, the effects of dust on flow fields necessitate more attention. In addition, to our knowledge, most previous studies used RCMs with atmospheric model only, which could hardly reproduce the aerosol impacts over the oceans. An interactive SST is recommended when considering the climatic impacts by aerosols [Yue et al., 2011; Nabat et al., 2015].

In this study, the mechanisms of mineral dust on the general circulation, precipitation, and SST in different regions over East Asia are investigated by using a state-of-the-art regional coupled atmosphere-ocean-land model with high-resolution aerosol distributions output from a global chemistry and transport model. The paper is organized as follows. The model and simulation strategy are described in section 2. Section 3 gives the model results of distributions, radiative forcings, and the climatic impacts of dust aerosol on the changes in temperature, circulation, precipitation, and SST over East Asia. Summary and conclusions are given in section 4.

2. Model and Numerical Experiments

2.1. Model Description

The Regional Integrated Environment Model System (RCM RIEMS 2.0) developed by the Key Laboratory of Regional Climate Environment Research for Temperate East Asia, China Academy of Science, was used in this study [Han, 2010; Han et al., 2012; Li et al., 2014]. The dynamical core of the model was based on the National Center for Atmospheric Research (NCAR) and Pennsylvania State Mesoscale Model MM5 [Grell et al., 1995]. RIEMS includes the major physical parameterizations, such as modified Column Radiation Model from CCM3 [Kiehl et al., 1996], BATS1e surface process [Dickinson et al., 1993], Medium-Range Forecast
planetary boundary scheme [Hong and Pan, 1996], parameterization of convective clouds [Grell, 1993], and the microphysical scheme of Reisner et al. [1998]. The new development in RIEMS is coupling with a regional ocean model, the Princeton Ocean Model (POM) [Blumberg and Mellor, 1987], which was modified by Fang et al. [2010, 2013]. Therefore, the current version of RIEMS-POM is capable to simulate climate with an interactive SST. Previous studies suggested that RIEMS-POM had a good performance in simulating multi-year means and variability of climate in East Asia [Fang et al., 2010, 2013; Zhao, 2013; Guo et al., 2015].

The daily aerosol distributions over a period 2000–2007, output from the GOCART model (the Goddard Chemistry Aerosol Radiation and Transport model) [Ramanathan et al., 2005; Lau et al., 2006, 2009; Nabat et al., 2015], were introduced into the radiation calculation in RIEMS. By comparison with satellite observations, the three-dimensional aerosol fields were found to have captured the spatial and temporal distributions of aerosol [Yu et al., 2003; Weaver et al., 2007].

In this study, aerosol optical parameters, i.e., mass extinction coefficient (β), single-scattering albedo (ω), and asymmetry factor (g) using Mie theory from the Global Aerosol Data Set [Köpke et al., 1997; Chin et al., 2002], were used to calculate the dust shortwave radiation by δ-Eddington approximation. In the longwave domain, the thermal infrared effects of dust were included by considering the emissivity and absorptivity parameterizations suggested by Kiehl et al. [1996].

Figure 2. Comparison between the (a, b) ERA-Interim observed and (c, d) RIEMS-POM modeled surface temperature (unit in K) in MAM (Figures 2a and 2c) and JJA (Figures 2b and 2d) in 2000 to 2007. Model results were from experiment ALL.
2.2. Experiments Design

The simulation covered most of East Asia, with the center at (28°N, 110°E) and a horizontal resolution of 60 × 60 km². Initial and boundary conditions were provided by 6-hourly National Centers for Environmental Prediction (NCEP)/NCAR reanalysis data. The experiments were carried out for 8 years (2000–2007) with 1 year time as spin-up for each year. The averaged results of the 8 years in spring and summer were analyzed in this study, because the dust loading is larger in boreal spring and smaller in summer. Previous studies with similar model setup showed that this kind of experimental design could capture the seasonal cycle of moisture transport and summer precipitation in China [Fang et al., 2010, 2013; Zou and Zhou, 2011; Yao et al., 2013] and cloud reflect the feature of local air-sea interactions [Huang et al., 2012; Yao et al., 2013]. Before the coupling of each year, the NCEP/NCAR Reanalysis data were also used to drive POM as an initial spin-up to get a stabilized ocean. The initialization methodology adopted in this study is similar to the previous RCM simulations in Mediterranean [Nabat et al., 2015] and East Asia [Zou and Zhou, 2011; Yao et al., 2013] and has also been used to study the evolution of East Asian summer circulation and precipitation [Fang et al., 2010, 2013].

Two experiments were carried out to assess the combined direct and semidirect radiative effects by dust. The indirect effect of dust is not considered because of its great uncertainties that could complicate our results. In the baseline experiment (labeled NDU), externally mixed four aerosol species were considered in the model, including black carbon, organic carbon, sulfate, and sea salt. The other anomaly experiment (labeled ALL) is identical to NDU, except for the inclusion of dust. The difference between the two experiments (ALL – NDU) is compared to deduce the radiative and climatic effects of dust. It is worth noting that this study considered the effects of dust mixed with other aerosol species; thus, it should be more realistic to assess the effects of dust on climate.

Figure 3. Same as Figure 2 but for precipitation (unit in mm d⁻¹). The observation data were taken from CRU.

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3. Results and Discussions

The topographic height over the domain of this study is shown in Figure 1. It covers the entire Chinese continent, including the major deserts and dust areas such as the Taklamakan Desert, the Tengger Desert, and the Gurbantunggut Desert, and the adjacent oceans. We focused on four specific regions for detailed analysis, including southern China (SC, 100–120°E, 25–32.5°N), central China (CC, 100–120°E, 32.5–37.5°N), northern China (NC, 100–120°E, 37.5–50°N), and northeastern China (NEC, 120–135°E, 40–50°N). In addition, East Asia (EA) is referred to the entire area of the domain (54–166°E, 20–56°N).

3.1. Basic Model Climatology

While the RCM RIMES-POM has been carefully evaluated with different observations in previous studies [Fang et al., 2010, 2013; Zhao, 2013], further assessments are necessary since our simulation covers a different time period (2000 to 2007) and spatial area. The simulated climatological surface temperature in spring and summer from experiment ALL and those from ERA-Interim reanalysis were compared in Figure 2. Generally, the RCM (with five aerosol species) could capture the major distribution features of the observed surface temperature. The distributions of major cooling centers over the Tibetan Plateau in MAM (March, April, and May) and the warming centers over the Taklamakan Desert and the eastern coast of China in JJA (June, July, and August) were well reproduced by RIEMS-POM, although the SST of oceans between 15 and 30°N was underestimated by 1.0–4.0 K by the model in JJA.

Figure 3 further compares the modeled climatological precipitation rate from experiment ALL and the observations from CRU (Climate Research Unit of the University of East Anglia) in MAM and JJA. The observed maximum values of precipitation rate appeared over the southern coast of China and the Bay of Bengal in MAM and decreased toward north and northwest (Figure 3a). These rainfall centers were greatly strengthened in JJA (Figure 3b) due to the prevailed monsoon in summer. The RIEMS-POM could reproduce the main characteristics of climatological precipitation patterns, especially in MAM (Figures 3c and 3d). As compared with observations, the higher precipitation amount appeared over the lower reaches of the Yellow River, as well
as less precipitation over the southern coast of China in JJA simulated by the model most likely resulted from a relative stronger northward airflow over land in summer (Figure 4d), while the precipitation difference between the model and observations over northwestern China could be attributed to sparse observation data in CRU data set [Zhang et al., 2009].

In order to assess the bias in precipitation mentioned above, the mean wind field at 700 hPa and the geopotential height of 5880 geopotential meters (gpm) were shown in Figure 4 from experiment ALL and ERA-Interim observations. Generally, the model could reproduce the circulation patterns in both spring and summer seasons, although it appears to be a weaker eastward airflow over the Bay of Bengal and a stronger northward one over southern and central China in JJA (Figures 4b and 4d). The difference in circulation between modeled and observations could be attributed to the anomalously strengthened Western Subtropical Pacific High (WSPH) in RIEMS-POM. The relatively northward and westward expansion of WSPH in summer may contribute to the stronger monsoon circulation over southern and central China seen in the simulation results. In general, the model captured the main climatological features over the research area, and the results from

![Figure 5. Dust column mass loading (shading plots) (unit in mg m\(^{-2}\)) and the ratio of absorbing AOD (AAOD) to total AOD (contour) at 550 nm averaged in (a) MAM and (b) JJA from GOCART.](image)

<table>
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<tr>
<th>Table 1. Regional and Annual Mean Dust Burden and Its Clear-Sky DRF Averaged Over East Asia From Experiment ALL – NDU</th>
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<tr>
<td>Dust burden (Tg)</td>
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RIEMS-POM are reasonable in comparison with other RCM studies [Zhang et al., 2009; Fang et al., 2010, 2013; Sun et al., 2012; Zhao, 2013].

### 3.2. Distribution of East Asian Dust

The horizontal distributions of dust column mass loading and the ratio of absorbing AOD (AAOD) to total AOD in MAM and JJA from GOCART are shown in Figure 5. Higher dust loading centers are mainly located over the Taklamakan Desert, the Tengger Desert, and the wide downwind areas from northern China to the Korean Peninsula and Japan around 40°N. The maximum dust loading over Xinjiang in northwestern China can exceed 1000 mg m⁻², with the higher atmospheric burden in MAM (average 184.83 mg m⁻²) and the lower in JJA (average 124.19 mg m⁻²). As shown in Table 1, the regional and annual mean dust burden is

**Figure 6.** Simulated annual mean clear-sky DRFs by dust aerosol from experiment ALL – NDU (a, c, and e) at the surface and (b, d, and f) at the TOA for shortwave DRF (Figures 6a and 6b), longwave DRF (Figures 6c and 6d), and net DRF (Figures 6e and 6f). Positive values indicate increases in downward radiation. Unit in W m⁻².
about 7.09 Tg over East Asia and is relatively higher in northern (0.89 Tg) and central (0.52 Tg) China and relatively lower in southern (0.38 Tg) and northeastern (0.30 Tg) China.

The heavy dust loading shown in Figure 5 is highly anticorrelated with the surface topography (Figure 1) because the dust source function used in GOCART is based on the assumption that a basin with pronounced

Figure 7. (a–c) Altitude-month and (d–f) altitude-latitude distributions of all-sky DRFs by dust aerosol from experiment ALL – NDU for shortwave (Figures 7a and 7d), longwave (Figures 7b and 7e), and net (Figures 7c and 7f), respectively. Figures 7a–7c were averaged over the entire research domain, while Figures 7d–7f were averaged over the longitudinal zone 54–166°E in the whole modeling period. Positive values indicate increases in downward radiation. Unit in W m⁻².

about 7.09 Tg over East Asia and is relatively higher in northern (0.89 Tg) and central (0.52 Tg) China and relatively lower in southern (0.38 Tg) and northeastern (0.30 Tg) China.
3.3. Radiative Forcing

3.3.1. Radiative Forcing

In this study, both the direct and semidirect radiative effects of dust are considered. If unspecified, it was abbreviated as DRF in the following sections. Predicted annual mean distributions of clear-sky DRF by dust aerosol are shown in Figure 6. As shown in Figures 6a and 6b, the DRF is negative at the surface due to the scattering and absorption effects of dust and is positive at the TOA over the high-albedo deserts [Liao and Seinfeld, 1998]. The changes in shortwave (SW) DRF sign at the TOA shown in Figure 6b along the coastline of Chinese mainland at about 120°E is due to a sharp decrease in surface albedo between land and oceans and a decrease of average dust burden away from its sources. In contrast, as shown in Figures 6c and 6d, the longwave (LW) DRF of dust is generally positive both at the surface and at the TOA. Although LW DRF was limited over deserts at the TOA, it was much stronger at the surface and could partially cancel out the SW surface cooling effect. Overall, the net DRFs were determined by SW forcings, either at the surface or at the TOA. After all, the horizontal distributions of DRFs by dust are consistent with its column loading patterns. Such patterns of DRFs agree with those shown in Solmon et al. [2008] and Yue et al. [2010a] in western Africa and in Han [2010] and Han et al. [2012] in East Asia.

The altitude-month distributions of all-sky DRFs produced by dust averaged over East Asia in Figures 7a–7c indicate a strong seasonal variation of dust forcings. The strongest negative forcings occur near the surface and the lower troposphere in April when dust storms are active. Furthermore, the DRF changes sign at about 700–850 hPa. The increase in DRF of dust with altitudes in Figures 7a and 7c indicates that the dust radiative forcing could produce an atmospheric heating. The cause of the time delay of the peak values between the surface DRF in April and the TOA in June mainly resulted from the climatic feedbacks, because the reduction in cloud cover, especially during wet seasons caused by dust, could result in more income solar radiation that could further interact with dust layer, leading to stronger atmospheric heating. Similarly, the annual mean altitude-latitude cross sections of DRF of dust averaged over 54°–166°E are shown in Figures 7d–7f. The altitude of the sharp contrast between the positive net DRF in the atmosphere and the negative near the surface was obtained to decrease from the north to the south, with the strongest DRF centers located around the dust transport route at about 40°N and with the positive forcings appeared at the surface south of 30°N (Figure 7f).

<table>
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<th>Table 2. Comparisons of DRFs by Dust in This Study and Results in Literaturea</th>
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<td>TOA</td>
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<td>CLR</td>
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<td>This study</td>
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<td>Zhang et al. [2013]</td>
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<td>Han et al. [2012]</td>
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<td>Wu et al. [2010]</td>
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<td>Park and Jeong [2008]</td>
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<td>Zhu et al. [2007]</td>
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<td>Wu et al. [2005]</td>
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<td>Wang et al. [2004]</td>
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aPositive values indicate increase in downward radiation. Units: W m⁻². TOA, top of the atmosphere. CLR, clear sky. ALL, all sky.
bResults from GEOS-Chem.
The simulated regional and annual mean DRFs of dust are listed in Table 1 and are compared with results in literature over East Asia in Table 2. All models predict negative all-sky DRFs of dust at the surface (−1.33 to −22.01 W m⁻²) in East Asia (Table 2). Our model results (−1.78 W m⁻²) are comparable with previous studies. On the other hand, the all-sky DRFs at the TOA could be either positive or negative, depending on the absorptive property of dust (Tanaka et al., 2007). Furthermore, our experimental design has considered the external mixture effects from other aerosols; thus, the nonlinear impacts could also be added to the final values of dust aerosol DRFs.

3.3.2. Changes in Temperature

In a radiative equilibrium Earth-atmosphere system, the net DRF at the surface by dust results in pronounced changes in surface fluxes and surface temperature. The seasonal distribution of the changes in surface temperature induced by dust over East Asia in spring and summer is shown in Figure 8. Statistically significant surface cooling appeared over the areas north of 30°N in MAM, with high dust burden, and the maximum cooling larger than −0.9 K was found around 45°N (Figure 8a). However, the enhancement in daily mean surface temperature was revealed over some arid areas, e.g., the Taklamakan Desert. This increase in surface temperature over deserts was also reported in previous studies [e.g., Weaver et al., 2002; Yue et al., 2010a] and could be attributed to the positive surface LW DRFs and the atmospheric counter radiation at nighttime. There is a statistically significant area with increased SST of 0.30–0.60 K over the subtropical Pacific Ocean south of 32°N. The increased SST over oceans is due to the reduction in cloud coverage and other climatic feedbacks. This increase in SST was also reported by Liao et al. [2004] and Yue et al. [2010b]. In contrast, as shown in Figure 8b in JJA, the negative surface temperature anomalies were greatly weakened in central and northern China, while the positive were strengthened in southern China and the Pacific Oceans, as compared with the case of spring.

Figure 8. Shading plots in (a) MAM and (b) JJA showing the changes in surface temperature by dust (unit in K). (c) The seasonal changes in surface temperature over different regions. Dots in Figures 8a and 8b indicate areas where the difference is statistically significant at the 90% confidence level according to t test.
The seasonal variations of surface temperature in different regions are shown in Figure 8c. The climatic impacts of dust tend to cool all these regions throughout the year except for the southern and central China during the relatively wetter seasons (May to September). Overall, the surface temperature experiences the strongest cooling in spring and least cooling (or even warming) in summer. Dust-absorbing effect also changes the vertical distributions of temperature and humidity and burns off cloud droplets \cite{Hansen et al., 1997; Yin and Chen, 2007}. The changes in vertical atmospheric temperature in MAM and JJA are shown in Figure 9. In MAM, dust tends to cool the lower troposphere below 700 hPa and heats the middle and upper troposphere in central, northern, and northeastern China. A colder lower troposphere and warmer middle and upper atmosphere in these areas help to stabilize the lower atmosphere and suppress the formation of convective cloud precipitation in these regions. In contrast, the atmospheric warming effect by dust was evident throughout the atmosphere in southern China in spring. However, as shown in Figure 9b in JJA, the cooling effects in central, northern, and northeastern China were weakened in lower troposphere while the warming effects above 700 hPa were strengthened, in comparison with those in spring. This atmospheric temperature structure induced by dust is also characterized by Yue et al. \cite{2010a} on the global scale.

Table 3 shows the regional mean surface temperature response to the presence of dust aerosol. On the regional and seasonal mean basis, the dust induced a surface cooling in central (−0.26 K), northern (−0.84 K), and northeastern (−0.71 K) China in spring and a warming effect in southern (0.20 K) and central (0.37 K) China and East Asia (0.26 K) in summer. The predicted reductions in surface temperature over central, northern,

![Figure 9. Changes in vertical temperature over different regions in (a) MAM and (b) JJA. Units in kelvin.](image-url)

Table 3. Changes in Meteorological Fields by Dust Over Different Regions in MAM and JJA

<table>
<thead>
<tr>
<th>Changes in</th>
<th>SC</th>
<th>CC</th>
<th>NC</th>
<th>NEC</th>
<th>East Asia</th>
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<tbody>
<tr>
<td>Surface temperature (K)</td>
<td>0.18 (0.20*)</td>
<td>−0.26* (0.37**</td>
<td>−0.84** (−0.14</td>
<td>−0.71** (−0.23</td>
<td>0.01 (0.26**)</td>
</tr>
<tr>
<td>Vapor burden (g kg(^{-1}))</td>
<td>0.53* (4.62**)</td>
<td>0.07 (1.13*</td>
<td>0.24 (1.17**)</td>
<td>−0.49* (−0.11</td>
<td>0.58** (1.82**)</td>
</tr>
<tr>
<td>Cloud fraction (%)</td>
<td>−1.64** (1.55*)</td>
<td>−2.13* (−2.14**)</td>
<td>−0.67 (−1.43**)</td>
<td>−0.82 (−1.21*)</td>
<td>−0.75* (−0.57**)</td>
</tr>
<tr>
<td>Total precipitation (mm d(^{-1}))</td>
<td>−0.19** (1.12**)</td>
<td>−0.21 (−0.32)</td>
<td>−0.07 (0.02)</td>
<td>−0.28** (−0.03)</td>
<td>−0.03* (0.28**)</td>
</tr>
<tr>
<td>Convective precipitation (mm d(^{-1}))</td>
<td>0.04 (0.49**)</td>
<td>−0.05 (−0.15*)</td>
<td>−0.03* (−0.11*)</td>
<td>−0.06* (−0.17**)</td>
<td>0.01 (0.10**)</td>
</tr>
<tr>
<td>Large-scale precipitation (mm d(^{-1}))</td>
<td>−0.22** (0.63**)</td>
<td>−0.16 (−0.17)</td>
<td>−0.04 (0.13)</td>
<td>−0.22** (0.15)</td>
<td>−0.03* (0.17**)</td>
</tr>
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</table>

**The difference passing the 90% significance level in MAM and JJA (in parentheses).**
*The difference passing the 80% significance level in MAM and JJA (in parentheses).
and northeastern China in MAM in this study are comparable with the range of $0.30$ to $0.60$ K in Zhao et al. [2008] in spring and the annual mean of $0.80$ K over deserts in Sun et al. [2012].

3.3.3. Changes in Circulation and Moisture Transport

In order to understand how the changes in vertical temperature structure by dust can feedback to the general circulation over East Asia, the mass-weighted column temperature changes in MAM and JJA are shown in Figure 10. In the lower troposphere below 700 hPa, cooling exceed $0.50$ K can be seen over land north of 35°N, while the maximum warming of $0.50$–$0.70$ K is seen over the oceans in the south in spring (Figure 10a). The temperature anomaly in the middle and upper troposphere in Figure 10c is different from that in the lower troposphere. Areas with increased temperature in the upper atmosphere cover almost the entire research domain. In comparison with the results in MAM, the positive air temperature anomaly is greatly strengthened in JJA (Figures 10b and 10d), while the negative anomaly is weakened and limited to areas north of 45°N below 700 hPa in summer (Figure 10b). The stronger atmospheric warming by dust in summer could be attributed to many factors, such as the stronger diabatic heating induced by dust, the higher ratio of dust AAOD (Figure 5), and the weaker surface cooling due to thinner dust concentration in JJA. In addition, the dust aerosol could also produce heavier atmospheric vapor burden (Figures 11a and 11b) and reduce more clouds (Figures 12a and 12b) in summer. It means that the dust-induced changes in hydrological cycle could feed back into the modeled changes in air temperature [Yue et al., 2011]. First, as typical greenhouse gas, the changes in air moisture burden have a positive feedback on air temperature; thus, the heavier column vapor burden contributes to stronger dust-induced atmospheric warming in JJA. Second, the changes in clouds contribute to the air temperature responses regionally. The dust-induced more reductions in clouds in JJA could further enhance the air temperature in that season. Those semidirect effects by dust indicate the complexity of climate response to aerosol forcings.

Figure 10. (a and b) The mass-weighted atmospheric temperature change under 700 hPa (shaded area) and the geopotential height change at 700 hPa (contour lines). (c and d) The atmospheric temperature change above 700 hPa (shaded area) and airflow change (arrows) at 850 hPa. Figures 10a and 10c for MAM and Figures 10b and 10d for JJA. Only the differential winds filled over statistically significant at the 90% confidence level were shown in Figures 10c and 10d.
As a result of temperature changes with the presence of dust aerosol, the geopotential height could also be changed (Figures 10a and 10b). A wide belt with lowered geopotential height is found covering a large area of East Asia, with the largest geopotential height reduction of \(-5\) to \(-7\) gpm occurring over Japan in both seasons. Evidently, the dust-induced lower pressure leads to a cyclonic wind field at 850 hPa over the eastern coast of China and the middle-latitude Pacific Oceans (Figures 10c and 10d).

**Figure 11.** (a, b) Changes in column water vapor burden (unit in g kg\(^{-1}\)), (c, d) changes in moisture divergence (shading plots) (unit in \(10^{-5}\) g s\(^{-1}\) m\(^{-2}\)) and vapor flux below 500 hPa (streamline), and (e, f) changes in evaporation rate (mm d\(^{-1}\)) from experiment ALL\(-\)NDU. Figures 11a, 11c, and 11e for MAM and Figures 11b, 11d, and 11f for JJA. Dots in Figures 11a, 11b, 11e, and 11f indicate areas where the difference is statistically significant at the 90% confidence level according to t test.

As a result of temperature changes with the presence of dust aerosol, the geopotential height could also be changed (Figures 10a and 10b). A wide belt with lowered geopotential height is found covering a large area of East Asia, with the largest geopotential height reduction of \(-5\) to \(-7\) gpm occurring over Japan in both seasons. Evidently, the dust-induced lower pressure leads to a cyclonic wind field at 850 hPa over the eastern coast of China and the middle-latitude Pacific Oceans (Figures 10c and 10d).
The changes in atmospheric temperature and circulation structure could further affect surface moisture transport and vapor content (Figure 11). Two belts with increased water vapor appeared in summer (Figure 11b). One belt extended from the Indian subcontinent, passing the Taklamakan and the Tengger Deserts to northern China, while the other covered most of southern China and oceanic regions. An area with increased vapor can also be found in MAM over the ocean but with smaller magnitudes (Figure 11a). The larger vapor burden over oceans in summer was mainly contributed by the stronger sea surface evaporation (Figure 11f), the stronger vapor transport, and the larger moisture convergence (Figure 11d). The statistically significant evaporation over middle-latitude Pacific Ocean could also be transported inland to northern China by the anomalously cyclonic wind field, along with the stronger local evaporation, resulting in larger vapor burden over central and northern China in JJA. In contrast, the decreased evaporation both over land and oceans in MAM (Figure 11e), along with the weaker vapor flux over oceans (Figure 11c), led to smaller positive vapor burden anomaly over oceans and negative moisture anomaly over land in spring.

In a word, the increased water vapor in northern China in summer could be attributed to the stronger local evaporation and the inland vapor transport from the oceans by the cyclonic wind field anomaly in JJA, while the negative vapor anomaly in most of the Chinese continent in MAM could result from the weakened surface evaporation and the stronger northerly anomaly at the west edge of the cyclonic circulation anomaly that blocks the water transport from lower latitudinal oceans. On the other hand, over oceans, the positive vapor anomaly in JJA resulted from the enhanced sea surface evaporation and the moisture convergence induced by the cyclonic circulation anomaly.

3.3.4. Possible Mechanisms for Changes in Precipitation

The changes in atmospheric stabilization and column vapor burden could affect the cloud coverage and precipitation over East Asia. The changes in cloud fraction and precipitation in MAM and JJA are shown in
Figure 12. The dust generally induces a reduction in cloud coverage over land in both seasons over East Asia except for the Bay of Bengal, the Taklamakan Desert, and some part of southern China, where an increase trend is found. On the regional and annual mean basis, the cloud fraction was reduced by about −0.75% in MAM and −0.57% in JJA over East Asia (Table 3). In general, the mean changes in precipitation over land in MAM, as shown in Figure 12c, are in line with the changes in vapor burden (Figure 11a) and cloud fraction (Figure 12a). The regional mean precipitation was significantly reduced over southern (−0.19 mm d⁻¹) and northeastern (−0.28 mm d⁻¹) China and East Asia (−0.03 mm d⁻¹) in MAM (Table 3). In contrast, the precipitation was revealed as a pattern of “+−+” over the Chinese continent in JJA, with the largest reduction appeared over central China (−0.32 mm d⁻¹) and increases at both sides (Figure 12d). The pattern is generally consistent with the changes in cloud coverage and vapor burden. Specifically, the precipitation was increased by about 1.12 mm d⁻¹ over southern China, 0.02 mm d⁻¹ over northern China, and 0.28 mm d⁻¹ over East Asia in JJA (Table 3).

Therefore, in the horizontal directions, the reduction in precipitation over the Chinese continent in MAM resulted by the reduced column vapor burden, the anomalously strong northerly wind at the west edge of the cyclonic circulation, the weakened evaporation, and the increased stability in lower atmosphere over land. On the other hand, the increased precipitation over southern and northern China in JJA could be attributed to the increased vapor burden, which was contributed by the local evaporation enhancement and the inland vapor transport from the middle latitudinal Pacific Ocean.

The climatic effect of uplifted dust layer is supposed to change the atmospheric temperature and the vertical circulation [Lau et al., 2006, 2009]. The transported dust layer in western Africa away from its source regions was revealed to induce increased precipitation, which was identified as the elevated heat pump mechanism [Lau et al., 2006, 2009; Solmon et al., 2008]. Thus, it was assumed that the mechanism might also take effect in East Asia. Figures 13a and 13b show the vertical distributions of meridional averages of dust concentration, dust transport flux, and changes in air temperature in MAM and JJA. It can be seen that dust aerosols are mainly concentrated at around 40°N averaged between 100°E and 120°E. The dust concentration in MAM was twice that in JJA and decreased with the increase in altitude. The higher surface dust loading resulted from the strong natural and anthropogenic origins, as well as the input from western deserts. It is noticed that the major dust input center located at the height of 500 hPa in both seasons is consistent with Zhao et al. [2006] and also coincide with the atmospheric temperature anomalous centers.

As a result, the relatively heavier surface dust loading in MAM induces stronger surface cooling in the lower troposphere below 700 hPa. However, the atmospheric diabatic heatings (e.g., radiative heating and condensational heating) by the transported dust layer at about 500 hPa could warm the atmosphere above 700 hPa in spring (Figure 13a). Although the strength of the uplifted dust layer is relatively weak in JJA (Figure 13b), the atmospheric temperature anomaly is enhanced in summer by the stronger atmospheric diabatic heatings, because the radiative heating and the condensational heating by dust are strengthened at that season.

Due to the strong surface cooling effect in MAM, the convective activities were suppressed. The reduction in cloud (rain, snow, and ice) liquid water was revealed below 600 hPa over the Chinese continent (Figure 13c), leading to decreased precipitation over southern, central, northern, and northeastern China in MAM (Figure 13e). On the other hand, due to the strengthened positive atmospheric temperature anomaly by dust above 700 hPa and the dramatically diminished surface cooling and atmospheric stabilization in JJA (Figure 13b), the differential circulation shows an intensified upward airflow at 40°N at 500 hPa (Figure 13d). This circulation pattern induced by the atmospheric diabatic heatings with the presence of dust is similar to the EHP mechanism proposed by Lau et al. [2006, 2009] and Solmon et al. [2008]. As a result, the total cloud (rain, snow, and ice) water increases in north of 40°N. This increase in water mixing ratio is consistent with the increase in precipitation north of 40°N over the dust downwind areas in northern and northeastern China (Figure 13f). Furthermore, the climatic effects of dust also induce a southerly anomaly south of 25°N and a northerly anomaly on the other side below 700 hPa in summer (Figure 13d). Thus, the upward movement was driven by these circulation anomalies at about 25°N and resulted in increased precipitation over southern China and the South China Sea in JJA (Figures 13d and 13f). Consequently, the upward movements both by the EHP effect north of 40°N over the dust downstream areas and by the circulation anomalies at 25°N arouse a secondary circulation with the downward movement at about 35°N. This downward airflow could further induce reductions in liquid water (Figure 13d) and precipitation (Figure 13f) over central China in JJA.
Overall, in the vertical directions, the effect of dust on precipitation exerts different mechanisms in different seasons over Chinese continent. As a result of the strong surface cooling effect, the strengthened atmospheric stabilization leads to decreased precipitation over most of China in spring. However, as a result of the weakened surface cooling in JJA, the EHP effect by dust poses an upward movement and increased precipitation north of 40°N over the dust downwind areas, while the atmospheric convergence at 25°N induces

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**Figure 13.** (a and b) The altitude-latitude distributions of the dust concentrations (blue dashed line), the dust transport flux in west-east direction (red solid line), and the temperature changes by dust (shading area). (c and d) The changes in meridional circulation and cloud (rain, snow, and ice) water mixing ratio. (e and f) The changes in precipitation. All these results averaged over the longitudinal bands from 100°E to 120°E. Figures 13a, 13c, and 13e for MAM and Figures 13b, 13d, and 13f for JJA.
enhanced precipitation over southern China. Both upward movements either in the north or in the south arouse secondary circulation and downward movement and reduced precipitation in central China. Thus, the +−+ pattern for precipitation by dust in summer was found.

3.4. Impacts on East Asian Summer Monsoon

The East Asian summer monsoon (EASM) system plays a critical role in determining the summer climate in East Asia. The horizontal changes in airflow at 850 hPa and precipitation in JJA are shown in Figures 10d and 12d, respectively. The climatologically horizontal circulations are defined as the pattern of the southerly monsoonal winds dominating East Asia. From experiment ALL − C0 NDU, it was seen that the EASM has been weakened notably by dust aerosols (Figure 10d). Hence, the cyclonic circulation anomaly at 850 hPa over Japan and surrounding oceans, which was induced by the vertical temperature anomalies by dust, could reduce the intensity of the EASM.

The enhanced northerly anomaly during monsoon seasons over Chinese continent led to reduced northward moisture transport (Figure 11d). Thus, the moisture was blocked in the south, resulting in enhanced vapor burden (Figure 11b) and strengthened convective activities over southern China in summer. As a result, the monsoonal precipitation was increased over southern China and decreased over central China in JJA (Figure 12d). Since the thermodynamic contrast between Asian continent and Pacific Oceans is considered as the main driving factor in building the EASM [Webster, 1987], it is necessary to investigate the changes in surface temperature between land and sea by dust.

As shown in Figure 14, the surface cooling effect by dust over Asian continent and the warming effect over oceanic surface resulted in a cooling tendency over land and a warming tendency over oceans. The different changes in ground temperature by dust modified the climatological temperature pattern over land and oceans, leading to weakened land-sea temperature contrast and EASM.

3.5. Impacts on Sea Surface Temperature

The East Asian dust aerosol could be transported from the land to the Pacific Ocean and modified the energy balance over oceanic surface, resulting in changes in oceanic surface wind and temperature. Yue et al. [2011] and Nabat et al. [2015] reported significant responses of SST to dust forcing at global and regional scales, respectively. Since the changes in SST have great impacts on East Asian climate factors, such as the WSPH, thus, detailed analysis is needed to investigate the dust impacts on SST over East Asia.

The climatological SST over the northwestern Pacific Ocean is warmer over lower latitudinal oceans in summer and relatively colder at higher latitudes in spring and winter. The warmer oceanic surface water could be transported by surface wind from tropical to subtropical oceans along the coastline of the Chinese mainland, especially in summer (figure not shown), and add other complexities in the final SST features.

The simulated regional mean changes in the SST, the oceanic surface energy fluxes, including latent heat (LH), sensible heat (SH), LW, SW, and NET flux, as well as the changes in surface wind stress and cloud water below 500 hPa are shown in Figure 15, averaged over the oceanic area of (15°N–35°N, 120°E–166°E). In general, the dust aerosol resulted in increased SST throughout a year, especially in summer. The local NET energy flux was mainly contributed by LH and SH in MAM, while the SW forcings became the controlling factor over wet seasons. The positive SW anomaly could be attributed to the reduction in convective...
clouds over oceans, which allows more solar radiation to reach the oceanic surface. It should also be noted that the NET local flux reached its maximum values in May and decreased in the following months. Thus, the positive SST anomaly, especially during summer and early autumn, was contributed not only by the NET local surface heat flux balance but also by the input energy from the surrounding oceans. The input energy was induced by the strengthened northward oceanic surface wind stress anomaly. Overall, the correlation coefficients between SST and SW (0.88), LW (−0.62), LH (−0.58), and northward wind stress anomaly (0.66) passed the 95% significance level.

In general, during most months of the year, the increased NET local energy fluxes by dust resulted in a higher SST anomaly over the middle latitudinal Pacific Ocean. On the other hand, because of the enhanced northward surface wind stress anomaly in wet seasons by dust, the input energy from the surrounding oceans could also contribute to the final SST anomaly.

4. Summary and Conclusions

The East Asian region is subject to high dust loading especially during spring and early summer. A state-of-the-art regional coupled atmosphere-ocean-land model RIEMS-POM with dust distributions, offline produced by GOCART, has been used to investigate the distribution of Asian dust aerosols, as well as its climatic effects on precipitation, summer monsoon, and SST in different seasons over East Asia.
First, three major dust sources, including the Taklamakan, Tengger, and Gurbantunggut Deserts were revealed by GOCART. The ratio of AAOD to AOD is higher in JJA (11.08%) and lower in MAM (10.73%). Regionally, the dust aerosol tends to induce the strongest negative DRF in April near the surface and the strongest positive DRF from April to July at the TOA. On the regional and annual mean basis, the clear-sky DRFs by dust were about $-6.65 \text{ W m}^{-2}$ at the surface and $3.79 \text{ W m}^{-2}$ at the TOA, while the presence of clouds (all sky) could weaken the surface dust forcing ($-1.78 \text{ W m}^{-2}$) and enhance it at the TOA (8.65 $\text{ W m}^{-2}$).

As a result of the reduced irradiance and the changes in cloud cover, the atmospheric temperature was decreased north of 35°N over land below 700 hPa and increased over other areas and altitudes in MAM by diabatic heating of dust. This cooling effect is greatly weakened in JJA. The vertical temperature anomalies help to stabilize the lower troposphere and suppress the formations of convective cloud and precipitation, especially in spring. The changes in vertical air temperature also form a cyclonic wind field anomaly over Japan and the surrounding oceans. These changes by dust, as well as the changes in surface evaporation and the inland vapor transport, result in a decreased vapor burden over Chinese continent in spring and the enhanced vapor burden over southern and northern China in summer.

On the regional and seasonal mean basis, the precipitation is reduced by about 0.03 mm day$^{-1}$ in spring and increased by 0.28 mm day$^{-1}$ in summer in East Asia. The surface cooling effect by dust dominates the Chinese continent in spring, resulting in intensified stabilization and weakened vapor and precipitation. However, the upward movements by the elevated heat pump (EHP) effect north of 40°N over the dust downwind areas in northern China and by the atmospheric convergence over southern China, along with the weakened lapse rate and the enhanced evaporation and vapor over the Chinese continent, resulted in increased precipitation in these regions in summer. Both upward movements in southern China and areas north of 40°N arouse a subsidence in central China and were responsible for the decreased vapor burden, clouds, and precipitation there in JJA.

In addition, the importance of dust on East Asian summer monsoon is also discussed. The dust aerosol tends to warm the SST and cool the continent and leads to a reduction in LSTC. Thus, the East Asian summer monsoon is weakened. The strengthened northerly wind anomaly at 850 hPa over Chinese mainland could weaken the northward moisture transport and block the vapor to the south and therefore enhance the precipitation in southern China and suppress it in central China.

The dust aerosol could also perturb the SST by the local net heat flux rebalance and by the northward oceanic heat transport. Overall, the changes in local SST are statistically correlated with the changes in SW, LW, LH, and northward oceanic surface wind stress. The effect of the local NET surface heat fluxes is important on the local SST anomaly throughout the year; however, the enhanced northward surface wind stress anomaly by dust contributes even larger on SST anomaly during wet seasons.

Since the RIEMS is new, it would be interesting to compare the new model with other latest RCMs, such as regional climate model version 4 [Sun et al., 2012]. Precipitation changes by dust aerosols, through either direct, semidirect, or indirect effects, could lead to precipitation increase or decrease, depending on the altitude of the dust layer and its interactions with clouds [Yin et al., 2002; Yin and Chen, 2007]. Most of previous studies focused on the indirect effect of dust through cloud microphysics; however, results from this study help to separate the dust dynamic effect on precipitation from the cloud microphysical effects.

It should be noticed that the offline produced dust distributions were taken into the RCM to study the climatic impacts of dust. The biases in simulated circulation and precipitation could affect the model results from this study, because the dust impact is dependent on the simulated meteorological fields. Although the approaches used in this study were also reported in other studies [Ramanathan et al., 2005; Lau et al., 2006, 2009; Yue et al., 2010b; Nabat et al., 2015] and were assumed to be adequate, more accurate enough studies with interactive dust emission scheme and aerosol chemical processes should be taken into account in the future.

Specifically, many previous studies have discussed the dust-induced changes in meteorology and its feedback to the modeled aerosol distributions [Perlwitz et al., 2001; Yue et al., 2010a; Han et al., 2013]. In comparison with the prescribed dust simulations, the offline simulation leads to 2%–15% lower dust production and about 13% higher dust burden on the global scale [Perlwitz et al., 2001; Yue et al., 2010a]. Although these changes in dust concentrations could enhance surface cooling [Han et al., 2013], the dust-induced increases in air temperature at higher levels (above 850 hPa) have been found by both observations [Alpert et al., 1998; Satheesh et al., 2007] and simulations [Weaver et al., 2002; Kim et al., 2006; Yue et al., 2010a]. The impacts of
surface cooling and atmospheric warming on precipitation by dust in this study are similar with those found in northern India [Ramanathan et al., 2005; Lau et al., 2006] and western Africa [Solmon et al., 2008; Lau et al., 2009]. Thus, although the prescribed dust distributions could produce biases to the final values of dust impacts on climate, the mechanism of dust impacts on the large-scale temperature and circulation structures and its further impacts on precipitation, summer monsoon, and SST over East Asia are more important and meaningful from this study.

Similar to previous studies [e.g., Yue et al., 2011; Nabat et al., 2015], our model results also suggest that using the climatological SST in RCMs without the interactive ocean may not be an adequate approach to study the climatic effects of aerosols, because the changes in SST by aerosol cannot be neglected, especially over the middle latitudinal oceans. In addition, the aerosols were considered mixed externally in this study; thus, in comparison with previous studies, results from this study could be regarded as an approximation for dust under more realistic atmospheric conditions.

Acknowledgments

This study was jointly supported by the National Science Foundation of China (grant 91373101), the Special Fund for Doctorate programs in Chinese Universities (201122810002), the Priority Academic Program of Development of Jiangsu Higher Education Institutions (PAPD), and the Priority Academic Program of Jiangsu Higher Education Institutions (PAPD). We also thank the Goddard Earth Sciences Data and Information Services Center for providing us the aerosol data set from GOCART model (http://disc.sci.gsfc.nasa.gov/giovanni). Daily reanalysis surface temperature, wind field, and geopotential height data are available at the European Center for Medium-Range Weather Forecasts (ECMWF) (http://www.ecmwf.int). The precipitation observation is available at Climate Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/data).

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