Potential of Mineral Dust in Changing the Sea Surface Temperature and Precipitation over East Asia

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Abstract

The distributions and radiative effects of mineral dust during winter half year over East Asia have been investigated in this study. The mineral dust is mainly located around 40°N, however, the aerosol optical depth (AOD) of dust can exceed over 0.6 over the Taklimakan desert both in MODIS observations and model simulations. The direct radiative forcings (DRFs) of dust are about -9.23 W m⁻² at the surface and 0.39 W m⁻² at the top of atmosphere (TOA) in winter half year. With the presence of an interactive ocean model, the dust will decrease surface air temperature over East Asia (-0.25 K) except for oceanic regions. The increase in atmospheric temperature (0.015 K) will weaken the total heat flux and affect air specific humidity, which will finally decrease the precipitation over East Asia (-0.06 mm day⁻¹). Sea surface temperature (SST) responses are very important when evaluating the climatic effects of dust over East Asia. If we fix the SST in regional model, the weakening trend of precipitation can reach up to -0.08 mm day⁻¹.

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Keywords: mineral dust; aerosol optical depth; radiative forcing; sea surface temperature; East Asia
1. Introduction

Aerosol is considered as an important atmospheric component in balancing the energy exchange in the Earth-atmosphere system through different mechanisms. In addition to different optical and microphysical properties, the direct and indirect effects of aerosol have a pronounced potential to change temperature and precipitation over East Asia \cite{1}.

Mineral dust is such an important aerosol species in East Asia due to scattering and absorbing of shortwave and longwave radiation. Wu et al. \cite{2} suggested that dust aerosol reveals negative direct radiative forcing (DRF) both at top of atmosphere (TOA) and the surface leading to reduction tendency of surface air temperature (T_{sa}) except for some high albedo regions. The change of rainfall caused by dust helps to offset the trend of increased wetness in southern China and increased dryness in northern China in recent years. Their results are supported by many other works \cite{3-5}. A so-called “elevated heat pump” (EHP) mechanism exists in both Southern Asia \cite{6} and West Africa \cite{7}, which indicates that the lifted absorbing dust layer can heat the middle/upper troposphere and strengthen monsoon circulation in India/West Africa monsoon regions \cite{8}.

When mineral dust transport to nearby oceans, they may also affect the sea surface energy exchange. Some studies indicated that aerosols can affect the oceanic heat content \cite{9}, in addition, the influence may even be expanded to the entire oceanic mixed layer \cite{10-11}. With a fully coupled atmosphere-ocean general circulation model (AOGCM), Yue et al. \cite{12} reported that, on a global basis, the dust DRF can influence T_{sa} and the heat fluxes, which will further change atmospheric temperature and precipitation, furthermore, the change of precipitation will in turn alter the dust burden. However, in-depth investigations with higher model resolutions on the regional scale (e.g. East Asia) are still needed as huge land-sea contrast and the relatively vast Taklimakan desert over East Asia.

The latest developed regional climate model with both atmospheric and oceanic components were used to consider the direct radiative forcing of mineral dust over East Asia, furthermore, the dust induced oceanic responses will also be discussed here. We tried to give the evidence of oceanic responses to mineral dust DRF, the results were useful to evaluate dust related climate change over East Asia.

2. Methods

2.1. Data

The Daily aerosol optical depth (AOD) at 0.55 μm of mineral dust during 2000-2007 were chosen from the Goddard Earth Sciences Data and Information Service Center (http://disc.sci.gsfc.nasa.gov/giovanni), which was simulated by the NASA Goddard Global Ozone, Chemistry, Aerosol, Radiation and Transport (GOCART) model. The 1°×1° MODIS Collection 51 (C51) Level 3 (L3) AOD data at 0.55 μm from TERRA satellite at the same period was also used to evaluate the results from GOCART.

2.2. Method

The regional climate model with both atmospheric and oceanic components was developed by the Key Laboratory of Regional Climate-Environment for Temperate East Asia (RCE-TEA). The atmospheric model that based on the fifth generation Pennsylvania State University–NCAR Mesoscale Model \cite{13} is named as RIEMS (the Regional Integrated Environment Model System). The oceanic component is the Princeton Ocean Model (POM). Previous studies \cite{14} pointed out that RIEMS-POM has a good performance in the Regional Climate Model Intercomparison Project (RCMIP).

In this study, daily distribution of mineral dust from GOCART was introduced into RIEMS-POM. The experiments setting is listed in table 1. Two sets of experiments were carried out. The first group uses the undivided regional model RIEMS-POM, including the control experiment (CTL) with none aerosol composition and the sensitivity experiment with the daily 3-D dust distributions from GOCART. The dust induced climatic change can be obtained from the difference between SEN and CTL based on the interactive ocean condition. The other group of experiments with fixed sea surface temperature (SST) is same as that in the first group, however, only the atmospheric model is applied to investigate the dust radiative effects. The discrepancy between the SEN minus CTL
and SENR minus CTLR will represent the oceanic responses to dust aerosol DRF over East Asia. The simulations cover most part of East Asia, with a horizontal resolution of 60 km and horizontal 148 and 80 points in the longitudinal and latitudinal directions respectively. Multiple years were carried out, however, only the average of winter half year (December to May) were considered in the following study. The first year in both sets of experiments is treated as regional model spin-up time. At the same time, the ocean model is beforehand spun up for another 30 years before the regional atmospheric model is started because of the relatively slower heat exchange process in the oceans.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Model descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>Without the dust aerosol</td>
</tr>
<tr>
<td>SEN</td>
<td>Same as CTL, with the dust concentration from GOCART</td>
</tr>
<tr>
<td>CTLR</td>
<td>Same as CTL, only using the atmosphere model RIEMS</td>
</tr>
<tr>
<td>SENR</td>
<td>Same as SEN, only using the atmosphere model RIEMS</td>
</tr>
</tbody>
</table>

### 3. Results Analysis

#### 3.1. Spatial Distributions of AOD from MODIS and simulations

Fig. 1 plots the spatial distributions of AOD from MODIS (Fig. 1a) and GOCART simulations (Fig. 1b) during winter half year from 2000 to 2007. It is shown clearly that there are three high aerosol burden regions in MODIS observations, which are the northwestern China (NWC), the entire northern (NC) and southern (SC) China, and the northeastern Indian subcontinent. However, the AOD in southwestern China (SWC) is very low. The AOD in Taklimakan desert in NWC and the Sichuan basin can exceed to 0.6 and 0.8, respectively. This characteristic of AOD distribution was attributing to the strong dust strom in winter half year and the development of cities in China. Over the climatological dust transport path around 40°N, the regional mean AODs of observation and simulation are listed in table 2 for domain A, B, and C, which indicates that the model can represent the mineral dust loading over East Asia both in magnitudes and spatial distributions. The dust is mainly located in inland desert, with the efforts of westerlies, it can reach remote Chinese coastal area and nearby ocean.

<table>
<thead>
<tr>
<th>AOD</th>
<th>Domain A</th>
<th>Domain B</th>
<th>Domain C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>0.42</td>
<td>0.24</td>
<td>0.23</td>
</tr>
<tr>
<td>GOCART</td>
<td>0.32</td>
<td>0.25</td>
<td>0.31</td>
</tr>
</tbody>
</table>

* A Stands for [35°N- 45°N, 75°E- 90°E], B Stands for [35°N- 45°N, 90°E- 100°E], and C Stands for [35°N- 45°N, 100°E- 110°E]. The above three domains are also listed in Fig. 1 (a).

#### 3.2. Radiative Effects of Mineral Dust

Dust is special as its ability of both scattering and absorption. Because of the dust source in Taklimakan Desert, the radiative effect of dust should be carefully taken into account. It is remarkable that DRF at surface induced by dust (Fig. 2a) is generally negative with a cooling centre -50 W m⁻² over the Taklimakan Desert. At the TOA (Fig. 2b), dust induced DRF is positive about 15 W m⁻² over the desert and negative about -3 W m⁻² over wide downwind regions including the northwestern Pacific Ocean. The regional mean DRFs of dust are -9.23 W m⁻² at the surface and 0.39 W m⁻² at the TOA based on the clear-sky condition over East Asia (Table 3). However, the value of DRF will be smaller at the surface and bigger at the TOA because of considering the effects of cloud based on the all-sky condition (Table 3). Our results are consistent with the previous work [4]. The net TOA DRF is positive over the desert, which can be explained as longwave and shortwave absorption by large particles and shortwave absorption
over high-albedo surface. The net TOA negative DRF over oceans may result from lower albedo over the ocean surface [15].

Table 3. The simulated DRF of dust in different regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Clear-sky DRF (W m(^{-2}))</th>
<th>All-sky DRF (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWC*</td>
<td>-26.22</td>
<td>-25.47</td>
</tr>
<tr>
<td>NC*</td>
<td>-22.77</td>
<td>-20.57</td>
</tr>
<tr>
<td>SWC*</td>
<td>-4.95</td>
<td>-4.29</td>
</tr>
<tr>
<td>SC*</td>
<td>-9.39</td>
<td>-7.50</td>
</tr>
<tr>
<td>EA*</td>
<td>-9.23</td>
<td>-8.01</td>
</tr>
</tbody>
</table>

* NWC, NC, SWC, and SC are listed in Fig. 1 (b), however, EA (East Asia) is the entire study domain in Fig. 1 (b).

3.3. Climatic responses to dust radiative forcing

Fig. 3 shows \(T_{sa}\) for the experiments SENR-CTLR (Fig. 3a) and SEN-CTL (Fig. 3b), respectively. The two experiments show the similar spatial distributions with cooling trend of -3 K - -0.05 K over almost the entire Chinese mainland except the Tibet Plateau [6]. However, a warming trend of 0-0.3 K can be found south of 35°N over the oceanic regions. The strongest cooling center exceeding -2 K located in the Taklimakan desert can be explained as the strong absorbing and scattering effects at the dust aerosol sources and its downstream areas. In addition, the weak warming trend over the Pacific Oceans can be attributed to the surface energy readjustment and the change in cloud and precipitation. The regional mean changes in \(T_{sa}\) during the winter half year, are about -0.32 K and -0.25 K for SENR-CTLR and SEN-CTL, respectively. The pattern of \(T_{sa}\) induced by dust is consistent with previous works [2, 5, 15]. The most important difference between the two sets of experiments can be found over the oceans, in which a warmer oceanic surface due to the changeable SST exists in the experiment SEN-CTL. However, because of a fixed oceanic boundary in the experiment SENR-CTLR, the SST will not be allowed to respond to dust forcing, in this way, the \(T_{sa}\) will be relatively smaller.

Figure 3 shows the vertical air temperature change in the experiments SENR-CTLR (Fig. 3c) and SEN-CTL (Fig. 3d), respectively. Both experiments have similar temperature distributions, with the regional mean changes of 0.006 K and 0.015 K for the experiments SENR-CTLR and SEN-CTL, respectively. In the experiment SENR-CTLR, a cooling center of -0.3 K locates at lower troposphere between 30~50°N. There are two warming centers, one addresses upper than 800 hPa north of 30°N and the other locates near the terrestrial surface between 15°N-30°N. The warming center will be even stronger in the experiment SEN-CTL. The thermal structure of the upper-warmer and lower-colder in the troposphere results from the radiative heating effect of dust (not shown), which is consistent with some previous research [15]. As known that, the scattering effect of dust can make up 88 % of total extinction, while absorption may account for the other 12 % [16]. Thus, scattering effects may be more important at lower troposphere especially over high albedo desert, while absorption will control the middle and higher troposphere.

The total surface heat flux response to dust forcing is shown in Fig. 4. The reduction in heat flux is relatively greater over the Pacific Oceans in the experiments SENR-CTLR (Fig. 4a) than SEN-CTL (Fig. 4b). The heat flux consisting of sensible heat flux and latent heat flux is determined by SST, \(T_{sa}\), wind speed (not shown), and surface air specific humidity. In the experiment SENR-CTLR, the increased \(T_{sa}\) but fixed SST leads to reduction in vertical heat flux, however, with the presence of a changeable ocean model, because of the increases in both SST and \(T_{sa}\), smaller temperature gradient (top to down) in vertical direction can be found over the oceans, thus, the weakening trend of heat flux will relatively weaker.

The warming and cooling trend at different layers induced by dust will affect air specific humidity (Fig. 3e, f), vertical convection (not shown) and atmospheric stability, which will finally influence cloud (not showed) and precipitation (Fig. 5a, b). In the experiment SENR-CTLR, air specific humidity (Fig. 3e) will increase in ascending movement areas (25°N and 32°N) and reduce in descending regions (32°N and 55°N). However, in the experiment SEN-CTL, a warmer SST will result in higher specific humidity over regions north to 32°N (Fig. 3f). The change in
circulation will produce decreased rainfall over Chinese mainland and increased precipitation over oceans north to 25°N (Fig. 5a). The regional mean precipitation is -0.08 mm day⁻¹ based on the fixed SST condition in winter half year, which is highly consistent with Wu et al. [2] (-0.04 mm day⁻¹). However, in the experiment SEN-CTL, the change in rainfall will relatively smaller (-0.06 mm day⁻¹) because of relatively better humidity condition and higher air temperature in the atmosphere with the presence of an interactive ocean model.

4. Conclusions

The distributions of mineral dust aerosol from GOCART model have been evaluated by MODIS observations and been further introduced into a latest developed regional climate model. The results showed that:

Firstly, the mineral dust is mainly located in its source and the climatological transport path around 40°N, of which, the AOD of dust can exceed over 0.6 over the Taklimakan desert in winter half year. Secondly, the regional mean DRFs in winter half year of dust are about -9.23 W m⁻² at the surface and 0.39 W m⁻² at the TOA, however, the values will be weakened at the surface (-8.01 W m⁻²) and strengthened at the TOA (1.57 W m⁻²) due to the performance of cloud forcing. With the presence of an interactive ocean model, the dust will decrease surface air temperature over East Asia (-0.25 K) during the winter half year except for increased trend over the Pacific Oceans. The increase in atmospheric temperature (0.015 K) will weaken the total heat flux and affect air specific humidity, vertical convection and atmospheric stability, which will finally decrease the precipitation over East Asia (-0.06 mm day⁻¹). Ocean has great influence on East Asian climate during winter half year when evaluating dust radiative effects and the related climatic readjustments. If we fix the SST in the regional model, the weakening trend of precipitation is even stronger (-0.08 mm day⁻¹).

![Fig. 1. The spatial distributions of observed AOD at 0.55 μm from MODIS (a) and the simulated mineral dust optical depth from GOCART (b) in winter half year over East Asia. The domain A, B, and C in (a) represent the different ranges of dust over its transport path. In figure (b), the NWC is the northwestern China, the NC is the northern China, the SW is the southwestern China, and the SC is the southern China, respectively.](image-url)
Fig. 2. The spatial distributions of clear-sky DRF of mineral dust at the terrestrial surface (a) and the TOA (b) in winter half year over East Asia (unit: W m⁻²). Downward is positive.

Fig. 3. The change in surface air temperature (a, b, unit: K, Tsa) and the longitudinal cross section of the average change in temperature (c, d, unit: K) and specific humidity (e, f, unit: g kg⁻¹) over 100°-150°E in winter half year by dust. The left column is the experiment SENR-CTLR, however, the right is the SEN-CTL.

Fig. 4. The change in surface total heat flux (unit: W m⁻²) from the experiments SENR-CTLR (a) and SEN-CTL (b), respectively. Upward is positive.
Fig. 5. The change in total precipitation (unit: mm day\(^{-1}\)) from the experiments SENR-CTL (a) and SEN-CTL (b), respectively.

**Acknowledgements**

This study was jointly supported by the National Science Foundation of China (Grant No. 91337101), the Priority Academic Program of Development of Jiangsu Higher Education Institutions (PAPD), and the Program for Postgraduate Research and Innovation in the Universities of Jiangsu Province, China (Grant No. CXLX12_0498).

**References**


