Dusty cloud radiative forcing derived from satellite data for middle latitude regions of East Asia*

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Abstract The dusty cloud radiative forcing over the middle latitude regions of East Asia was estimated by using the 2-year (July 2002—June 2004) data of collocated clouds and the Earth's radiant energy system (CERES) scanner and moderate resolution imaging spectroradiometer (MODIS) from Aqua Edition 1B SSF (single scanner footprint). The dusty cloud is defined as the cloud in dust storm environment or dust contaminated clouds. For clouds growing in the presence of dust, the instantaneous short-wave (SW) forcing at the top of the atmosphere (TOA) is about −275.7 W/m^2 for cloud over dust (COD) region. The clouds developing in no-dust cloud (CLD) regions yield the most negative short-wave (SW) forcing (−311.0 W/m^2), which is about 12.8% stronger than those in COD regions. For long-wave (LW) radiative forcing, the no-dust cloud (CLD) is around 102.8 W/m^2, which is 20% less than the LW forcing from COD regions. The instantaneous TOA net radiative forcing for the CLD region is about −208.2 W/m^2, which is 42.1% larger than the values of COD regions. The existence of dust aerosols under clouds significantly reduces the cooling effect of clouds.

Keywords: dust storm, cloud radiative forcing, global warming, dust aerosol-cloud-climate interaction.

Radiative forcing by aerosol and cloud is recognized as an important contributor to climate change[1]. Aerosol influences radiative forcing directly by scattering/absorption of solar radiation (direct effect), and indirectly by altering the cloud droplet size distribution and concentration (indirect effect). Depending on the chemical composition, aerosols exert a cooling or warming influence on climate. Ramanathan et al.[2] suggested that a combination of the aerosol direct and indirect effects can weaken the hydrological cycle, which could be a major environmental issue in this century. Absorbing aerosols, such as black carbon and mineral dust, could contribute to high diabatic heating in the atmosphere that often enhances cloud evaporation (semi-indirect effect)[3—5]. Li and Trishchenko[6] found that there are a larger reduction of the solar radiation budget at the surface than that at the top of the atmosphere due to absorbing aerosols. The absorbing aerosols may need to be included in emissions controls because of their potentially large warming effect on climate[7]. The magnitude of the global mean radiative forcing of dust aerosols is comparable to that of anthropogenic aerosols from sulphate and biomass combustion[8,9]. There are considerable uncertainties in estimating the radiative effects of dust aerosols. The net radiative forcing at the top-of-atmosphere (TOA) could be either positive or negative, depending on several key variables such as surface albedo, particle size, vertical distribution of the dust layer, dust optical depth, and the imaginary part of the refractive index[10,11].

On the other hand, clouds are an important regulator of the Earth's radiation budget. About 60% of the Earth's surface is covered with clouds. Clouds cool the Earth-atmosphere system on a global average basis at the top-of-atmosphere. Losses of 48 W/m^2 in the solar spectrum are only partially compensated (30 W/m^2) by trapped infrared radiation. Measurements of the Earth radiation budget experiment (ERBE)[12] indicate that small changes to microphysical (coverage, structure, altitude) and microphysical properties (droplet size, phase) have significant effects on climate. For instance, a 5% increase of the shortwave cloud forcing would compensate the increase in greenhouse gases within the years 1750—2000[13].

Asia dust storms may have serious impacts on the global climate system. These storms originate in the Taklamakan Desert of China and the Gobi Desert of Mongolia and occur most frequently in late winter and

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early spring. The dust aerosol layers of these storms are capable of traveling thousands of kilometers at high altitude and flowing out from the continent over the open sea near Korea and Japan[14—16]. Asian dust may also have a significant effect on the atmospheric radiation budget because of the large emission amount. The annual mean dust emission from China is estimated to be around 800 teragrams (Tg)[17]. However, there have been few studies focusing on the effect of Asian dust aerosols on cloud properties and radiative forcing. The radiative forcing of dust aerosol was evaluated using AVHRR and ground observations made during the HEIFE experiment[18]. In Beijing, solar radiative heating of the atmosphere is larger on dust storm days than on no-dust days by 80%—318%[19]. Zhao et al.[20] monitored aerosols in Beijing with a seven-band sun photometer, from which the aerosol size distribution was retrieved. The radii of dust particles were found to be generally larger than 2.1 μm, while the radii of pollutant aerosols were generally less than 2.1 μm[21]. However, these values are very crude estimates from broadband solar direct and sky diffuse radiance measurements using shadowband radiometers for the simultaneous retrieval of aerosol optical thickness, size distribution, refractive index, and surface albedo[22—24]. Using routine ground-based solar radiation measurements made across China since the 1960s, Luo et al.[25] obtained the long-term trend and spatial variations of aerosol optical depth in China. Zhang et al.[26,27] found that elemental concentrations (Ca, Fe, K, Mn, and Ti) were mainly associated with Asian dust aerosols containing a certain fraction of K from biomass burning in mainland China characterized with a ratio of 1.3 for organic carbon (OC)/K.

Recently, Huang et al.[28] studied the effect of Asia dust aerosols on cloud properties for selected ten cases. They found that the ice cloud effective particle diameter, optical depth and ice water path of cirrus clouds under dust polluted conditions are 11%, 32.8% and 42%, respectively, lower than those derived from ice clouds in no-dust atmospheric environments. However, the results mentioned above represent only a few cases and more observation data need to be examined to develop robust statistics. A goal of this paper is to document the effects of dust aerosols on radiation budgets over the middle latitude regions of East Asia. This goal will be achieved through the use of a quantity known as the TOA cloud radiative forcing, which represents the radiative effects of clouds at the top of the atmosphere. The TOA cloud radiative forcing is based on the CERES observed upward radiative fluxes under clear and cloudy conditions. This analysis should lead to a better understanding of the interaction between dust aerosols, clouds and radiation.

1 Data and methodology

In this study, we use the 2- year CERES SSF MODIS Edition 1B data on board Aqua covering the period from July 2002 to June 2004. The most recent single scanner footprint (SSF) dataset combines radiation budget data from CERES with cloud property retrievals from an imager on the same platform to provide a vastly improved characterization of the instantaneous state of the atmosphere[29]. The SSF dataset describes instantaneous measurements including surface information, radiances, radiative fluxes at the surface and the top of the atmosphere (TOA) and a variety of parameters describing the clear and cloudy portions of the footprint[30—32]. In addition, the SSF incorporates new CERES angular distribution models (ADMs)[33] based on improved scene identification[29]. The visible-infrared-solar-infrared-split-window technique (VISST) was used to derive daytime cloud properties from Aqua and Terra MODIS data taken between April 2001 and June 2004. VISST is a 4-channel update of the retrieval algorithm of Minnis et al.[30,31]. The retrieved cloud properties include cloud effective droplet radius (r_e) or ice crystal diameter (D_e), optical depth (τ), effective cloud top temperature (T_e), and water path (W_P). Cloud W_P retrievals are calculated from the cloud optical depth and effective particle size estimated from the VISST. The CERES instruments measure broadband radiances at the TOA in three spectral regions (0.2—5.0 μm; 8—14 μm; 5—100 μm) at a spatial resolution of about 20 km at nadir. The short-wave (SW) and long-wave (LW) upwards TOA fluxes are used to examine the cloud radiative forcing. Cloud radiative forcing is defined as the difference of the net radiative fluxes between cloudy and clear sky at the top of the atmosphere[34].

$$\begin{aligned} C_{sw} &= F_{clr}^{sw} - F^{sw} \\ C_{lw} &= F_{clr}^{lw} - F^{lw}, \\ C_{net} &= C_{sw} + C_{lw} \end{aligned} \quad (1)$$

where F_{clr}^{sw} and F_{clr}^{lw} are the CERES clear sky broadband short-wave and long-wave fluxes at the TOA, respectively; F^{sw} and F^{lw} are the short-wave and long-wave fluxes at the TOA in the presence of dusty or no-dust cloud.

2 Results analysis

To detect cloud modification induced by dust aerosols, two regions are selected to represent the clouds in different environments. CLD (no-dust cloud) represents an area where overcast clouds occurred in a no-dust atmosphere, while COD (cloud-over-dust) denotes overcast clouds in dusty conditions in the area of 30°N—40°N and 80°E—110°E. The CLD and COD regions are selected based on 701 surface meteorology station observations over China and Mongolia. The surface station observes the dust at three-hour intervals and provides four categories of information, i.e. dust storm, wind-blown sand, floating dust, and no-dust. If the surface observation record shows that there is not any dust storm, wind-blown sand, floating dust, in all staitions over the region of 30°N—40°N and 80°E—110°E, the cloud in such region is defined as CLD. If the surface observation records dust storm, or wind-blown sand, or floating dust, and the satellite detects the cloud in the same region, this region is defined as cloud-over-dust (COD) region. Totally 33 cases are selected during the 2-year period. Those cases mainly occurred in the spring (March, April, May). There are only a few dust storms, less than 6%, occurring over late summer and autumn.

Histograms of the TOA cloud radiative forcing for CLD and COD are compared in Fig. 1. This figure indicates the effect of dust aerosols on TOA cloud radiative forcing. For example, smaller (less than -350 W/m^2) values of SW forcing occur more frequently for COD regions compared to that for CLD regions, while smaller values (less than -350 W/m^2) of LW forcing occur more frequently for CLD regions. The regional, frequency-bin weight averaged forcing derived for the CLD and COD regions is listed in Table 1. For clouds growing in the presence of dust, the instantaneous TOA SW forcing values are about -275.7 W/m^2 for COD region. The clouds developing in CLD regions yield the most negative SW forcing (-311.0 W/m^2), which is about 12.8% stronger than those in COD regions. The standard deviations are 0.37 W/m^2 and 1.89 W/m^2 for CLD and COD region, respectively. It indicates that the variability of SW forcing in COD region is about 5 times larger than that in CLD region. For LW radiative forcing, the no-dust cloud (CLD) is around 102.8 W/m^2, which is 20% less than the LW forcing from COD regions, respectively. The standard deviations are 0.06 W/m^2 and 0.47 W/m^2 for CLD and COD region, respectively. The instantaneous TOA net radiative forcing for the CLD region is about -208.2 W/m^2, which is 42.1% larger than the values from COD regions. If the diurnal cycle of the atmosphere is considered, the estimated mean net radiative forcing is -52.7, -9.35 W/m^2 ((SW + 2LW forcing)/2) for CLD and COD regions, respectively. Thus, the existence of dust aerosols under clouds significantly reduces the cooling effect of clouds. These reduced cooling effects of dust aerosols for COD ($-9.35+52.7=43.4$ W/m^2) regions on clouds can be considered to be actual warming effects of dust aerosols. Since the long-term averaged frequency of dust storm occurring days observed from the surface meteorology stations and its standard deviation are about 2.3% and $\pm1.5\%$, respectively, the averaged climate forcing (warming) of dust storms is about (1 ± 0.6) W/m^2 (i.e. $(43.4\times2.3\%\pm43.4\times1.5\%)$ W/m^2).

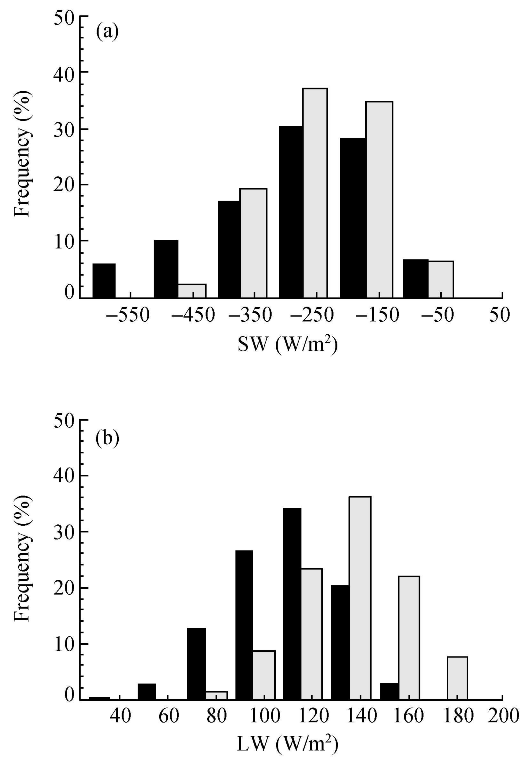

Fig. 1. Comparison of the TOA radiation forcing over the no-dust cloud (CLD) region (black bar), and clouds over the dust (COD) region (gray bar) for (a) SW forcing; (b) LW forcing. The histogram intervals are 100 g/m^2 for (a) and 20 g/m^2 for (b).

Table 1. Comparison of weight averaged radiative forcing (W/m^2) at the TOA

Region	SW forcing	LW forcing	Net forcing
CLD	−311.0	102.8	−208.2
COD	−275.7	128.5	−147.2

Fig. 2 compares the TOA cloud radiative forcing of CLD with that of COD region as a function of solar zenith angle (SZA). It shows that the clouds developing in the CLD region yield the most larger negative SW and net forcing for all ranges of SZA. Although the forcing derived from both CLD and COD regions varies with SZA, the SW and net forcing difference between CLD and COD increases linearly with increasing SZA. Fig. 3 shows the cloud radiative forcing in the CLD and COD regions as a function of effective cloud top temperature (T_e). The TOA radiative forcing in COD regions represents the combined effects of upper-layer clouds and lower-layer dust aerosols. For dusty cloud tops with temperatures in the range of 245 K $< T_e \leqslant$ 260 K, the SW forcing in Fig. 3(a) is less than that for no-dust clouds by more than 30%. The effects of dust aerosols are even more significant on net forcing in Fig. 3(c). For the warmer dusty clouds ($T_e >$ 245 K), the net forcing is less than those from no-dust clouds by more than 50%, due to reduced humidity and less condensation caused by mixing of dry dust air masses with humid cloud air masses in lower atmospheric layers[28]. Fig. 4 shows the radiative forcing as functions of cloud water path (W_P). For the dusty cloud with 300 $g/m^2 < W_P \leqslant 700$ g/m^2, SW forcing is considerably smaller than that of no-dust clouds in COD regions and the difference increases with increasing W_P. However, LW forcing of dusty cloud forcing is smaller than that of no-dust clouds with $W_P <$ 300 g/m^2. This behavior is not surprising because of the effect of dust aerosols on cloud and radiative properties.

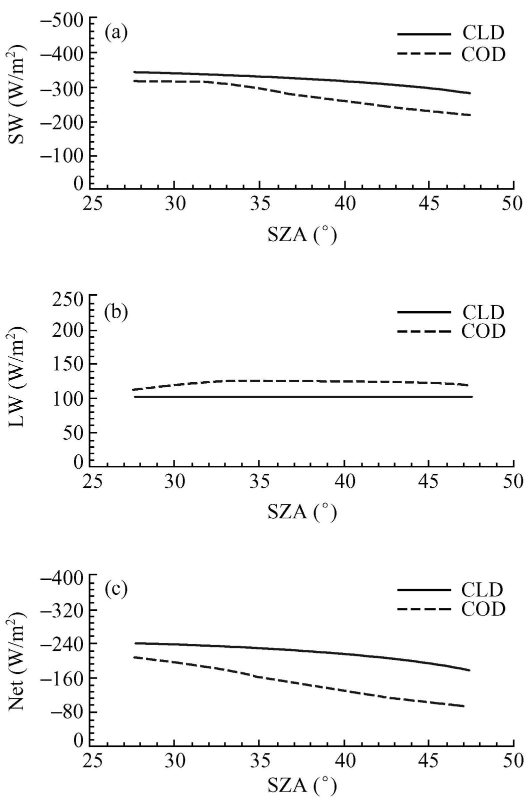

Fig. 2. Comparison of the TOA radiation forcing for CLD and COD regions as a function of solar zenith angle for (a) SW forcing, (b) LW forcing, and (c) net forcing.

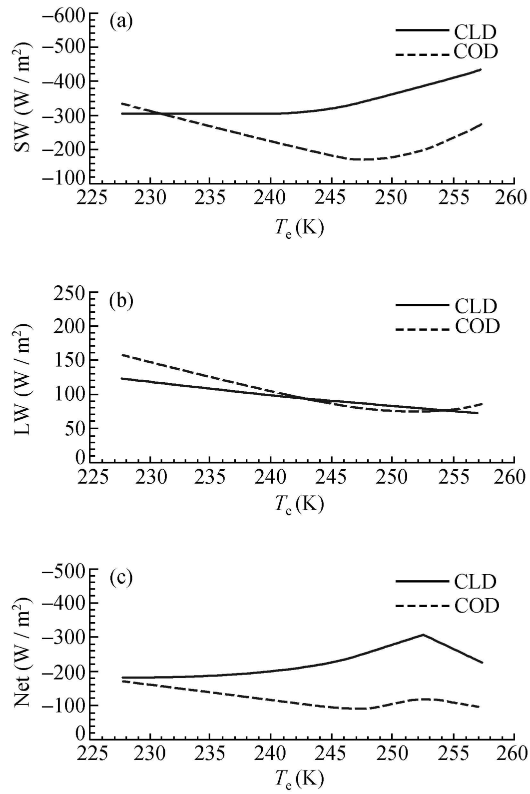

Fig. 3. Comparison of the TOA radiation forcing for CLD and COD regions as a function of effective cloud top temperature T_e for (a) SW forcing, (b) LW forcing, and (c) net forcing.

3 Discussion and conclusions

This study shows the effect of Asian dust aerosols on TOA cloud radiative forcing. Satellite data may not be a perfect measurement to detect the effect of dust on clouds but is the only conveniently available one. The results show that the impact of dust aerosols on cloud radiative forcing is very complex. Despite the general agreement that clouds cool the earth-at-

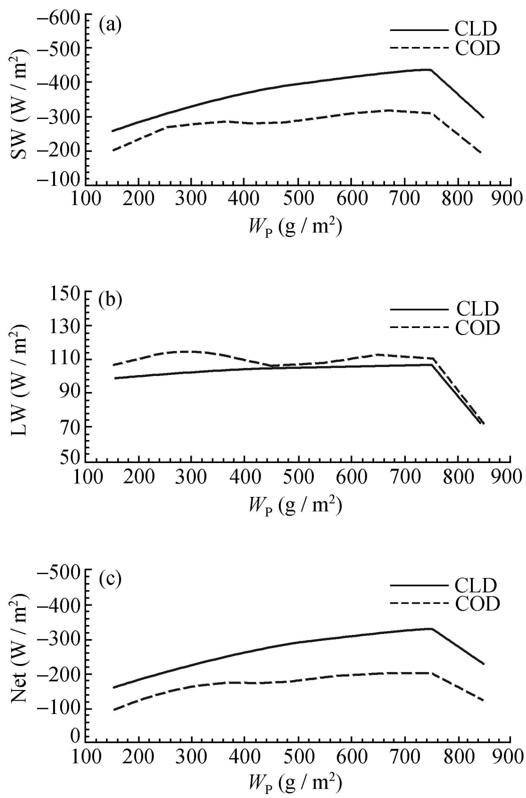

Fig. 4. Comparison of the TOA radiation forcing for CLD and COD regions as a function of cloud water path for (a) SW forcing, (b) LW forcing, and (c) net forcing.

mosphere, there are substantial differences in the estimated magnitudes of the cloud radiative forcing between CLD and COD regions. Since the COD and CLD regions are determined from the similar meteorological conditions, the differences in radiative properties are considered to be dust effects. The dust aerosol has a cooling effect on the TOA in daytime and a net warming effect when both day and night are considered. These aerosols also cancel or reduce the cloud cooling effect on the TOA in COD regions due to the decreasing water path. If confirmed, the net cloud radiative forcing ((1 ± 0.6) W/m^2) of dust storms estimated from the current study will be the strongest aerosol forcing in the studied region during dust storm seasons, and have profound warming influences on the atmospheric general circulation and climate. Due to the large spatial extent and temporal variation of desert dust in the atmosphere, the interactions of desert dust with clouds can have substantial climatic impacts. The decreasing of cloud optical depth and water path partially reduces cloud cooling effect and increases the warming effect due to the increased greenhouse gases. Of course, the results presented here represent a first step in better understanding of the effect of Asian dust on climate. In this study, we only studied the effect of dust aerosol on TOA radiative forcing in cloud over dust system. Further research should be undertaken to develop a more complete understanding of these interactions, such as dust effect on surface radiatiave flux, semi-direct effect of dust aerosol. Furthermore, more dust events need to be examined to develop more robust statistics.

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