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Satellite-based assessment of possible dust aerosols semi-direct effect on cloud water path over East Asia

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[1] The semi-direct effects of dust aerosols are analyzed over eastern Asia using 2 years (June 2002 to June 2004) of data from the Clouds and the Earth's Radiant Energy System (CERES) scanning radiometer and MODerate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite, and 18 years (1984 to 2001) of International Satellite Cloud Climatology Project (ISCCP) data. The results show that the water path of dust-contaminated clouds is considerably smaller than that of dust-free clouds. The mean ice water path (IWP) and liquid water path (LWP) of dusty clouds are less than their dust-free counterparts by 23.7% and 49.8%, respectively. The long-term statistical relationship derived from ISCCP also confirms that there is significant negative correlation between dust storm index and ISCCP cloud water path (CWP). These results suggest that dust aerosols warm clouds, increase the evaporation of cloud droplets and further reduce the CWP, the so-called semi-direct effect. The semi-direct effect may play a role in cloud development over arid and semi-arid areas of East Asia and contribute to the reduction of precipitation. **Citation:** Huang, J., B. Lin, P. Minnis, T. Wang, X. Wang, Y. Hu, Y. Yi, and J. K. Ayers (2006), Satellite-based assessment of possible dust aerosols semi-direct effect on cloud water path over East Asia, *Geophys. Res. Lett.*, *33*, L19802, doi:10.1029/2006GL026561.

1. Introduction

[2] Dust aerosols not only have direct effects on the climate through reflection and absorption of short- and long-wave radiation but also modify cloud properties, such as the number concentration and size of cloud droplets. This change in cloud properties, which could alter both cloud albedo and cloud lifetime [*Twomey et al.*, 1984; *Ackerman et al.*, 2000; *Liu et al.*, 2003] if the total cloud water content remained unaffected, constitutes the indirect effect on climate [*Penner et al.*, 1992; *Twomey*, 1977]. Another important aspect of aerosols, especially absorbing aerosols, such as black carbon and mineral dust, is their semi-direct effect. Aerosol absorption at solar wavelengths could contribute to increased diabatic heating in the atmosphere and enhance cloud evaporation [*Ackerman et al.*, 2000; *Koren et al.*, 2004; *Krüger and Graßl*, 2004].

[3] The term 'semi-direct effect' was introduced by *Hansen et al.* [1997] to describe the impact of absorbing aerosols on clouds. A series of experiments with a simple general circulation model (GCM) showed that increased shortwave absorption could reduce relative humidity and subsequently decrease cloud cover. Similar results were later obtained by *Cook and Highwood* [2003] who used a more sophisticated GCM. When the aerosol-induced cloud feedbacks were included, the GCM-predicted warming increased from 2.5 K to 2.9 K. The additional warming was related to decreases in the fractional coverage of large-scale clouds, particularly at mid and high latitudes. The semi-direct aerosol effect was also investigated by *Ackerman et al.* [2000] using Large-Eddy-Simulations (LES) and observations from the Indian Ocean Experiment (INDOEX) during 1998–99. They found that absorbing aerosols reduced the relative humidity in the boundary layer and caused a 5–10% reduction in cumulus cloud fraction. *Lohmann and Feichter* [2001] provided the first assessment of the global annual mean aerosol semi-direct forcing using the European Center HAMburg 4 General Circulation Model (ECHAM4 GCM). The strong warming influence of absorbing aerosols was also emphasized by *Jacobson* [2002], who found a decrease in global averaged column liquid water and ice associated with the semi-direct effect.

[4] Recently, special attention has been dedicated to cloud interactions with desert aerosol particles [*Rosenfeld et al.*, 2001; *Bréon et al.*, 2002; *DeMott et al.*, 2003; *Kawamoto and Nakajima*, 2003; *Huang et al.*, 2006]. Measurements of the complex refractive index of atmospheric dust aerosols in central Asia [*Sokolik et al.*, 1993] suggested that significant absorption of solar radiation could exist due to the considerable range of values for the imaginary part of the refractive index. *Costa et al.* [2006] found that the single scattering albedo of Asian dust can be as low as 0.76, which suggested that Asian dust could be strongly absorbing aerosols. However, the knowledge of the indirect and semi-direct effects of Asian dust aerosols on clouds is still very limited due to the lack of observations. A difficulty in substantiating aerosol effects on clouds is that cloud evolution can be profoundly affected not only by aerosols but also by cloud dynamics and thermodynamics. Since aerosol amounts and dynamical factors are often correlated, distinguishing between them requires either special circumstances, e.g., a uniform cloud field that is only perturbed in certain locations by aerosol sources, or statistical analysis of a sufficiently large amount of data in specific cloud dynamic regimes. This study follows both courses. Long term, multi-sensor and multi-platform satel-

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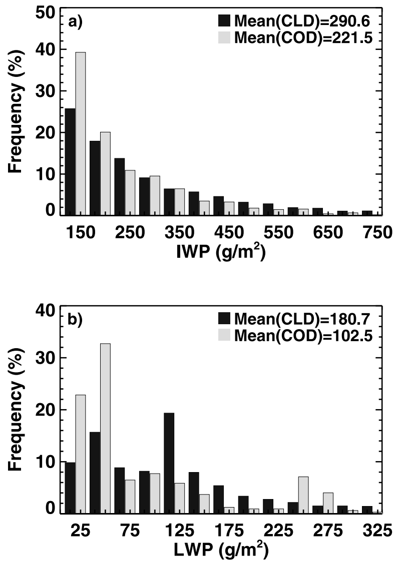

Figure 1. Histogram comparison of the cloud water path over the dust-free cloud region (CLD, black bar), and overcast clouds over the dust region (COD, gray bar) for (a) IWP and (b) LWP. The histogram intervals are 50 g/m^2 for Figure 1a and 25 g/m^2 for Figure 1b.

lite data are analyzed to evaluate the semi-direct effect of Asian dust aerosols on cloud properties.

2. Data

[5] Two years (June 2002 to June 2004) of CERES Aqua Edition 1B SSF (Single Scanner Footprint) data are used here. CERES SSF data sets combine CERES radiation measurements, MODIS cloud microphysical retrievals, and ancillary meteorology fields to form a comprehensive, high-quality compilation of satellite-derived cloud, aerosol, and radiation budget information for radiation and climate studies. There are about 140 parameters in the SSF data set. The current analysis uses three of the SSF parameters, IWP, LWP, and cloud top effective temperature (T_e), which were derived with the Visible-Infrared-Solar-infrared-Split-window Technique (VISST) [*Minnis et al.*, 2004]. VISST has typically relied on the assumption that all clouds are homogenous in a single layer. The cloud properties derived from the entire reflected visible radiance represents the combined effects of all cloud layers. When the entire reflected radiance is interpreted with an ice cloud model, the optical depth of the ice cloud can be severely overestimated because the underlying water cloud can significantly increase the reflectance [*Huang et al.*, 2005]. However, in this study we are only interested in the dust effect on the total cloud water path (i.e., the ice water path + liquid water path of the entire atmospheric column). The retrieval of total water path is accurate enough for this analysis.

[6] The monthly mean cloud amounts from the ISCCP D2 dataset from 1984–2002 [*Rossow and Schiffer*, 1991] are also analyzed here. Like VISST, the ISCCP only detects clouds with optical depths greater than about 0.3. The errors for liquid water should be within ~20% while those for ice increased to ~50% [*Han et al.*, 2000; *Lin and Rossow*, 1996]. ISCCP data may not be the best means for detecting the effect of dust on clouds but it is the longest available data record. To combine the effect of the cloud optical depth (τ) and cloud amount (cloud fraction), the composite cloud albedos (CCA) [*Matsui et al.*, 2006] are estimated using the formula:

$$CCA = \sum_i CF^i * \alpha^i_{cloud}, \tag{1}$$

where CF^i is the cloud amount for specific cloud type i, such as cirrus cloud in a 2.5° × 2.5° box from ISCCP D2 dataset, and α^i_{cloud} is the cloud albedo, expressed as $\alpha^i_{cloud} = \tau^i/(\tau^i + 6.7)$ obtained from a two-stream radiative transfer model [*Hobbs*, 1993].

3. Analysis and Results

[7] To detect cloud modifications induced by dust aerosols, the dusty cloud properties from CERES are compared with those from dust-free cases. The discrimination of dust storms and dust-free weather conditions is based on surface station observations over Northwest China (30°N–50°N and 80°E–110°E). If the surface station observed a dust storm in the region, the clouds in this region are defined as dusty clouds (hereafter, COD). The clouds in the same weather system, without dust storms reported at the cloud site, are classified as dust-free cloud (hereafter, CLD). However, this definition may not be adequate for a dust region that is far away from its source since it is difficult to separate COD from CLD regions in remote areas. A total of 33 dust storm cases for January to May during the 2-year CERES period were selected based on the surface observations. During those months, the environment was generally cold with low-level (<2 km) clouds as cold as ~260 K. The averaged surface skin temperature of the CLD regions for the 33 selected cases was 6.1°C less than that for the COD region since the dust storms were generally at the edges of cold fronts where surfaces are warmer than those behind the fronts.

[8] Figure 1 shows the IWP and LWP histograms derived from the CLD (black bar) and the COD (gray bar) datasets. On average, the COD mean IWP and LWP are less than the corresponding CLD values by 23.7 and 49.8%, respectively. Another difference between these two categories is that 55% of the COD pixels have LWP $\leq$ 50 g/m^2 (Figure 1b), while only 22% of the CLD pixels meet this condition. For LWP > 50 g/m^2 (Figure 1b), the COD frequencies are less than their CLD counterparts in most LWP bins. Since the CLD and COD regions were in the same cold frontal systems, and the CLD regions were colder than COD regions, and located in drier places (even within deserts), the moisture supply for cloud formation in CLD regions could not be larger than that in COD regions. Except that the COD occur at leading edge of fronts and therefore might have different characteristics than behind the front. The clouds formed in the CLD region should be thinner and with less water amount than that in the COD region. However, the observations here are significantly different from the classical meteorology picture. Thus, the large decrease in the IWP and LWP values of COD clouds cannot be explained by insufficient water vapor in the atmosphere or by moisture transports during

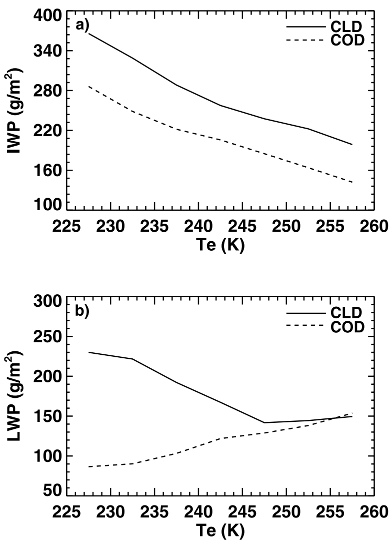

Figure 2. Comparison of the cloud water path over the CLD region with the COD region as a function of effective cloud top temperature Te for (a) IWP and (b) LWP.

the cloud formation. This difference suggests that evaporation in the bottom of the cloud caused by dust aerosol heating, due to the aerosol absorption of solar radiation, plays a critical role in the cloud development.

[9] To compare cloud properties at similar meteorological conditions the CWP in the CLD and COD categories were plotted as a functions of T_e (Figure 2). Both the COD IWP (Figure 2a) and LWP (Figure 2b) are less than the corresponding values for dust-free clouds over the full range of observed cloud top temperatures (225 K < Te $\leq$ 260 K). In Figure 2a, the variation of IWP shows that the IWP decreases with increasing T_e. The significant IWP difference between the CLD and COD clouds occurs throughout the full range of the ice cloud temperatures. For example, the CLD IWP is around 250 g/m^2 when Te = 245 K, while the COD value is about 200 g/m^2. For water clouds, the large difference between dust-free and dusty CWP can be found in middle layer clouds (Te $\sim$ 250 K). The LWP values in the COD category increase with T_e while the variations of CLD LWP are generally similar to those for CLD IWP and only decrease with increasing Te. This indicates that the effects of dust aerosols are more significant on LWP in middle layer clouds, where upper layer aerosol heating due to the absorption of solar radiation may be strong and directly affect the cloud evaporation. Figures 1 and 2 suggest that the dusty CWPs are considerably smaller than those of dust-free clouds, which may be due to cloud evaporation caused by dust aerosol absorption or wet precipitation of dust.

[10] To study the long-term statistical relationship between dust storm and cloud properties, the dust storms index for the Taklamakan desert (38°N–48°N, 78°E–88°E) is studied and compared to ISCCP cloud properties. For each given month at each surface site, the index is defined as the number of days when dust storms occur during the month. The Taklamakan dust storm index (TDI) used here is the averaged index for 4 surface stations around Taklamakan. Because the Taklamakan is the major source of dust storms, the TDI can explain more than 60% of the dust storm activity

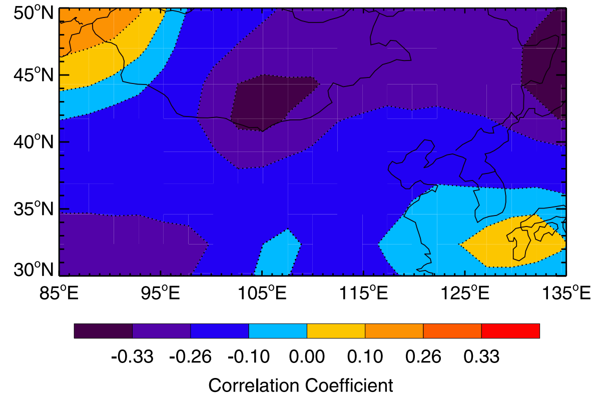

Figure 3. Distribution of correlation coefficients between monthly anomalies of Taklamakan dust storm index (TDI) and ISCCP composite cloud albedo (CCA) for total cloud.

over East Asia. The index increases with increased frequency and strength of the dust storms. Because both dust aerosol and cloud datasets contain large seasonal cycles, we have removed the climatological monthly means and considered only the monthly anomalies in this analysis.

[11] For the 18 years of ISCCP and surface data, this analysis reveals that the composite cloud albedos (CCA) from ISCCP have statistically significant (correlation coefficient, r, less than −0.26 for 95% significance and −0.33 for 99% significance) negative correlations with TDI in a large part of the studied area for total clouds (Figure 3). The areas with significant negative correlation are basically in the north or northeast Asia where the atmosphere is generally dry and cold and rainfall is infrequent. In these areas, dust aerosol storms can have long lifecycles and significant interactions with cloud systems. In contrast, over wet and humid regions such as Southeast China, especially over the Yangtze River basin, the ISCCP clouds and dust aerosols are generally uncorrelated. An explanation for this phenomenon is that the dust was either not transported to these regions or washed out quickly by local precipitation. The statistical analysis of TDI with TWP shows similar results to those with CCA suggesting that the dust aerosols may statistically reduce the cloud albedo due to changes in CWP (Figure 4). These statistics may be explained by two potential causes. The first is that the mixture of dry air

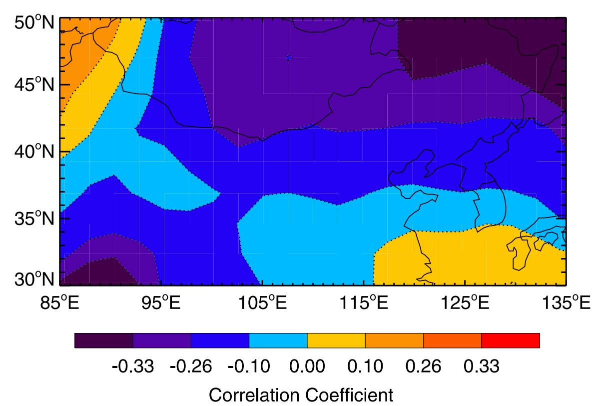

Figure 4. Same as Figure 3 but for the total water path of total cloud.

masses associated with dust storms in moist cloudy air masses could reduce the relative humidity of the atmosphere and lower the condensed water amount. In this case, the dry dust aerosols could also absorb moisture from cloudy layers, and become heavy particles that produce wet dust precipitation [*Huang et al.*, 2006]. The second could be that dust aerosols absorb incoming solar radiation, which heats the cloud layer and increase evaporation, as previously discussed. The observed results may be due to a combination of the two causes. It can also be seen that positive correlations between CCA and TDI exist in portions of Northeast Asia. Although the correlations seen in Figures 3 and 4 can be explained by the two causes mentioned previously, we cannot eliminate the possibility that some meteorological factors are simultaneously forcing both dust aerosol and cloud changes. In a given month, windy/stormy conditions at Taklamakan are generally associated with more frequent cold front systems over China that move along the path from northwest to southeast China. These fronts can cause a significant number of dust storms in the arid and semiarid areas of northern China and produce more clouds in the wet regions of south China. This is the reason for the huge negative correlation stripe in northern China starting from the dust source region all the way to the east end of the analyzed domain. For the branch of southward dust movement, additional clouds could be generated in southeast China due to humid environments, especially for areas near ocean. The region of positive correlation (upper-left corner) contains areas typically behind dust storm cold frontal systems, where additional clouds would be produced by more frequent and/or stronger cold fronts. While the negative areas in the western and southern corner of the analyzed domain are typically mountainous regions that have different dynamics from the Taklamakan.

4. Conclusions and Discussions

[12] Aerosols are generally believed to exert a cooling influence on climate directly by scattering solar radiation and through their indirect effects on clouds. However, the semi-direct effect has the potential to offset this cooling by reducing low cloud cover and water path. Although the potential importance of the semi-direct effect has been addressed by model simulations, there are few reports discussing the semi-direct effect as seen from observational data. This study shows some evidence of the semi-direct effect of Asian dust aerosols on cloud properties. Analysis of the satellite observations indicates that, on average, the water path of dusty clouds is considerably smaller than that from dust-free clouds in the same frontal systems. The key issue may be related to the dust aerosol warming effect through the absorption of solar radiation. This effect may be less important for Saharan dust and unique to Asian dust because of differences in their compositions. The absorption or diabatic heating of Asian dusts can cause the evaporation of cloud droplets and reduce the CWP. The observed reduction in cloud water amount is consistent with our previous case study [*Huang et al.*, 2006]. Due to the large spatial and temporal extent of desert dust in the atmosphere, the interactions of desert dust with clouds can have substantial climatic impacts. The decrease of cloud optical depth and water path partially reduces the cloud-cooling effect. A previous study indicates that the desert dust might contribute significantly to the observed reductions in cloud droplet size and precipitation over Africa [*Rosenfeld et al.*, 2001]. However, this study shows that the semi-direct effect may be the dominating factor of dust aerosol-cloud interaction over arid and semi-arid areas in East Asia, and contribute to the reduction of precipitation via a significantly different mechanism as compared to that in Africa. Dust storms may have contributed to the desertification of the Northwest China during recent decades. The results presented here represent only a first step in better understanding the effect of Asian dust on climate. Further research should be focused on measurements of physical processes of aerosol-cloud interactions.

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