Satellite Remote Sensing of Dust Aerosol Indirect Effects on Cloud Formation

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Abstract

We undertook a new approach to investigate the aerosol indirect effect of the first kind on cloud formation by using available data products from MODIS, and obtained physical understanding about the interaction between aerosols and clouds. Our analysis focused on the examination of the variability in the correlation between cloud parameters (optical depth, effective particle size, cloud water path, and cloud particle number concentration) and aerosol optical depth and number concentration that were inferred from available satellite cloud and aerosol data products. Correlation results for a number of selected scenes containing dust and clouds are presented and dust aerosol indirect effects on clouds are directly demonstrated from satellite observations.

1. Introduction

Major species of atmospheric aerosols include: mineral dust particles lifted from desert surfaces by dust storms and transported across continents and oceans by atmospheric general circulation; organic suspensions and inorganic particles injected by biomass burning and wild fires; and haze particles associated with urban air pollution. Moreover, due to the substantial increase in air traffic in recent years, soot particles composed mainly of black carbon (BC), along with sulfur compounds and water vapor, have infiltrated the upper troposphere, causing increased frequency in the occurrence of contrails and contrail-induced cirrus clouds (Liou et al. 1990, Frankel et al. 1997, Wylie et al. 1994, 1999, 20052005, Ou and Liou 2008).

Effects of both anthropogenic and naturally occurring mineral dust on the Earth's climate system have yet to be fully realized and remain to be a topic of contemporary research. Forster et al. (2007) pointed out that mineral dust is an important source of aerosols, which covers the sky over Africa, Equatorial Altlantic Ocean, Middle East, South Asia, Northern China, and Northwest Pacific Ocean. Interactions between dust aerosols and clouds in the upper troposphere and lower stratosphere can produce a significant impact on atmospheric radiative forcing, and hence on global and regional climates. By means of absorption and scattering processes, dust aerosols affect atmospheric radiative transfer through their direct interaction with solar and thermal infrared radiation. Dust aerosols also affect atmospheric radiative and climate forcings indirectly through their interaction with clouds by modifying cloud optical properties and precipitation efficiency.

The direct aerosol radiative effect is much smaller than the direct cloud radiative effect. However, the aerosol indirect effects on cloud formation and the coupled modifications on radiative transfer and hydrological cycle can be significant processes in the atmosphere. Nevertheless, there are large uncertainties associated with the quantification of these processes, primarily due to uncertainties inherent in key dust properties, and competing thermal effects of both long-wave and short-wave radiative interactions. Based on works of previous investigators (Hansen et al. 1997, Sokolik and Toon 1999, Tegen et al. 1996, and others), a tentative global annual mean dust radiative forcing in the range of -0.6 to +0.4 Wm^{-2} was reported with large uncertainties, which stem from model assumptions, a lack of observational data, and difficulties in measurement techniques. Besides causing climatic perturbations, major dust events can severely reduce near-surface visibility and contribute to a number of problems in military (Miller 2003) as well as commercial activities.

The aerosol indirect effect of the first kind is currently referred to as the “Twomey effect” (Twomey 1977), an effect involving increases in the solar cloud albedo due to decreases in cloud particle size caused by additional aerosols serving as cloud condensation nuclei (CCN) and ice nuclei (IN). Other types of indirect effects have also been identified and are referred to as the aerosol indirect effect of the second kind, including the effect on cloud lifetime and precipitation efficiency associated with additional smaller cloud particles (Liou and Ou 1989, Albrecht 1989), and the solar absorption effect of soot particles related to decreases in precipitation efficiency (Grassl 1979, Hansen et al. 1997). In particular, Liou and Ou (1989) postulated that if the cloud effective particle sizes are increased due to the greenhouse warming, then the precipitation generation rate is enhanced, resulting in a decrease in cloud liquid water content and a positive feedback to surface temperature increase. The quantification of dust aerosol indirect effect in association with clouds is subject to large uncertainties, because of our limited understanding of the physical and chemical processes controlling cloud formation in the presence of dust aerosols, particularly heterogeneous ice nucleation (Cantrell and Heymsfield 2005).

The Twomey effect of the enhancement of reflectance by low stratiform water clouds of smaller cloud particle sizes due to the presence of aerosols has been directly observed by satellite radiometers. The most notable example is the observation of ship tracks that perturb the marine stratus cloud decks off the coast of California (e.g. Coakley et al. 1987). In another example, the high concentration of aerosols obtained from *in situ* measurements at the Sichuan Basin, China, has been found to correlate well with the large cloud optical depth obtained from the ISCCP data archive, thus illustrating that highly polluted air can cause significant increases in cloud optical depth, and hence cloud albedo (Zhou et al. 1999). At this point, the aerosol indirect effect of the first kind on water clouds has been well studied (e.g. Kaufman et al. 2005). However, investigation of this effect in association with ice clouds has been extremely limited.

The formation of ice in high-level clouds involves the homogeneous freezing of solution droplets formed on soluble CCN at temperatures below -37°C as well as the heterogeneous freezing processes involving insoluble or partially insoluble IN. The leading IN candidates are mineral dust and BC (Cantrell and Heymsfield 2005). In particular, dust particles generally originate from arid desert surfaces and can be transported thousands of miles away before they eventually settle again onto the surface (Chung et al. 1996, Chiapello et al. 1999, Prospero 1999). Studies have shown that dust particles can also be vertically transported by air flow and move into the middle and upper troposphere, where they can interact with high-level clouds, such as cirrus and wave clouds, and modify their microphysical and radiative properties (Sassen et al. 2003). Also note that elevated particles can serve as IN via deposition nucleation. Based on laboratory studies, surrogates for mineral dust particles proved to be strong potential contributors to heterogeneous IN populations and, furthermore, heterogeneous freezing rates increased with particle size under the same thermodynamic conditions (e.g., Archuleta et al. 2005). BC is generally quite hydrophobic, but can become hydrophilic after exposure to sulfuric acid prompting it to act as immersion IN. DeMott (1990, 1999) showed that soot particles are effective heterogeneous IN at temperatures between -25°C and -40°C and below -53°C.

At the level where cirrus clouds form, information on aerosols, including dust and BC, has been extremely limited because of the requirement of high-flying aircraft and the limitation of our understanding about the physical and chemical processes controlling ice formation in the presence of aerosols, particularly heterogeneous ice nucleation (Cantrell and Heymsfield, 2005). An adequate understanding of aerosol-ice cloud interaction must be derived from *in situ* microphysics measurements. However, it is difficult to isolate and quantify aerosol indirect effects based solely on *in situ* observations because of measurement uncertainties and sampling considerations as well as separation of these effects from the natural variability of meteorological conditions.

A number of researchers (Sassen and Dodd 1988, Kärcher and Lohmann 2002, DeMott et al. 1997, Gorbunov et al. 2000, Kärcher and Lohmann 2003, Liu and Penner 2005, and Kärcher et al. 2006) have developed parameterizations of homogeneous and heterogeneous ice nucleation for incorporation in model studies. Attempts to mechanistically relate aerosol number density to cloud formation in general circulation models (GCMs) has focused on the initiation of warm/liquid clouds. But much less attention has been given to the study of potential impacts of aerosols on high-altitude ice clouds for the reasons stated above. To evaluate the aerosol indirect effects simulated by GCMs, Boucher and Lohmann (1995) compared results from two models to examine differences in the prediction of the Twomey effect associated with sulfate aerosols. Lohman (2002) introduced a prognostic equation for the number concentration of ice crystals in the ECMWF-Hamburg (ECHAM4) GCM, which is used to investigate the potential effect of aerosol-ice cloud interaction by contact nucleation. Menon et al. (2002) suggested that absorbing aerosols such as BC could significantly affect the large-scale circulation and water cycle in both India and China. Chen and Penner (2005) examined a set of simulations using different model formulations to understand how different parameterization choices impact the magnitude of the Twomey effect. More recently, Penner et al. (2006) compared the Twomey and secondary indirect effects estimated by six GCMs and found that the prediction of aerosol concentration is the major source for differences between GCM simulations. In terms of regional impact, it has been suggested that mesoscale variability, including the spatial inhomogeneity of vertical velocity and complex local terrain, is a critical factor that must be considered in modeling aerosol radiative effects over a large area (Giorgi et al. 2002, Lohmann 2002, Kim et al. 2006).

In view of the preceding uncertainties and difficulties in determining aerosol indirect effects involving ice clouds by means of direct *in situ* observations, and GCM and regional climate model simulations, our study adopts an alternative approach to investigate these effects through analysis of ice cloud and aerosol remote sensing data. We utilize retrieval data products from space-borne and ground-based active and passive sensors currently in operation. These data contain rich and valuable information that can be used to investigate the relationship between aerosols and ice cloud formation. This approach has been successfully undertaken by a number of investigators for water clouds. Nakajima et al. (2001) correlated the column aerosol number concentration and low-cloud microphysical parameters employing AVHRR data over ocean for four months in 1990. Chameides et al. (2002) examined the correlation between the International Satellite Cloud Climatology Project (ISCCP) cloud amount and model simulated anthropogenic aerosol optical depth. Bréon et al. (2002) related the POLDER derived cloud particle radius to aerosol parameters over tropical oceans. In addition, Massie et al. (2007) analyzed MODIS reflectances and aerosol products over India and the Indian Ocean from 2003-2005 to study aerosol indirect effects as a function of cloud-top pressure. Limited analyses have also been conducted of ground-based remote sensing observations from Raman lidar, microwave radiometer, radar, and optical particle counter to quantify the Twomey effect (Feingold 2003, Feingold et al. 2003, Rosenfield and Feingold 2003). Finally, Chylek et al. (2006) obtained a statistically significant correlation between the ice crystal effective radius inferred from MODIS and the level of aerosol loading during the Indian Ocean Experiment (INDOEX), which suggests a significant aerosol impact on ice clouds.

Satellite remote sensing of clouds and aerosols has made much progress in recent years, thanks to the availability of data from a great variety of meteorological satellites (Ou and Liou 2008). Many remote sensing algorithms have been developed, and the most notable is the archived retrieval products from MODIS for the last 10 years. The authors of this paper also contributed to the progress in this discipline. On the detection of clouds and aerosols, we have developed an integrated method for the simultaneous detection/separation of mineral dust and clouds for both daytime and nighttime conditions using MODIS thermal infrared window brightness temperature data (Hansell et al. 2007). Based on the spectral variability of dust emissivity at 3.75, 8.6, 11 and 12 μm wavelengths, we have combined three heritage approaches to identify dust and cirrus clouds. MODIS data for three dust-laden scenes have been analyzed to demonstrate the effectiveness of this detection and separation method. The detected daytime dust and cloud coverage for the Persian Gulf case compares reasonably well to those from the ‘‘Deep Blue’’ algorithm developed at NASA-GSFC (Hsu et al. 2004). We have demonstrated that the integrated detection method is effective for local nighttime applications by validating nighttime dust and cloud detection method using the cases over Cape Verde and Niger, West Africa, on the basis of the coincident and collocated ground-based MPL measurements.

On the retrieval of ice cloud properties, we devised a novel and unique method for inferring cirrus cloud-top and cloud-base effective sizes and cloud optical thickness from 0.645, 1.64 and 2.13 and 3.75-μm band reflectances/radiances (Wang et al. 2009). This approach uses a successive minimization method based on a look-up library of pre-computed reflectances/radiances from an adding-doubling radiative transfer program, subject to corrections for Rayleigh scattering at the 0.645μm band, above-cloud water vapor absorption, and 3.75μm thermal emission. The algorithmic accuracy and limitation of the retrieval method were investigated by synthetic retrievals subject to the instrument noise and the perturbation of input parameters. The retrieval algorithm was applied to three cirrus scenes over the ARM-Southern Great Plain (SGP) site, North Central China, and Northeast Asia. The reliability of retrieved cloud optical thicknesses and mean effective sizes was evaluated by comparison with MODIS cloud products, and qualitatively good correlations were obtained for all three cases, indicating that the performance of the vertical sizing algorithm is comparable with the MODIS retrieval program. Retrieved cloud-top and cloud-base ice crystal effective sizes were also compared with those derived from the collocated ground-based millimeter wavelength cloud radar (MMCR) for the first case and from the Cloud Profiling Radar (CPR) onboard CloudSat for the other two cases.

We also developed another novel approach for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) / Visible Infrared Imaging Radiometer Suite (VIIRS) to retrieve pixel-level, mixed-phase cloud optical thicknesses and effective particle sizes using 0.67, 1.6, 2.25 and 3.7μm bands reflectance/radiance (Ou et al. 2009a). This approach utilizes look-up tables of reflectances constructed from radiative transfer simulations and a numerical iterative search method. The capability of this new approach has been demonstrated using MODIS data as proxy to VIIRS. Two proxy scenes, October 14, 2001 over North Platte, Nebraska during the ninth Cloud Layer Experiment (CLEX-9), and November 9, 2006, over the Great Lakes and Eastern Canada during the Canadian CloudSat/CALIPSO Validation Project (C3VP) have been analyzed. The performance of the mixed-phase retrieval algorithm was assessed by comparison with MODIS retrieval products, airborne *in situ* observations during CLEX-9 and CloudSat data during C3VP.

In this work, we have undertaken a novel and unique study of the dust aerosol properties and their associated indirect effect of the first kind on cloud formation by using the collocated NAMMA satellite (Terra/Aqua-MODIS, CloudSat-CPR, CALIPSO-CALIOP), and ground-based (AERI/MPL) remote sensing, and airborne and surface *in situ* measurements over the Cape Verde site. These data sets contain rich and valuable information that can be used to investigate the cause-and-effect relationship between dust aerosols and cloud formation and to obtain new understanding and physical insight on interactions between them.

We have gathered and analyzed a substantial number of cases involving aerosols. We investigated dust aerosol properties and their associated indirect effect on cloud formation. MODIS images provide horizontally resolved information on the discrimination of aerosol and cloud particles. Our analysis has been focused on examining the variability in the correlation between cloud parameters (optical depth, effective particle size, cloud water path, and cloud particle number concentration) and tropospheric dust aerosol parameters (optical depth and number concentration) inferred from the available cloud and aerosol data products of MODIS. This research work provides important insights into the radiative and climatic impact of aerosol-cloud indirect effects.

2. Analysis of Satellite Data

The analysis of satellite data begins with the identification of MODIS scenes and dust/ice-cloud areas. For a selected scene, we first search for regions that clearly display the simultaneous presence of aerosols and ice clouds over both water and land surfaces. Heavy aerosol areas over dark surfaces normally appear in hazy light-yellow-brownish or light-blue color. Aerosols are identified as clear pixels based on the MODIS cloud mask along with aerosol optical depths available from the existing database. Over dust-prone regions, aerosols were determined to be primarily consisting of mineral dust. In addition, examination of the MODIS red-green-blue images indicates that ice cloud areas are normally characterized by white-colored hairy cloudy pattern. Ice clouds are identified by the MODIS cloud and cloud-phase masks when their optical depths are larger than zero.

To determine the ice crystal number concentration (N_i), we first define the ice water content (IWC) as follows:

$$IWC = \rho_i \int v_i(L) n(L) dL , \qquad (1)$$

where L is the ice crystal maximum dimension, $v_i(L)$ is the single ice crystal volume as a function of L, and ρ_i is the ice crystal mass density. We can define a characteristic mean particle volume, $\bar{v}_i$ in the form:

$$\bar{v}_i = \frac{\int v_i n(L) dL}{\int n(L) dL} = \frac{\int v_i n(L) dL}{N_i} . \qquad (2)$$

To get N_i, we first use the MODIS-retrieved ice cloud optical depth, τ_c, and mean effective particle radius, r_e, to determine IWC based on parameterization of these three variables as follows Liou (2002):

$$IWC = \tau_c / (a + b / r_e) . \qquad (3)$$

Subsequently, we obtain $\bar{v}_i$ from a relationship between ice particle size distribution and cloud temperature developed from statistical analysis of aircraft *in situ* microphysical observations[22]. Since the mean ice crystal effective size increases with cloud temperature, we expect that $\bar{v}_i$ also increases with cloud temperature.

To compare the dust aerosol indirect effect on cirrus and water clouds, we also determined water cloud droplet number concentration (N_w) for water cloud pixels. The Gamma size distribution is assumed (Liou 1992, p.188), that is

$$n(r) = C r^{(1-3b)/b} \exp(-r / ab), \qquad (4)$$

where $a = r_e$, and $b = \nu_e$. The parameter ν_e.is the effective variance, which is defined as

$$\nu_e = \frac{\int (r - r_e)^2 r^2 n(r) dr}{r_e^2 \int r^2 n(r) dr}, \qquad (5)$$

and the cloud water content (*CWC*) for spherical droplets can be expressed as

$$CWC = \frac{4\pi\rho_w}{3} \int r^3 n(r) dr \; . \qquad (6)$$

By substituting Eq. (3) into (5). the constant *C* can then be expressed in terms of *CWC*. Finally, from the integration of *n(r)* over the size spectrum, we obtain N_w as

$$N_w = k \frac{\tau_c}{r_e^{\;2}} \; , \qquad (7)$$

where the proportionality constant *k* is determined from the integration of Gamma functions. Thus N_w can be computed using MODIS retrieved τ_c and r_e following Eq. (6).

Likewise, the aerosol number concentration (N_a) can be determined from a similar procedure. The aerosol mass concentration (*AMC*) can be expressed as follows:

$$AMC = \rho_a \int v_a(r) n(r) dr \; , \qquad (8)$$

where *r* is the aerosol particle radius, $v_a(r)$ is the aerosol volume as a function of *r*, and ρ_a is the aerosol mass density. We can define a mean aerosol particle volume such that

$$\bar{v}_a = \frac{\int v_a n(r) dr}{\int n(r) dr} = \frac{\int v_a n(r) dr}{N_a} = \frac{AMC}{\rho_a N_a} \; . \qquad (9)$$

The value of $\bar{v}_a$ and ρ_a can be estimated based on *in situ* or laboratory observations or an aerosol composition and a size distribution assumed *a priori*[23]. To get N_a from Eq. (9), we use the MODIS-retrieved aerosol optical depth, τ_a, together with a prescribed mean effective particle size, r_a, defined by

$$r_a = \frac{\int r^3 n(r) dr}{\int r^2 n(r) dr}; \quad \tau_a = 2\pi \int r^2 n(r) dr \; .$$

Assuming that aerosols are spherical ($v_a = \frac{4}{3}\pi r^3$), we obtain from Eq. (4) the following relationship:

$$AMC = \frac{2}{3} \rho_a r_a \tau_a \; . \qquad (10)$$

Both the estimated $\bar{v}_i$ and $\bar{v}_a$ can be subject to uncertainties whose effects on correlation analysis require detailed sensitivity studies based on *in situ* measured ice crystal and aerosol size distributions (also subject to large uncertainties) that are collocated with satellite observations, a subject requiring further investigations. Nevertheless, we have demonstrated the validity of derived cloud and aerosol properties by comparing with *in situ* measurements (see section 3 below).

To correlate cloud and aerosol properties, we have divided the identified aerosol/cloud domain into a number of multi-pixel sub-grids. Because the MODIS cloud mask program identifies a pixel either as clear/aerosol or cloud, and because the current MODIS cloud and aerosol algorithms cannot simultaneously detect/retrieve aerosol and cloud parameters for a single pixel, we have performed the correlation analysis using the average aerosol and cloud properties within each sub-grid that contains both ice cloud and aerosol pixels. Aerosol/cloud optical depth and particle size have been routinely retrieved by MODIS algorithms. We searched for statistically meaningful correlations between cloud and aerosol number concentrations based on the criterion that the correlation coefficient is larger than a threshold value. Subsequently, a parameterized relationship between them is developed using a least-square fitting technique.

For visible and near-IR window bands used in the MODIS cloud retrieval program, effects of water vapor absorption/emission on reflectance/radiance is minimum in relation to the quantification of aerosols in the vicinity of clouds. The horizontal variation of satellite-inferred cloud properties within these relatively small sub-grids would be primarily caused by microphysical processes involving aerosol-cloud interactions, since the spatial and time scales associated with the variability of aerosols (on the order of microns and seconds) are substantially smaller than those associated with meteorological drivers (on the order of kilometers and hours). Moreover, because of the very high spatial resolution of MODIS data (~ 0.25 – 1 km^2) and the excellent and effective capability of the MODIS cloud mask program to separate clear and cloudy pixels, it is anticipated that possible cloud contamination on the inference of the aerosol field would be minimal (Liou 2002).

We have also carefully taken into account the complexity of retrieving aerosol products in the presence of thin cirrus clouds. Since the MODIS cloud mask program contains the state-of-art operating algorithms that have been developed and implemented specifically for the effective detection of thin cirrus, the problem of their contamination in aerosol products has been minimized. In our study, we have ensured that only the aerosol property products for pixels flagged by the MODIS cloud mask program as "confidently clear" were extracted for analysis. These confidently clear pixels have been identified through a series of stringent threshold tests, including the 1.38 μm band reflectance test, which is particularly efficient in identifying high thin cirrus clouds (Gao et al. 2002). Thus, it is anticipated that the probability of a detected aerosol pixel being contaminated by cirrus is extremely small. Because of the strong domination of cloud reflection relative to the aerosol counterpart, the effects of contamination by aerosols imbedded in ice cloud pixels on the retrieved cloud optical depth and effective particle size are expected to be negligible. We have excluded thin cirrus cloud pixels with optical depths less than 1 in the analysis.

3. Application to the MODIS Scenes Containing Dust and Clouds

We have performed correlation analysis for a number of MODIS scenes containing dust aerosols and ice clouds. As described in Ou et al. (2009), we examined the MODIS data covering the regions of frequent dust outbreaks in East Asia, Middle East, and West Africa, and the areas associated with long-range dust transportation such as the Equatorial Tropical Atlantic Ocean. Based on visual inspection and cloud mask results, we have chosen a number of interesting MODIS dust scenes to study the Twomey effect on ice clouds. These scenes contain both dust/aerosols and clouds. For these scenes, we collected suitable aerosol/ice-cloud data, correlated ice cloud and aerosol parameters by means of a statistical analysis, and interpreted resulting correlation trends based on the physical principles governing cloud microphysics.

Aerosol and cloud optical depths and cloud effective particle sizes inferred from MODIS for selected domains were analyzed from which the parameters including dust aerosol number concentration, ice/liquid cloud water path/content, and ice and water cloud particle number concentration, were subsequently derived. To correlate aerosol and cloud properties using aerosol/cloud optical depth and particle size that have been routinely retrieved by MODIS algorithms, we divided the identified aerosol/cloud domain into a number of multi-pixel sub-grids. Because the MODIS cloud mask program identifies a pixel either as clear/aerosol or cloud, and because the current MODIS cloud and aerosol algorithms cannot simultaneously detect/retrieve aerosol and cloud parameters for a single pixel, we performed the correlation analysis using the average aerosol and cloud properties within each sub-grid that contains both aerosol and cloudy pixels. In this manner, meaningful statistical correlations between subgrid mean cirrus clouds and dust parameters can be developed, while the variability and physical significance of these correlations can be physically investigated.

a. *Qualitative investigation of dust indirect effect on cirrus clouds with different dust loadings.* We first invetigate aerosol indirect effect by comparison of aerosol optical thicknesses and effective particle sizes for a number of cirrus cloudy regions with different dust loadings. To the best of our physical understanding, cirrus clouds over a heavier dust area (with many of dust particles serving as potential IN) would likely be affected more than those over a lighter dust region. With this understanding, Ou et al. (2009b) performed statistical analysis involving two cases that occurred in western Africa and Korea. For each case, we compared the mean effective cloud particle sizes for cirrus in proximity with different dust loadings. For the Korean case, we also compared the dust AIE indices evaluated for different cirrus cloudy regions.

Here we present analysis results of a third case. Figure 1(a) shows a Terra/MODIS scene for the date April 8, 2006 at 0440 UTC over the Northeast Asian continent, Korea and Japan. This scene contains a significant presence of original and transported dust layers with imbedded clouds over Eastern Siberia, Inner Mongolia, Japan, Korea, and China's Shangdong peninsula. These regions were denoted by domains A, B, C, D, and E, respectively. Over Eastern Siberia (A) and Inner Mongolia (B) the brightness temperature differences between 11 and 12 μm bands (BTD11-12) and between 8.55 and 11 μm bands (BTD8-11) vary between 0 and 4K and between 0 and 5K, respectively. Positive values of BTD11-12 and BTD8-11 indicate semi-transparent to opaque cirrus clouds. The non-zero values of 1.38 μm band reflectance and low T_c values for both regions

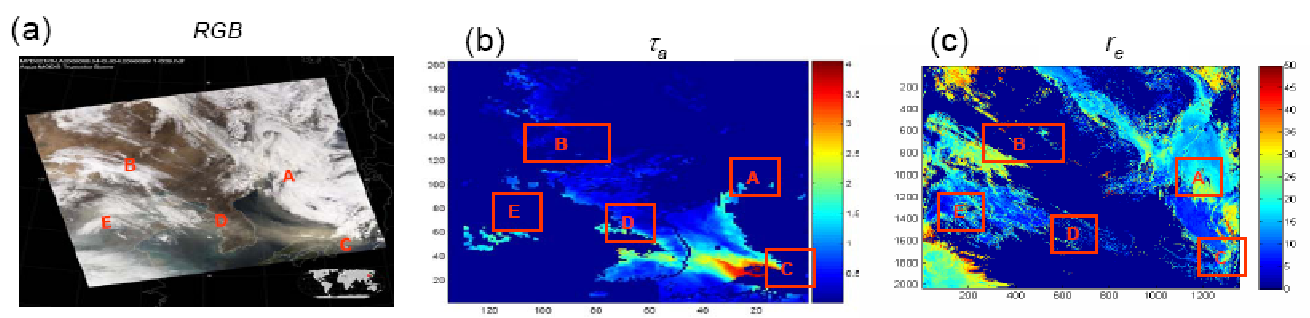

Figure 1 MODIS scene with simultaneous presence of cirrus cloud and dust layers. Images for MODIS overpass on 8 2006 at 0440 UTC over Northeast Asian continent, Korea and Japan. (a) RGB, (b) aerosol optical depth, and (c) cloud effective particle size. Domains A,B, C, D, and E are areas of dusts with imbedded clouds.

Table 1. Parameter Ranges and Their Mean Values for Domains A and B of the MODIS Scene for 23 September 2006 at 1210 UTC over Eastern Tropical Atlantic Ocean and Western Africa

Domain	Parameter Range (mean value)		
	τ_c	$r_e(\mu m)$	τ_a
A	0-50(10.9)	5-35(17.3)	0.9-1.8(1.20)
B	0-60(6.7)	5-80(23.8)	0-0.9(0.28)

further confirming that both domains contain cirrus clouds. In addition, MODIS cloud mask shows that the area is masked by cloudiness and its cloud-phase mask indicates that parts of the cloudiness within both regions are ice clouds. Table 1 provides a list of parameters and their mean values for domains A and B. For domain A, τ_a varies between 0.9 and 1.8 [Fig. 1(b)] with a mean value of 1.2, while r_e varies between 5 and 35 μm, with a mean value of 17.3 μm [Fig. 1(c)]. For domain B, we determine τ_a in the range 0-0.9 [Fig. 1(b)] with a mean value of 0.28, and r_e in the range 5-80 μm [Fig. 1(c)], with a mean value of 23.8 μm. It is evident that for domain A, the dust optical depth is larger, but at the same time the cloud particle size is smaller, consistent with the Twomey effect for aerosol-water cloud interactions.

b. *Quantitative investigation of dust indirect effect on cirrus clouds with different dust loadings.* With the support of ground-based lidar observations (Sassen et al. 2003), we identified a region of ice clouds formed on top of a transported African dust layer for a CRYSTAL-FACE case occurring on 29 July 2002 (Ou et al. 2009b). The MODIS-derived ice cloud and dust properties were shown to reasonably agree with the *in situ* and ground-based measurements. Correlations of dust and cloud properties on the basis of satellite observations indicate that a significant aerosol indirect effect existed within this region. Through correlation of the MODIS retrieved mean effective sizes and aerosol optical depths, we demonstrated that there is a negative correlation trend between these two parameters, consistent with the hypothesis of the Twomey effect.

The MODIS-derived cloud number concentration have been compared with the collocated cloud number concentration measurement provided by the Colorado State University's continuous flow diffusion chamber (CFDC, DeMott et al. 2003) onboard the University of North Dakota Citation II for validation purposes. However, the results were not compared to cloud number concentration values with those determined from the cloud aerosol spectrometer (Baumgardner et al. 2001), which is subject to uncertainty due to the shattering effect of large ice crystals. The shattering effect from CFDC appears to be small in view of the fact that this instrument did not have a shroud at the inlet and the cross sectional area of the inlet tube wall is much smaller than that of the inlet. Thus, we may select *in situ* measurements to help validate the satellite-derived cloud number concentration. The Twomey effect can be statistically quantified based on the slope of best-fit straight lines in the correlation study. The slope values are indicative of the sensitivity of cloud properties to variation in aerosol properties and are dependent on such factors as relative humidity and dust aerosol and cloud optical properties that vary with location and time. We estimate that the AIE is 0.65, nearly twice as large as the maximum value (0.33) proposed by Feingold et al. (2003). In deriving the maximum value of AIE, Feingold et al. assumed that cloud liquid water content is constant and that cloud droplets are spherical. In our study, ice water content was a variable and increased with aerosol optical depth. Using the AIE index, it appears that the case presented in our previous study illustrates a significant dust indirect effect on ice cloud formation that is more prominent than typical aerosol indirect effects for water clouds.

As a further test for the statistical correlation approach, we studied the dust aerosol indirect effect on co-existing water clouds by analyzing a dust water cloud scene. Although aerosol indirect effect of the first kind for water clouds has been extensively studied, the interaction between dust and water clouds based on satellite observations have been extremely limited. The case studied is the same Aqua/MODIS scene for 8 April 2006 at 0440 UTC over Eastern Asian continent and surrounding oceans, as shown in Fig. 1. Over Japan(domain C), Korea(D) and China's Shandong Peninsula (E) there was a distinctively presence of heavy aerosol loading mixed with water clouds.

Figures 2(a)-2(d) display the correlation between τ_c (cloud optical depth) and τ_a (aerosol optical depth), r_e (cloud particle radius) and τ_a *IWP* and τ_a, and N_w (cloud particle number concentration) and N_a.(aerosol number concentration). The dust aerosol indirect effect on water clouds is clearly demonstrated in this case. The slopes $\Delta\tau_c/\Delta\tau_a$, $\Delta r_e/\Delta\tau_a$, $\Delta IWP/\Delta\tau_a$ and $\Delta N_i/\Delta N_a$ are 1.7, -4.1 µm, 6.5 g m^{-2}, and 0.002, respectively. The estimated aerosol indirect effect (AIE) is 0.52, which is larger than the maximum value of 0.33 proposed by Feingold et al. (2003), indicating an unusually strong dust aerosol indirect effect on water clouds. Although aerosol indirect effect on water clouds has been well observed and studied, results shown here are an additional evidence that dust aerosols and water cloud properties are highly correlated and that the dust indirect effect on cloud formation can be detected and reasonably quantified on the basis of satellite observations.

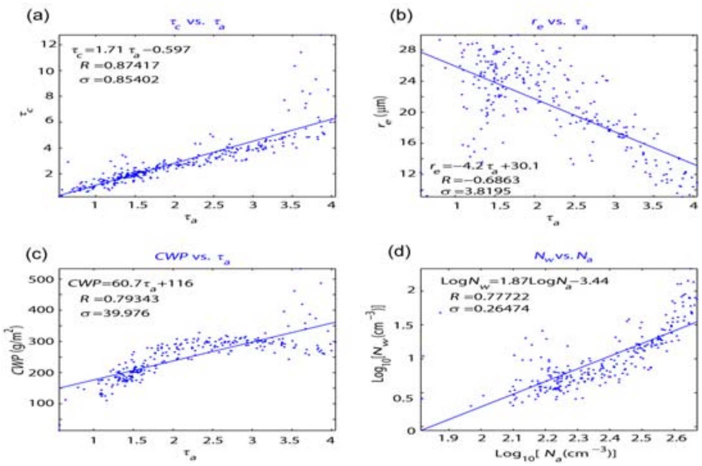

Figure 2 Correlations between water cloud and dust aerosol properties over Japan on April 8, 2006 at 0440UTC: (a) τ_c vs. τ_a, (b) r_e vs. τ_a (c) Cloud water path (*CWP)* vs. τ_a, and (d) cloud droplet number concentration N_w vs. aerosol number concentration N_a. The straight lines denote linear fittings of data points, with the fitting equation given in each frame.

4. Concluding Remarks

This study addresses the aerosol indirect effect of the first kind on ice cloud formation by analyzing pertinent data from Terra/Aqua/MODIS. Our analysis focused on the examination of variability in the correlation between ice cloud parameters and tropospheric dust parameters inferred from the available satellite cloud and aerosol data results. We selected and collected suitable aerosol/cloud scenes, identified analysis regions, statistically correlated ice cloud and aerosol parameters, and interpreted resulting correlation trends based on physical principles.

We demonstrated that the dust indirect effect on cirrus clouds can be detected and reasonably quantified by satellite observations. We first showed that, based on qualitative investigation of the Eastern Asian case (April 8, 2006, 0440 UTC), cirrus cloud mean effective particle sizes decrease with increasing dust aerosol optical depth for different dust loadings. We then showed that based on quantitative investigation of the same case, correlations of water cloud and dust properties indicate strong aerosol indirect effect existed within selected regions. By means of the MODIS retrieved cirrus mean effective sizes and aerosol optical depths, we demonstrated that there is a negative correlation between dust aerosol optical thickness and cloud effective particle sizes. The preceding demonstrative results represent further evidence of dust and cloud interactions that are in consistent with the hypothesis of the Twomey effect for clouds in general.

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