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Impacts of Asian dust on the determination of cloud thermodynamic phase from satellite observations

Hongchun Jin[1], Yuhong Yi[2], Shaima L Nasiri[3], Chao Liu[4], Wengcai Wang[5], Jiming Li[1], Yonghang Chen[6] and Tianhe Wang[1]

[1] Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, Lanzhou, People's Republic of China
[2] Research School of Arid Environment and Climate Change, Lanzhou University, Lanzhou, People's Republic of China
[3] Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, USA
[4] School of Atmospheric Physics, Nanjing University of Information Science and Technology, Nanjing, People's Republic of China
[5] Physical and Oceanography Laboratory, Ocean University of China, Qingdao, People's Republic of China
[6] College of Environmental Science and Engineering, Donghua University, Shanghai, People's Republic of China

E-mail: hongchunjin@gmail.com

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Abstract

The impact of Asian dust on the determination of cloud phase is analyzed over dust sources and downwind using cloud phase products from cloud-aerosol lidar and infrared pathfinder satellite observations (CALIPSO), atmospheric infrared sounder (AIRS), moderate resolution imaging spectroradiometer (MODIS), and polarization and anisotropy of reflectances for atmospheric sciences coupled with observations from a lidar (PARASOL). The results show that the presence of dust greatly affects determination of cloud phase in both source and downwind regions. CALIPSO products demonstrate better ice cloud discrimination of about 70% and 60% over source and downwind regions, respectively, compared to passive sensors. These results suggest that semi-direct effects of dust, which act to warm clouds and evaporate large cloud particles, may play a role in cloud phase determination. This study suggests that the presence of dust tends to increase misclassification of ice clouds as water or uncertain phase by AIRS, MODIS, and PARASOL.

1. Introduction

Cloud thermodynamic phase retrievals from satellite measurements refer to whether a cloud is composed of liquid water droplets, ice crystals, or mixed-phase (a mixture of liquid and ice particles). An accurate knowledge of cloud phase is critical to infer satellite-based cloud properties because ice and water clouds have very different scattering and absorption properties (Platnick *et al* 2003). Small changes in cloud properties can lead to significant variations in cloud feedbacks (Zelinka *et al* 2012). However, the determination of cloud phase from satellites is challenging for several reasons. First, clouds may be contaminated by absorbing aerosols such as dust (Huang *et al* 2007a) within a field of view (FOV) on the order of kilometers such as that observed by atmospheric infrared sounder (AIRS) or PARASOL. The combination of cloud and dust particles is henceforth called dusty clouds in this study. Recent satellite observational studies suggest that dust can modify cloud properties, resulting in a warming effect of dusty clouds (Huang *et al* 2006a, 2006b, Su *et al* 2008, Wang *et al* 2010), particularly in semi-arid regions (Huang *et al* 2012). Therefore, it is important to understand the impact of dust on cloud phase determination and to provide useful information for cloud property retrievals and cloud feedback calculations.

Satellite active and passive sensor measurements are being used to infer cloud phase on a global scale. A number of previous studies had demonstrated the cloud phase determination from satellite platforms and comparisons with other CALIPSO instruments (Baum *et al* 2012, Cho *et al* 2013, Jin and Nasiri 2014, Riedi *et al* 2010, Zeng *et al* 2013). These results show that the cloud thermodynamic phase from the active and passive sensors generally agree with each other with some certain discrepancies. A difficulty in inferring cloud phase for dusty clouds is that passive satellite instruments may cover a large horizontal area but

Table 1. Cloud phase information from AIRS, MODIS, PARASOL, and CALIPSO data products. The four cloud phases listed are ice, water, mixed, and uncertain (unc.).

	Cloud phase					
	Ice	Water	Mixed	Unc.	Product resolution	Product version
AIRS	Yes	Yes	No	Yes	13 km	V6
MODIS	Yes	Yes	No	Yes	5 km	C6
PARASOL	Yes	Yes	Yes	Yes	18.5 km	V17.18
CALIPSO	Yes	Yes	No	Yes	5 km	V3

have limited detection sensitivity to the simultaneous presence of dust and clouds (Cho *et al* 2013), whereas active satellite instruments have better vertical resolution but a narrow FOV. Further, the signal tends to be attenuated by dense dust layers (Chen *et al* 2010, Liu *et al* 2014).

Despite the fact that cloud phase is important in deriving satellite-based cloud properties and radiative forcing, there have been few studies focusing on the impact of dust on cloud phase, especially over a desert source and its downwind regions. In this study, our focus is on Asian dust storms that originate in the Taklimakan and Gobi Deserts and occur frequently during late winter and early spring. These dust layers often appear a few kilometers above sea level, mixing with clouds and affecting cloud development (Rosenfeld *et al* 2001, Wang and Huang, 2009, Yi *et al* 2014). Besides contributing to regional climate, the dust layers are capable of traveling thousands of kilometers at high altitude from the continent to the open sea near Korea and Japan under westerly wind conditions (Takemura *et al* 2002). The emission and transport of dust from a desert region to a downwind area can lead to a large population of dusty clouds (Wang *et al* 2010). It is therefore of great importance to use satellite observations to monitor the cloud phase interactions between dust and clouds.

This study investigates the influence of Asian dust on the determination of cloud phase using A-Train satellite observations of the Taklimakan and Gobi deserts source regions and open sea downwind regions. The classification of dusty cloud and satellite data are described in section 2. Analysis and results are presented in section 3. Major conclusions and discussions are given in section 4.

2. Data and methodology

This study makes use of official cloud thermodynamic phase products (see table 1) from four satellite instruments: The cloud-aerosol lidar with orthogonal polarization on the CALIPSO satellite, moderate resolution imaging spectroradiometer (MODIS) on Aqua, AIRS on Aqua, and POLDER on PARASOL. The CALIPSO cloud phase product (Hu *et al* 2009) is based on lidar profiles of linear depolarization ratio and backscatter at a wavelength of 532 nm with additional information from the ratio of backscatter profiles at 532–1064 nm and temperature profiles. This approach is based on the fact that ice crystals are non-spherical and therefore depolarize the backscattered while liquid water droplets are spherical and cause little depolarization. A similar approach with different thresholds and ancillary information is taken by CALIPSO to classify aerosols (Omar *et al* 2009). The value of the depolarization ratio information, vertical profile information, and aerosol classification capability are the reasons why the CALIPSO products are used as reference data in this study.

MODIS cloud phase for this study comes from the infrared Collection 6 (C6) products (Baum *et al* 2012). The MODIS C6 infrared cloud phase product is a major refinement over the previous C5 products. C6 uses emissivity ratios from three channel pairs to discriminate ice and water clouds: the 8.5 and 11 μm band pair provides the most information about ice-phase clouds, the 11 and 12 μm band pair is most sensitive to cloud opacity, while the 7.3 and 11 μm pair is most sensitive to cloud height.

AIRS is a hyperspectral scanning infrared sounder with high sensitivity to ice clouds (Kahn *et al* 2014). The AIRS phase algorithm is applied to non-desert scenes with AIRS effective cloud fraction greater than 0.01 and is designed to detect ice clouds to enable further ice cloud property retrievals. The algorithm makes use of changes in the spectral scattering and absorption efficiencies of ice and water and employs a set of six brightness temperature or brightness temperature difference threshold tests involving AIRS channels around 1227 cm^{-1} (8.15 μm), 1231 cm^{-1} (8.12 μm), 960 cm^{-1} (10.42 μm), and 930 cm^{-1} (10.75 μm) to classify scenes as ice, water, or unknown. Because of the dependence on the 1227 and 1231 cm^{-1} channels, the AIRS algorithm cannot be applied to desert regions until a correction for low surface emissivity scenes is developed. Jin and Nasiri (2014) show that while AIRS is unable to detect as many ice clouds as CALIPSO, in single-layer cloud scenes the AIRS ice category contains few false-positives. Jin and Nasiri (2014) also show that AIRS is much more sensitive to ice clouds to water clouds and that many of the clouds classified as water by CALIPSO will be classified as unknown by AIRS.

While the MODIS and AIRS cloud phase products used in this study are based on infrared radiances, the

PARASOL phase product is based on the angular behavior of polarized radiances at a wavelength of 0.86 μm (Goloub *et al* 2000). The PARASOL phase algorithm is based on the fact that liquid water clouds are composed of spherical water drops that show a strong angular dependence of polarized radiance with a maximum at a scattering angle near 140°, a polarization value of 0 at a scattering angle of 90°, and supernumerary bows for scattering angles greater than 145°. Ice clouds are composed of non-spherical particles that demonstrate only moderate polarization that decreases with increasing scattering angle (Riedi *et al* 2010). Because polarization is not saturated below an optical depth of approximately 3, the POLDER technique is less accurate for thinner clouds and near cloud edges.

In this study, a dusty cloud is defined as either a cloud existing in a dust storm environment (i.e., dust is observed within 50 m of the cloud) or a cloud that has been contaminated by dust. The same selection criterion using combined CALIPSO and CloudSat data in Wang *et al* (2010) is adopted here. In summary, the CALIPSO layers of enhanced backscatter (Winker *et al* 2006) are used to identify either dust aerosol or cloud signatures. Then the CloudSat 2B-GEOPROF cloud mask data (Mace *et al* 2007) are used to confirm the presence of clouds to provide confidence in the dusty cloud scenarios. All data in this study meet the Wang *et al* (2010) criteria for dusty clouds.

Aqua, CALIPSO, and PARASOL are part of the NASA A-Train satellite constellation. These satellites fly in a close formation, providing near simultaneous observations of the same cloudy area that can be easily obtained and compared with each other. Table 1 lists the cloud phase products from the CALIPSO, AIRS, MODIS, and PARASOL, including cloud phase and product resolution and version. Because of the horizontal resolution difference, we follow the CALIPSO ground track and use the nearest-neighbor approach to spatially collocate the coincident observations between CALIPSO and AIRS, MODIS, and PARASOL. Recent efforts have shown the strengths and limitations of the instrumentation sensitivities to cloud phase determination (Baum *et al* 2012, Hu *et al* 2009, Jin and Nasiri 2014, Riedi *et al* 2010). AIRS C6 products, CALIPSO products, and MODIS C6 infrared products provide liquid, ice, and uncertain phases. While MODIS C5 products also tried to provide a ‘mixed-phase’ class, it was discontinued in MODIS C6 products. PARASOL, on the other hand, has demonstrated sensitivity to mixed-phase clouds.

A typical dusty cloud case, containing a complex cloud scene over the East Asia (China, Korea, and Japan), is displayed in figure 1. Because CALIPSO only makes near-nadir measurements, its track (in magenta) passes through the central part of the AIRS, MODIS, and PARASOL swaths. Figure 1(a) shows the Aqua MODIS true color red-green-blue (RGB) image for the granule at 0430 UTC 15 April 2008. It shows that a thin dust layer (slightly brown) and clouds (generally white) are observed simultaneously over the land in the scene. Although it is difficult to see the thin dust layer over the ocean in the MODIS RGB image, Cho *et al* (2013) reported low values of aerosol optical thickness and developed a novel method to detect the thin dust for the same case. Figures 1(b)–(e) show the cloud phase retrievals from CALIPSO, MODIS, PARASOL, and AIRS, respectively. As seen from the CALIPSO phase in figure 1(b), dust layers, water clouds and ice clouds reside at different levels from 25° to 50°N. A strong ice cloud signature around 10 km between 37.5° and 39°N is clearly identified.

From the figures 1(c)–(e), it is obviously seen that the cloud phase retrievals from MODIS, PARASOL, and AIRS demonstrate significant differences along and off the CALIPSO track. The major ice cloud feature generally shows a similar pattern for AIRS, MODIS and PARASOL, with all three capturing the ice cloud between 37.5° and 39°N. PARASOL finds some mixed-phase cloud pixels, while AIRS and MODIS identify them either as water or uncertain phase. Unlike MODIS and PARASOL, AIRS does not produce a cloud mask product. For this scene, the black ‘no retrieval’ color in the AIRS scene indicates regions where either the AIRS effective cloud fraction was less than the 0.01 threshold required to perform a phase retrieval or the land surface type was desert (Kahn *et al* 2014). In addition, the AIRS instrument reports a higher percentage of data in the uncertain category than MODIS and PARASOL. AIRS has a fairly large FOV, and the result for a given FOV will be labeled as ‘uncertain’ phase if there are no strong spectral sensitivities to either liquid water or ice clouds (Jin and Nasiri 2014); i.e., the measurements lead to an ambiguous result. The major cloud phase difference and ambiguity from these instruments is located on the edge of clear or cloudy region. This is likely due to the different instrumental sensitivities to dust and cloud, which can also lead to difficulties in retrieving consistent cloud optical and microphysical properties across the instruments.

3. Analysis and results

To detect when cloud phase has been modified by dust aerosols, the dusty cloud phase products from CALIPSO, AIRS, MODIS, and PARASOL are investigated over the dust source and downwind regions. The most common Asian dust storms arise from strong winds behind a cold front and generally coexist with cirrus clouds. These dust plumes often become entrained in the westerlies and are thus transported to the far open sea region. Figure 2 displays the desert source region (35°–45°N and 70°–110°E) and downwind region (35°–45°N and 120°–160°E). A total of 1079 and 1018 dusty cloud pixels were selected in the desert source and downwind regions between March

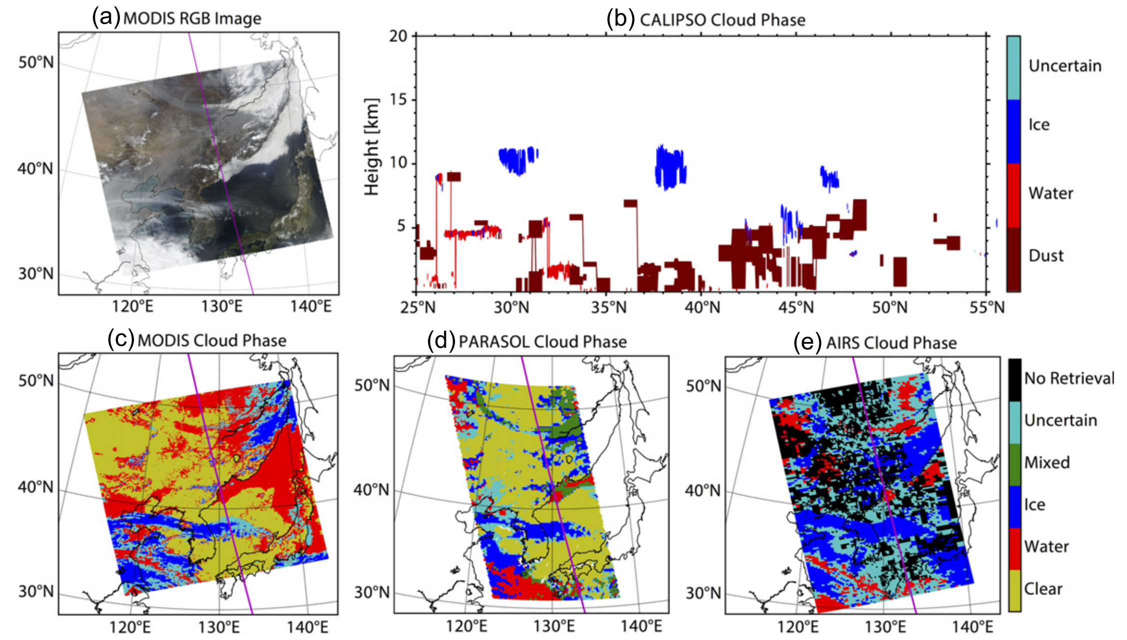


Figure 1. Dusty cloud case over southern part of China at 0430 UTC 15 April 2008. (a) MODIS true color image, (b) CALIPSO cloud phase profile, (c) MODIS infrared cloud phase, (d) PARASOL cloud phase, (e) AIRS cloud phase. The CALIPSO ground track in (a) and (c)–(e) is in magenta. In the colorbar, 'no retrieval' means that a retrieval was not made and 'clear' indicates clear sky.

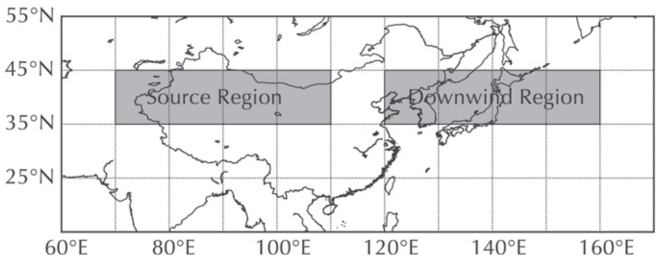


Figure 2. Source and downwind regions selected to compare dust effect on cloud phase.

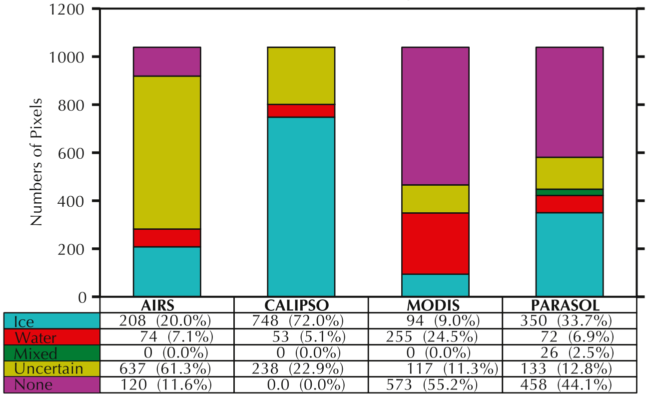
and May 2007 during the Pacific Dust Experiment (PACDEX).

Figure 3 shows cloud phase histograms derived from the AIRS, CALIPSO, MODIS, and PARASOL datasets. Ice and water phases are displayed in cyan and red, respectively. The frequency of each phase category is also provided in the parenthesis. A 'none' category (magenta bar) is also displayed, which means that the pixel is either clear sky or there was no phase retrieval. For instance, if a pixel is detected as dust, then no cloud phase will be output. The results show that the determined cloud phases from the four instruments are quite distinct over both the desert source and downwind regions.

Over the source region, figure 3(a) shows that CALIPSO determines about 72% of all the pixels as ice phase, whereas AIRS, MODIS, and PARASOL are about 20%, 9%, and 34%, respectively. These differences suggest that CALIPSO and PARASOL are more sensitive to ice than AIRS and MODIS for dust contaminated ice clouds, because the IR radiance is primarily sensitive to the upper ice cloud layer. If the dust layer exists within 50 m of the ice clouds within a FOV, the brightness temperature difference (BTD) approach to detect dust and clouds needs to be improved (Cho *et al* 2013, Huang *et al* 2007b) to reduce the misclassification between dust and clouds. We note that in general, operational cloud phase algorithms do not account for the potential presence of an absorbing aerosol co-existing with the cloud layer.

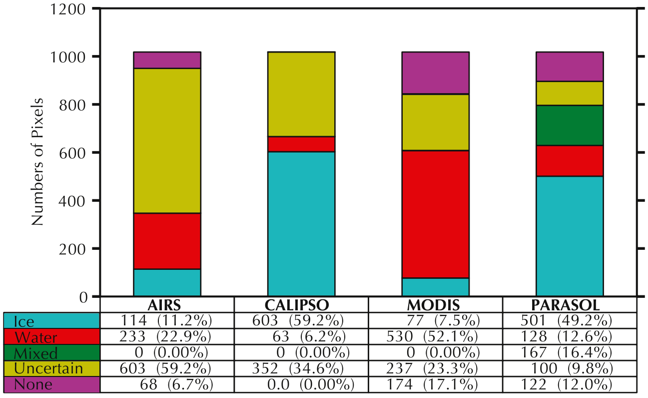
MODIS determines approximately 24.5% of all pixels as water phase, which is about 17%–18% higher than the other three instruments. The MODIS IR cloud phase heavily depends on the 11 and 8.5 μm channels in C5 products, which tend to misclassify optically thin cirrus clouds and opaque ice clouds with small particles as water clouds (Nasiri and Kahn 2008). In addition, PARASOL classifies about 2.5% of the dataset as mixed-phase clouds. In the recently released CALIPSO V3 and MODIS C6 datasets, the mixed-phase category has been merged into the uncertain category; hence there are no mixed-phase values in the

a) Source Region



	AIRS	CALIPSO	MODIS	PARASOL
Ice	208 (20.0%)	748 (72.0%)	94 (9.0%)	350 (33.7%)
Water	74 (7.1%)	53 (5.1%)	255 (24.5%)	72 (6.9%)
Mixed	0 (0.0%)	0 (0.0%)	0 (0.0%)	26 (2.5%)
Uncertain	637 (61.3%)	238 (22.9%)	117 (11.3%)	133 (12.8%)
None	120 (11.6%)	0.0 (0.0%)	573 (55.2%)	458 (44.1%)

b) Downwind Region



	AIRS	CALIPSO	MODIS	PARASOL
Ice	114 (11.2%)	603 (59.2%)	77 (7.5%)	501 (49.2%)
Water	233 (22.9%)	63 (6.2%)	530 (52.1%)	128 (12.6%)
Mixed	0 (0.00%)	0 (0.00%)	0 (0.00%)	167 (16.4%)
Uncertain	603 (59.2%)	352 (34.6%)	237 (23.3%)	100 (9.8%)
None	68 (6.7%)	0.0 (0.00%)	174 (17.1%)	122 (12.0%)

Figure 3. CALIPSO, MODIS, AIRS, and PARASOL cloud phase at the (a) source region and (b) downwind region. The category 'none' means no cloud phase retrievals. The number in the parenthesis is the fraction of each phase category within the total number of pixels in each region.

histograms for these instruments. Furthermore, AIRS determines about 61.3% of pixels as uncertain phase due to lack of spectral sensitivities (Jin and Nasiri 2014). Another major difference among the phase categories is that MODIS and PARASOL do not retrieve cloud phase for over 55% and 44% of all the pixels. Due to some spectral similarities between clouds and dust in passive remote sensing, it is possible that these pixels are being classified as clear sky instead of clouds by MODIS and PARASOL. AIRS, on the other hand, only has 11.6% as 'none' category mainly because AIRS cannot perform cloud phase retrievals over desert regions or for scenes with extremely low effective cloud fraction (Kahn *et al* 2014).

Figure 3(b) shows similar cloud phase histograms for the four satellite instruments over the downwind region. After long-range transport by the prevailing winds, a large portion of dust, particularly the large dust particles, falls out of the atmosphere through the dry and wet deposition processes. The finer dust aloft is carried much farther and higher by strong winds and, therefore, would likely affect the high clouds more than low clouds. Further, the optical properties of the clouds can change along the trajectory (Yi *et al* 2014). AIRS, CALIPSO, and MODIS determine about 11.2%, 59.2%, and 7.5% of ice phase in this area, which are clearly less than the source region. PARASOL, however, finds approximately 49.2% as ice phase, which is about 15% more ice compared to the source region. Additionally, the four instruments classify more water phase pixels than the source region, particularly from AIRS and MODIS. A possible explanation for this phenomenon is that there is more moisture over the downwind region than the source region and a variety of hydrophilic aerosols from anthropogenic sources can facilitate the formation of low water clouds, which are then retrieved by AIRS and MODIS infrared measurements. Another major signature is that fewer pixels are reported as the 'none' category for AIRS, MODIS, and PARASOL, indicating that the dust indeed affects the passive instruments to determine cloud phase for dusty clouds in the source region.

To compare the impact of dust on the determination of cloud phase, CALIPSO ice clouds are further investigated and compared in detail with AIRS, MODIS, and PARASOL in the desert source and downwind regions (table 2). The numbers in the parentheses are percentages of the pixels for each category. For those ice clouds as determined by CALIPSO, approximately 22.06% (9.95%), 12.17% (12.11%), and 39.84% (52.24%) of the pixels are inferred as

Table 2. CALIPSO ice clouds selected for source and downwind regions between March and May 2007. The sum of the numbers and frequencies of AIRS, MODIS, and PARASOL is the total number of CALIPSO ice pixels and 1. In the table, unc. and N/R refer to uncertain and no retrieval, respectively.

	AIRS phase				MODIS phase				PARASOL				
CALIPSO ice	Ice	Water	Unc.	N/R	Ice	Water	Unc.	N/R	Ice	Water	Mixed	Unc.	N/R
Source	165	54	447	82	91	204	102	351	298	53	15	105	277
748	(22.1%)	(7.2%)	(59.8%)	(11.0%)	(12.2%)	(27.3%)	(13.6%)	(46.9%)	(39.8%)	(7.1%)	(2.0%)	(14.0%)	(37.0%)
Downwind	60	118	387	38	73	277	184	69	315	79	111	45	53
603	(10.0%)	(19.6%)	(64.2%)	(6.3%)	(12.1%)	(45.9%)	(30.5%)	(11.4%)	(52.2%)	(13.1%)	(18.4%)	(7.5%)	(8.8%)

being ice by AIRS, MODIS, and PARASOL in the source region (downwind region), respectively. A recent study showed that over 77% of CALIPSO ice is determined as AIRS ice globally for one year of data (Jin and Nasiri 2014). The discrepancy between CALIPSO ice and AIRS ice for dusty clouds seems to be significantly influenced by the existence of dust. In addition, AIRS, MODIS, and PARASOL misclassify about 7.2% (19.6%), 27.3% (45.9%), and 7.1% (13.1%) of CALIPSO ice pixels as water in the source region (downwind region). Wang *et al* (2010) found that the dusty clouds have smaller particle sizes, lower optical depths and hence lower water paths compared to pure clouds, perhaps suggesting dust aerosol heating and cloud evaporation. This can lead to a reduction of large ice crystals in the ice clouds. In addition, the atmosphere and surface can also contribute to the IR radiation absorbed by and solar radiation reflected by optically thin ice clouds. Thus, the likelihood of ice clouds composed of small ice particles being classified as water clouds tends to be increased due to the presence of dust within the clouds.

4. Conclusions and discussion

This study presents the impacts of Asian dust on the determination of cloud phase for dusty clouds. Dust aerosols, one of the major atmospheric aerosol species, are important in climate studies through direct, indirect, and semi-direct mechanisms. Asian dust generated in the Taklimakan and Gobi deserts can be entrained and transported by westerly jets across eastern Asia and the Pacific. Once the dust enters the cloud in a dust storm or other lofting mechanism, they will form dusty clouds and participate in the cloud physical process as cloud condensation and ice nuclei as well as in an external mixture. As the dust aerosols heat the aerosol layer and cool the Earth's surface, the atmospheric stability within and above the boundary layer become unstable, resulting in enhanced vertical motion, which allows more dust particles to enter the atmosphere and clouds. Most dust detection algorithms based on passive remote sensing are effective in the case of and optically thick dust layer but may fail to differentiate optically thin dust from clouds (Cho *et al* 2013). Active remote sensing, such as CALIPSO, on the other hand, has greater sensitivity to a small loading of dust particles but may falsely classify a dense dust layer as cloud (Chen *et al* 2010). The CALIPSO algorithm does not permit both dust and clouds to exist in a given measurement. This can lead to ambiguities in cloud thermodynamic phase determination and cloud property retrievals from satellite platforms.

Analysis of A-Train satellite observations indicates that the discrepancy of cloud phase detection for dusty clouds in desert source and downwind regions is pronounced. CALIPSO products have a higher detection of ice clouds (source: ~70%; downwind: ~60%) as opposed to the IR based passive instruments. By measuring polarized shortwave radiation, PARASOL also demonstrates relatively higher sensitivity to ice clouds compared to AIRS and MODIS. A previous study indicates that the majority of the dusty ice clouds have optical depths greater than 5 with cloud effective temperature between 250–260 K (Wang *et al* 2010). These clouds with the simultaneous existence of dust particles can cause cloud phase ambiguity for AIRS and MODIS (Jin and Nasiri 2014, Nasiri and Kahn 2008). One of the key issues may be related to the dust aerosol warming effect through the absorption of solar radiation, causing the evaporation of cloud particles and reduction of cloud water path. This can further affect the redistribution of cloud particles, leading to the difficulties in determining cloud phase for dusty clouds from satellite observations. The results presented here represent only a first step in better understanding the cloud feedbacks of dusty clouds on climate. Further research should be focused on detecting dusty cloud phase with synergy observations (Riedi *et al* 2010) and the physical processes of dust induced cloud phase modification.

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