Evaluation of the Effect of Upper-Level Cirrus Clouds on Satellite Retrievals of Low-Level Cloud Droplet Effective Radius

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Introduction

The earth's radiation budget is sensitive to changes in the microphysical properties of low-level stratiform clouds. Their extensive coverage can significantly reduce the solar energy absorbed by the earth system. An estimate of reducing the global-mean droplet effective radius (r_e) of these low-level clouds by ~2 µm, while keeping the column liquid water constant would balance the warming due to CO_2 doubling in the atmosphere (Slingo 1990). Accurate determination of the droplet r_e of low-level clouds is hence essential in radiative transfer and climate modeling studies.

Satellite observations have been the primary source for routinely obtaining cloud droplet r_e on a large spatial scale. However, due to the ubiquitous presence of ice clouds that regularly cover ~20-30% of the globe, almost a third of the global cloud cover resides in upper-level clouds and yet, half of this coverage is in the form of optically thin cirrus (Hartmann et al. 1992). These upper-level thin cirrus clouds may have a large impact on the emitted radiation and solar radiative transfer when absorption by ice crystal is significant. Distinguishing thin cirrus clouds from satellite measurements is especially challenging owing to the wide range of ice particle sizes and shapes and their various scattering and absorbing properties. The large spatial and temporal variability of cirrus emittances and optical thickness make cloud property retrieval a difficult task. The task becomes even more difficult when the cirrus clouds are simultaneously overlain with low-level water clouds. Despite these challenges, our capability of remote-sensing cloud properties from space can be enhanced with the National Aeronautics and Space Administration (NASA) moderate-resolution imaging spectrometer (MODIS) satellite observations, which provide cloud images at 36 bands of high spectral resolutions located between 0.415-14.2 µm (King et al. 1992).

In this preliminary study, the effects of thin cirrus clouds on satellite retrievals of low-level cloud droplet r_e are evaluated by comparing between the retrievals with a correction of cirrus effect and those without the correction. The evaluations were of the retrievals made by the MODIS at 1.65, 2.15, and

3.75 µm. The existence of cirrus clouds was identified using MODIS 1.38-µm measurements. Such cirrus detection is impossible for the advanced very high resolution radiometer (AVHRR) satellite retrievals without a 1.38-µm channel. The conventional threshold methods that are commonly applied to observations at visible and infrared channels for cloud type classification is not optimal for discriminating the contamination of upper-level thin ice clouds. The evaluation focuses on the MODIS overcast pixels that were both covered by low-level clouds and contaminated by thin cirrus with an optical depth in the range of 0.2-0.5.

Radiative Transfer Model

Lookup tables of modelled reflectances and emissions were calculated for MODIS 0.63, 1.65, 2.15, 3.75, 11, and 1.38-µm channels by employing an adding-doubling radiative transfer model. The atmospheric column was divided into 12 vertical layers with the cirrus cloud layer placed at 10 km. Low-level water-cloud layer were placed at five different altitudes from zero to 5 km. Mie theory and lognormal droplet size distribution were adopted to calculate the water cloud optical properties for 18 droplet r_e and 23 cloud optical depths. Atmospheric transmission and scattering properties were calculated using the moderate-resolution atmospheric radiance and transmittance model 4. Lambertian surface reflection was assumed, but the cloud property retrievals were insensitive to the uncertainty in surface reflectance.

The cirrus optical properties were following the MODIS Algorithm Theoretical Basis Document (King et al. 1997). Figure 1 shows the refractive indices of real and imaginary parts for water and ice in the visible and near-infrared wavelengths (0.5-4.5 µm). The refractive indices are appreciably different between water and ice at wavelengths of 1.65, 2.15, and 3.75 µm. Notably, ice has a much larger absorption at 1.65 µm than water as seen in Figure 1b for the imaginary part of refractive indices. The extinction coefficients, single-scattering albedos, and asymmetry parameters for the cirrus clouds are listed in Table 1.

Figure 2 shows the model-calculated reflectances at 0.63 µm (x-axis) versus (a) 3.75 µm, (b) 2.15 µm, and (c) 1.65 µm for low-level clouds with various cloud optical depths of 6, 12, 24, 48, and 96 and droplet effective radii of 4, 10, and 20 µm, respectively. Such reflectance sensitivities have been presented in many previous studies (e.g., Arking and Childs 1985; Nakajima and King 1990; Platnick and Twomey 1994; Han et al. 1994). Also plotted in the figure (dashed curves) is the similar reflectance, which was calculated with an overlaying thin cirrus layer of cloud optical depth at 0.5 placed at 10-km altitude. The effects of the thin cirrus above the low-level water clouds are small at the 0.63-µm visible wavelength, but significantly reduce the reflectances at near-infrared wavelengths.

Data Analysis

The MODIS satellite observations on April 2, 2001, passing over the Oklahoma Southern Great Plains (SGP) site of the U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) Program were analyzed to examine the effects of thin cirrus clouds on the retrievals of low-level cloud droplet r_e. The ARM SGP site was overcast by a low-level stratus cloud layer on this date as observed

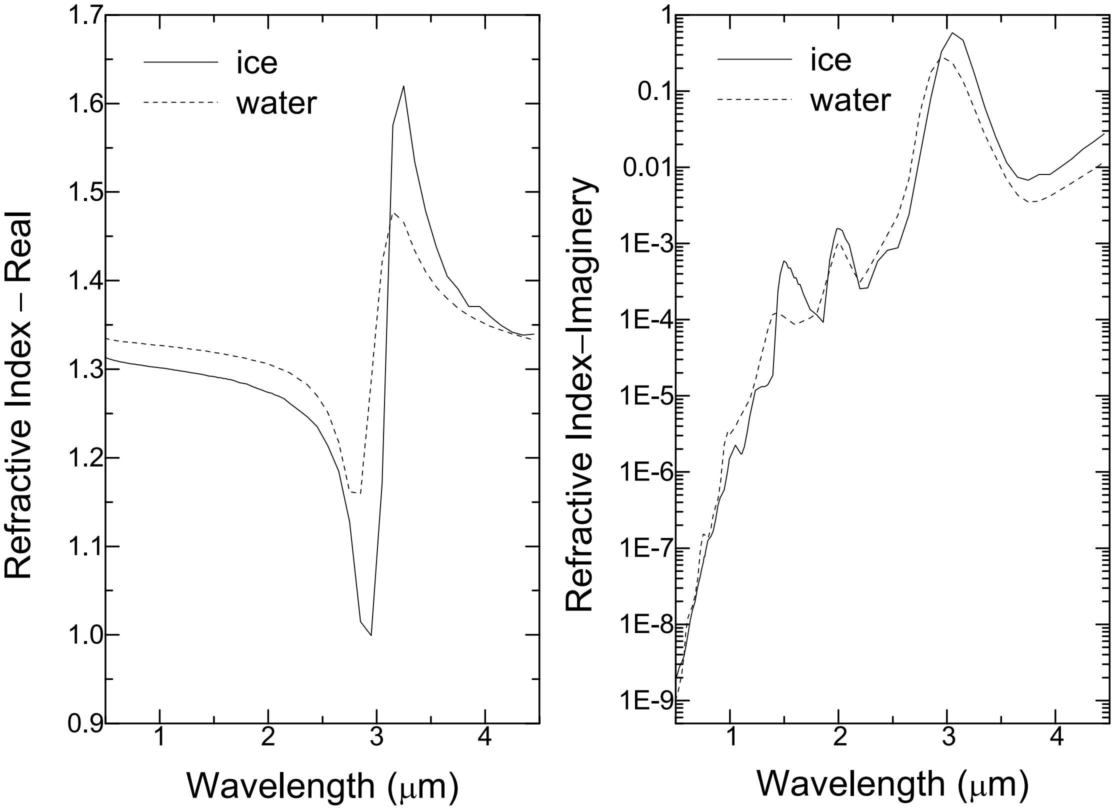

Figure 1. Refractive indices of water and ice.

Table 1. Single-scattering albedos (ω_0) and asymmetry parameters (g) for a water cloud model (front) with r_e = 10 μm and the cirrus model (rear).

λ (μm)	ω_0	g
0.63	1.00000/1.00000	0.8628/0.8458
1.65	0.99414/0.93823	0.8442/0.8742
2.15	0.97613/0.91056	0.8401/0.8904
3.75	0.89983/0.79240	0.7944/0.9003
11.0	0.47706/0.54167	0.9229/0.9574

by ground radar measurements. Some upper-level thin cirrus clouds covered the area, indicated in the MODIS 1.38-μm satellite image (not shown). The MODIS satellite pixels that were overcast by the low-level stratus system were identified based on the spatial coherence method (Coakley and Bretherton 1982).

Figure 3 shows the spatial coherence analyses of the MODIS observations at 0.63, 1.38, 1.65, and 11-μm channels for an area of ~(100 km)^2. In the spatial coherence analysis, for instance, the foot appeared in the scatter plots at near 80 for the 11-μm emission (Figure 3d), and the foot near 0.5 for the 1.65-μm reflectance (Figure 3b), is associated with the low-level stratus cloud layer. The pixels

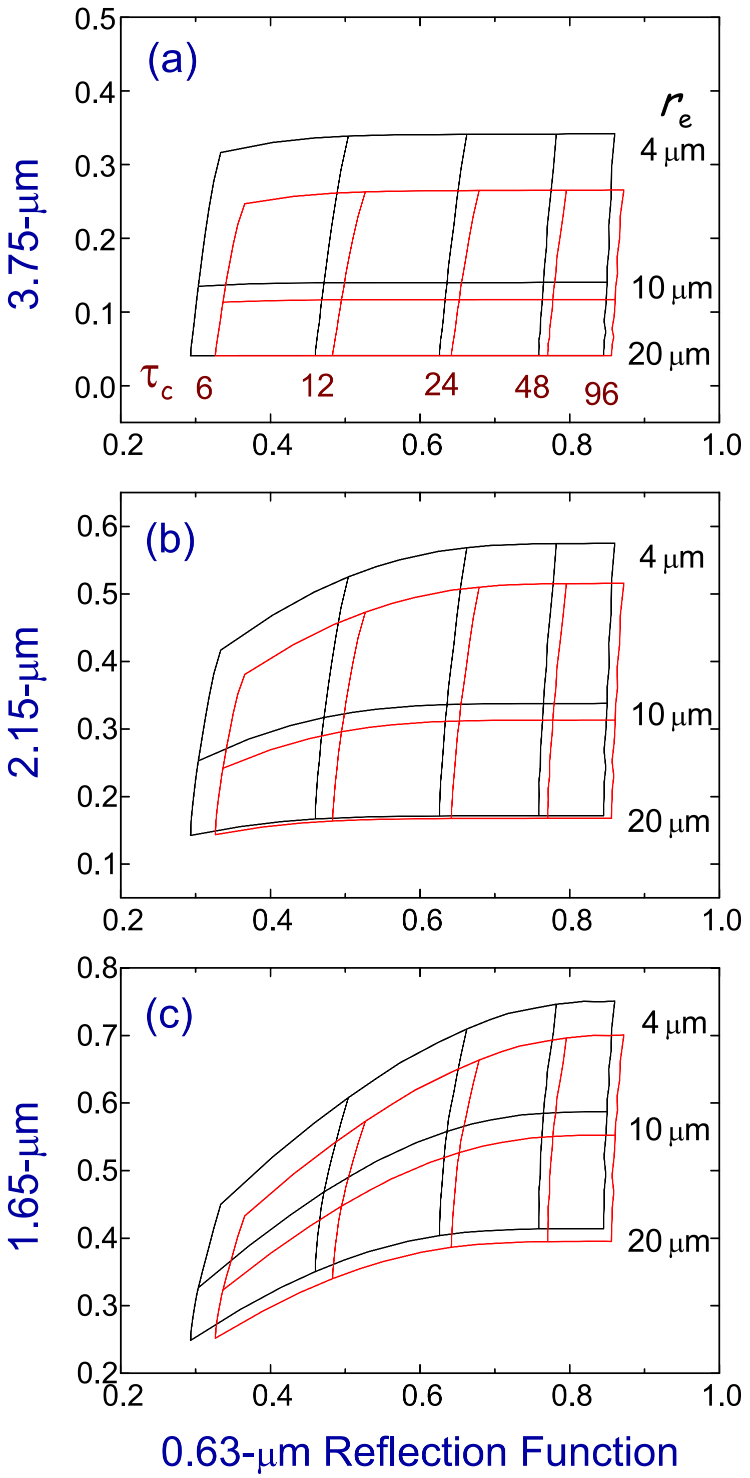

Figure 2. Theoretical 3.75-, 2.15-, 1.65-, and 0.63-μm reflectances for a low-level stratus cloud layer for various cloud optical depths of 6, 12, 24, 48, and 96 and droplet effective radii of 4, 10, and 20 μm. The reflectances were calculated for two cases, one with an overlaying thin cirrus (red) and another without the cirrus (black).

appearing in Figure 3d with the 11-µm emissions colder than 80 with large standard deviations were attributed to cirrus contaminations. However, in this study, cirrus contaminations were determined by applying threshold technique to the MODIS 1.38-µm reflectance measurements. Only cirrus-contaminated pixels with thin cirrus cloud optical depths ranging between 0.2 and 0.5 were selected for this study. The cirrus cloud optical depths were calculated by comparing the MODIS 1.38-µm reflectance measurements with radiation model calculations.

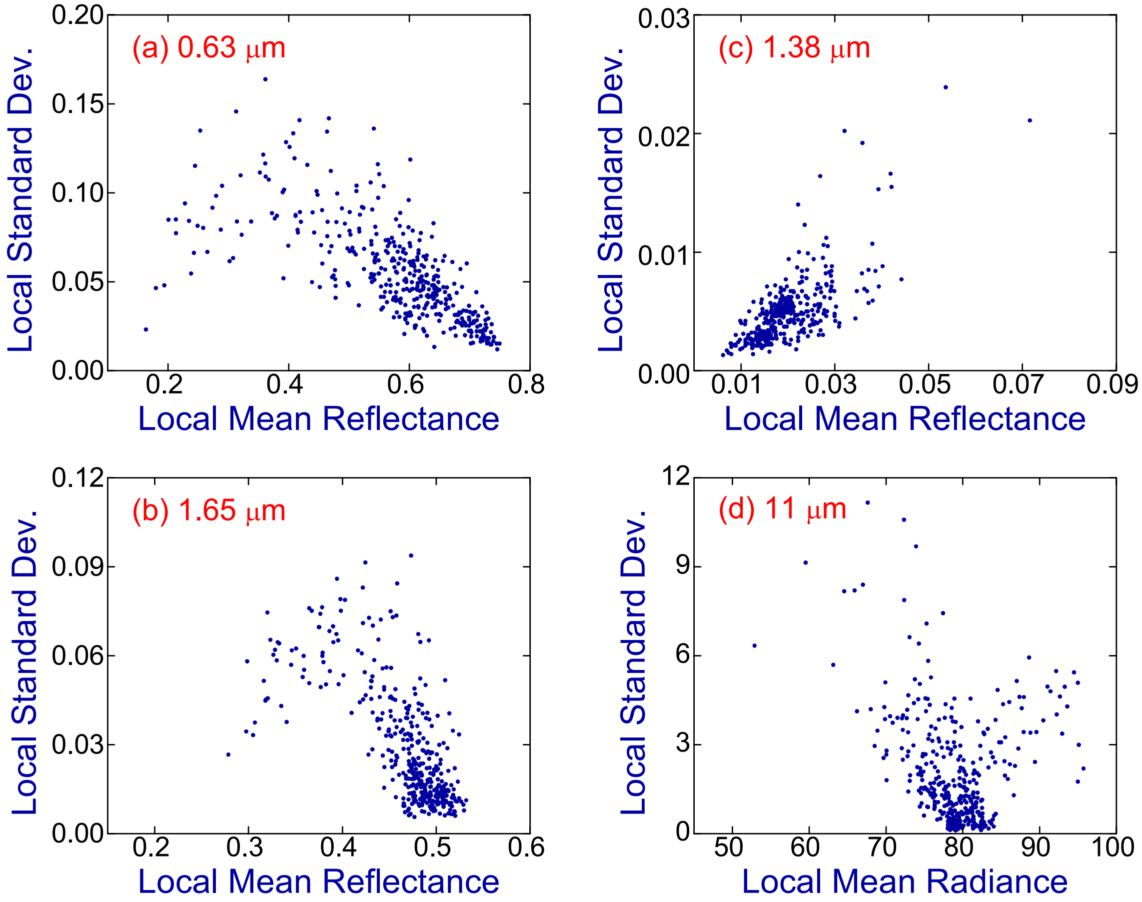

Figure 3. The spatial coherence analyses of the MODIS 5 × 5 pixel arrays taken from an area of ~(100 km)^2 over the ARM SGP site on April 2, 2001.

Results

Figure 4 shows comparisons of the retrieved cloud droplet r_e with and without correction of the thin cirrus effect. The largest effects of thin cirrus contaminations were found in the 1.65-µm retrievals as shown in Figure 4a. The mean droplet r_e was reduced from 12.7 µm to 10.0 µm after correcting for the cirrus effects. For the 2.15-µm retrievals, the mean r_e reduced from 11.0 µm to 9.5 µm after the correction. The effects seemed to be the smallest with the 3.75-µm retrievals, which was attributable to a counteract effect in subtracting the emission contributions in the 3.75-µm radiance measurements. As

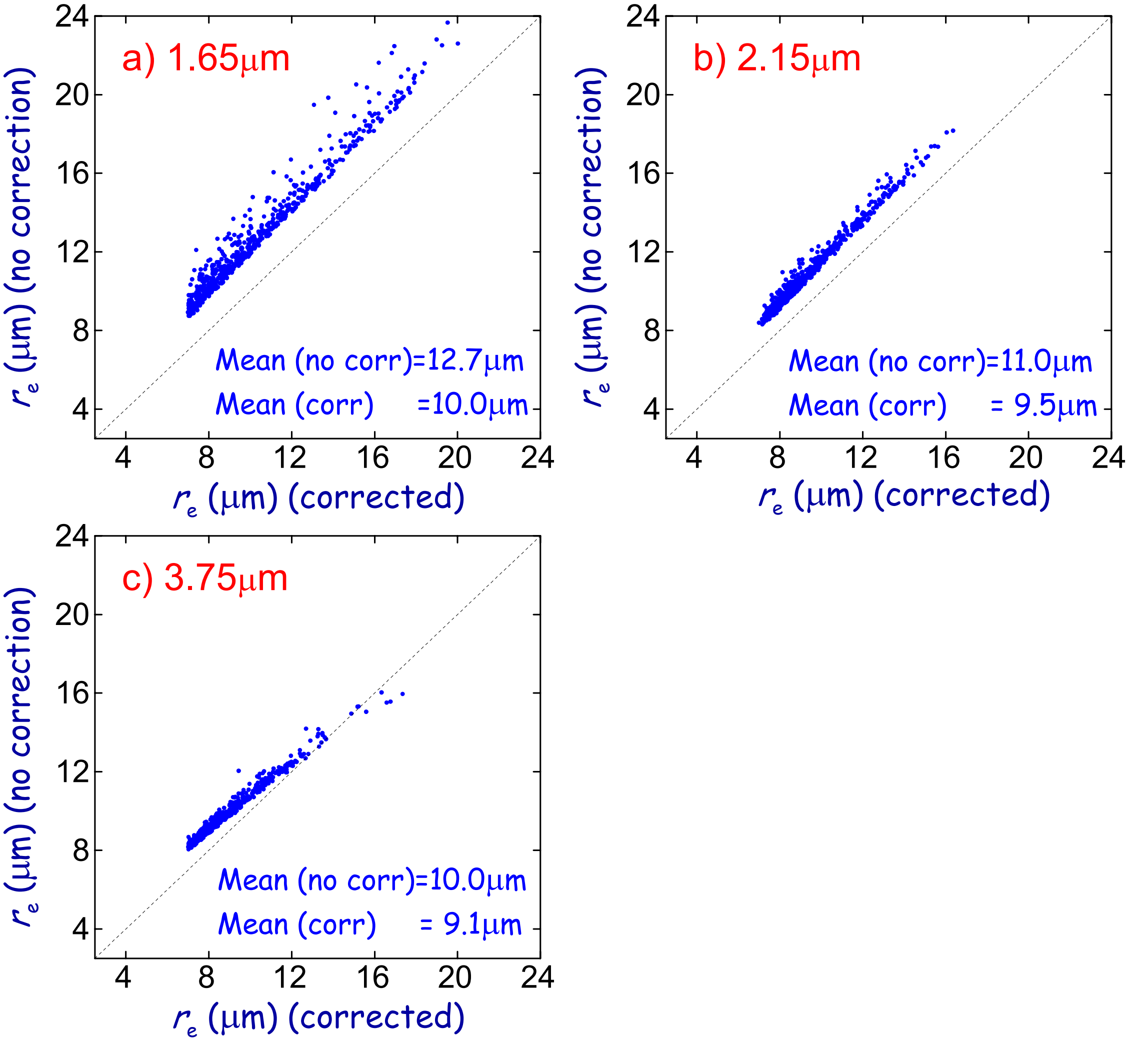

Figure 4. Comparisons of the MODIS satellite-retrieved droplet effective radii with a correction of the cirrus effect (x-axis) and without the correction (y-axis). Results are shown for the retrievals obtained using a) 1.65, b) 2.15, and c) 3.75 µm.

the 3.75-µm measured radiance contained both solar reflectance and commeasuring thermal emission, it is required to remove the unwanted emission. Such removal relies on the accurate determination of cloud emission temperature, which is usually retrieved from the 11-µm measurement. However, when a pixel is contaminated by upper-level thin cirrus, the 11-µm retrieved cloud top temperature will be significantly colder than the low-level cloud temperature. As a result, the subtraction of the 3.75-µm emission contribution will be underestimated, leading to an overestimation in the 3.75-µm solar reflectance. This overestimation creates an offsetting effect and compensates the actual reduction in the 3.75-µm reflectance caused by the thin cirrus contamination.

Figure 5 shows the effects of thin cirrus contaminations on the retrievals of cloud top temperature (Figure 5a) and cloud optical depth (Figure 5b). As shown in Figure 5a, the 11-µm retrieved cloud temperatures were much colder with no correction for the cirrus effect. The mean cloud temperature was ~270.6 K for no correction, which was 9.1 K colder than the mean cloud temperature of 279.7 K with the correction. The effect on cloud optical depth retrieval, as shown in Figure 5b, is less significant because both the ice and water were nonabsorbing in the visible wavelengths.

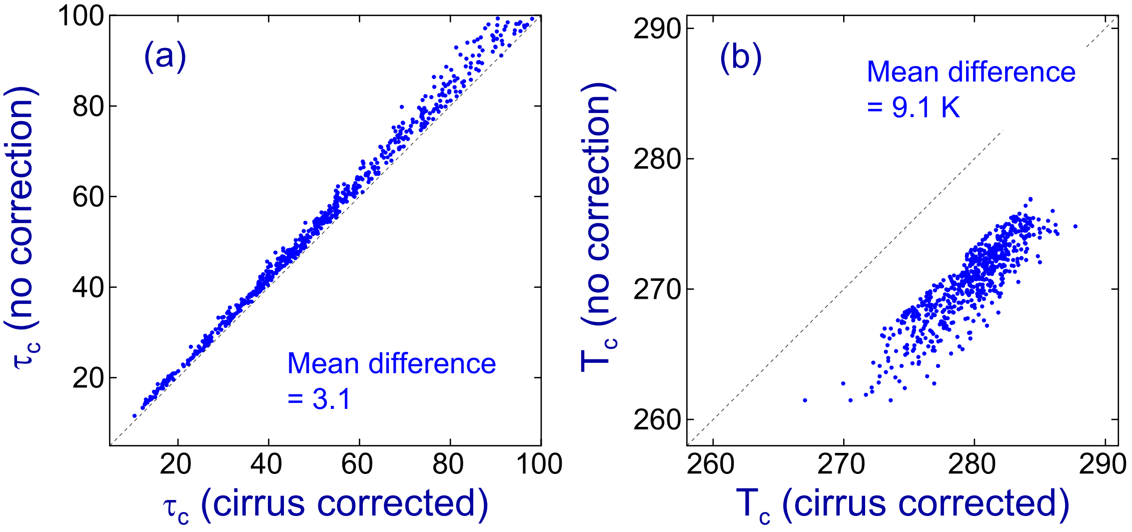

Figure 5. Comparisons of the MODIS satellite-retrieved (a) cloud emission temperatures (Tc) and (b) cloud optical depths (τ_c) with a cirrus correction (x-axis) and without the correction (y-axis).

Conclusions

Water and ice are nonabsorbing and therefore transparent in the visible wavelengths of the spectrum. They begin to absorb appreciably in the near-infrared spectrum, in particularly at 1.65, 2.15, and 3.75 µm. Yet, the spectral reflectances at these near-infrared wavelengths differ between water and ice clouds; the retrieval of low-level cloud droplet r_e requires meticulous cloud-type classifications. As threshold techniques are commonly applied to satellite observations at visible and infrared channels for cloud type classification, the method is subject to the contamination of upper-level thin cirrus clouds that reside above the low-level water cloud system. While such thin cirrus clouds have weak effects on cloud optical depth retrievals, their influence on the retrievals of cloud droplet r_e and emission temperature may be rather significant. As satellite measurements are dictated primarily by cloud particles encountered first, high-level thin cirrus containing mostly large ice crystals will absorb significant solar reflectances. The contamination of thin cirrus clouds can reduce the solar reflectances at above-mentioned near-infrared wavelengths and cause overestimates in satellite-retrieved droplet r_e when the pixels were assumed to be only covered by low-level water clouds. The overestimation was found most significant in the 1.65-µm retrievals ($\Delta r_e \approx 2.7$ µm) as compared to 2.15- ($\Delta r_e \approx 1.5$ µm) and 3.75-µm retrievals ($\Delta r_e \approx 0.9$ µm). The upper-level thin cirrus clouds were found to have an offset effect on the 3.75-µm retrievals when the emitted radiances in the 3.75-µm measurements were subtracted.

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