Comparing the Overlapped Cloud Top Altitudes Deduced from A Satellite-Based Retrieval Scheme with Atmospheric Radiation Measurement Ground-Based Measurement

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Introduction

The overlapping of high-level cirrus cloud and low-level stratus cloud has posed a major challenge in determining their cloud top altitudes using passive satellite observations. Chang and Li (2005) present a novel satellite retrieval method that takes advantage of the Moderate Resolution Imaging Spectroradiometer (MODIS) data to detect the presence of overlapped cirrus and stratus clouds and determine their cloud top properties using combined information acquired from the MODIS CO_2-slicing channels and the visible and infrared window channels. The cloud top height of high-level cirrus cloud is determined from the CO_2-slicing retrieval and the cloud top altitude of the lower stratus clouds is estimated from its neighboring cloudy pixels that are identified as single-layer stratus clouds. The Atmospheric Radiation Measurement (ARM) Active Remotely-Sensed Cloud Locations (ARSCL) Value-Added Product (Clothiaux et al. 2000) combines ground-based active measurements from laser ceilometers, microwave radiometers, and micropulse lidars and produces an objective determination of cloud height information.

This study is concerned with the validation of the satellite inverse-retrieved cirrus and stratus cloud top altitudes based on the method of Chang and Li (2005) under situations when the two cloud types are overlapped. Because satellite observations are snapshot measurements, the comparisons are achieved by means of averaging the ground-based vertical-pointing measurements over a period of time at ± 15 minutes of the MODIS overpass.

The Method of Chang and Li (2005)

Fundamental information concerning the presence of overlapped clouds in the MODIS cloud data is obtained by combining information of cloud-top pressure (Pc) and temperature (Tc) retrieved from the

CO_2-slicing method (Menzel et. al. 2002) for cirrus clouds and from the 11-µm channel for low clouds (King et al. 2003; Platnick et. al. 2003). A cloud-column total optical depth is retrieved from a visible channel.

Figure 1 shows an example of the information contained in a 5-minute satellite overpass (granule) of the Terra/MODIS data. The images are constructed for a) the 0.65-µm visible reflectance, b) the 11-µm infrared brightness temperature, and c) the retrieved Tc data obtained from (MOD06, Collection 4). The data was acquired on 2 April 2001 (1715 UTC), and covers an area of approximately 4000 km × 4000 km with the part of the ARM Climate Research Facility (ACRF) Southern Great Plains (SGP) site marked by the boxed area that centered at about (36.6°N, 97.5°W). In the images, clouds appear brighter with larger 0.65-µm reflectances and colder 11-µm brightness temperatures. Due to semi-transparency of the thin cirrus clouds, the MODIS Tc data as seen in Figure 1c reveal more high-cold clouds from the CO_2-slicing retrieval than what is revealed by the 11-µm brightness temperature as seen in Figure 1b.

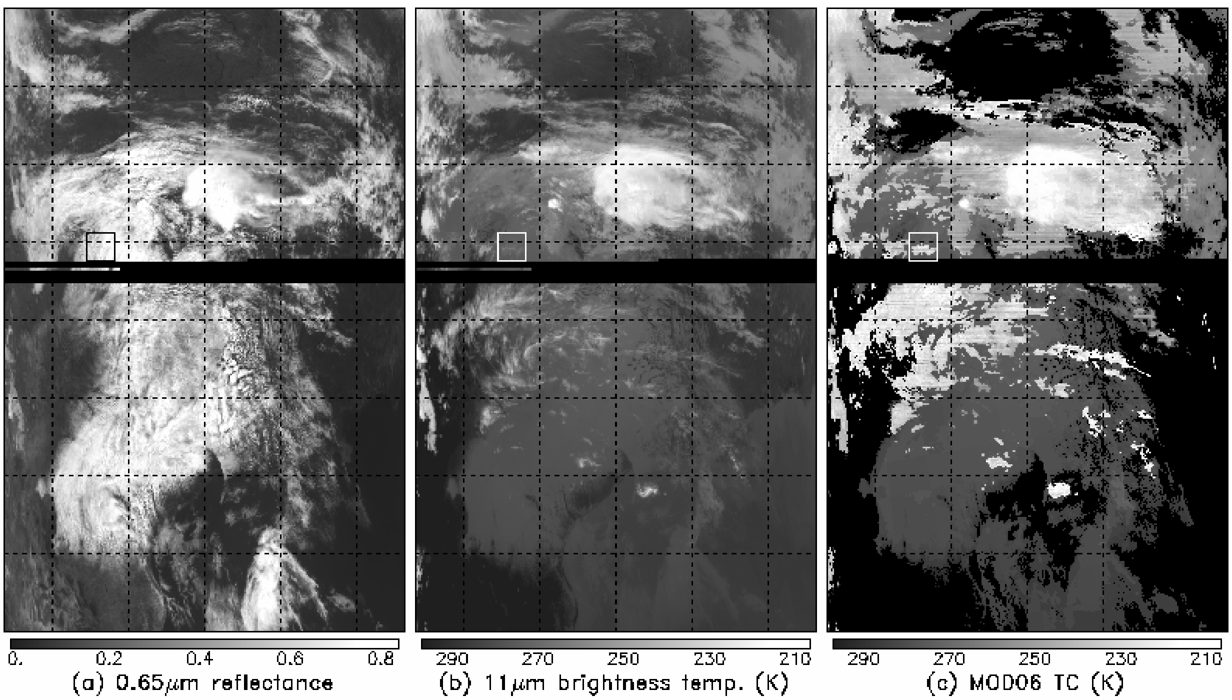

Figure 1. MODIS images (5-minute orbital passes ~1350 × 2000 pixels) constructed for the a) 0.65-µm reflectance, b) 11-µm brightness temperature (K), and c) retrieved cloud top temperature (K) obtained on 2 April 2001 (1715 UTC). The boxed area ~$(100\ km)^2$ is centered on the ACRF SGP site (36.6°N, 97.5°W). Dashed lines are for every 250 × 250 pixels.

Figure 2 illustrates the new method of Chang and Li (2005) in a flow chart diagram. The method classifies all high clouds having Pc < 500 hPa into three different categories of 1) High1: single-layer cirrus cloud (infrared cloud emissivity < 0.85 or cirrus optical depth < ~4), 2) High2: overlapped cirrus cloud (infrared cloud emissivity < 0.85 or cirrus optical depth < ~4), and 3) High3: thick high cloud

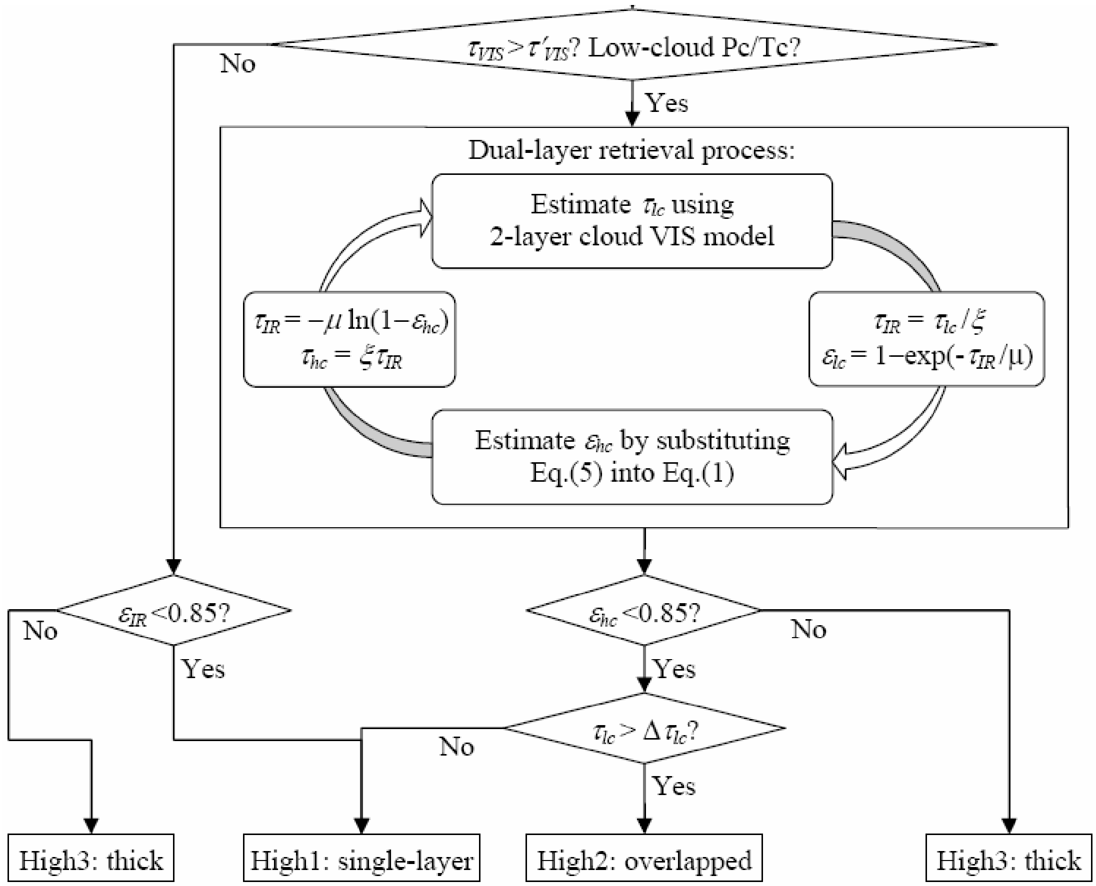

Figure 2. Schematic illustration of the retrieval algorithm, following Chang and Li (2005a).

(infrared cloud emissivity ≥ 0.85 or high-cloud optical depth > ~4). One basic fundamental in differentiating the single-layer cirrus and overlapped cirrus clouds are examining the differences between the total cloud-column optical depth (τ_{VIS}) and the cirrus-layer cloud optical depth (τ'_{VIS}). The total cloud-column optical depth (τ_{VIS}) is retrieved from the visible reflectance. The cirrus-layer cloud optical depth (τ'_{VIS}) is retrieved based on the infrared emissivity of cirrus clouds. Figure 3 shows the comparisons of the two cloud optical depths (τ_{VIS} versus τ'_{VIS}) for a) an overlapping cirrus cloud system with underlying thick-water cloud system and b) a single-layered cirrus cloud system with no overlapping. It is clearly seen that in Figure 3a the total cloud-column optical depths (τ_{VIS}) for all the MODIS pixels are much larger than the cirrus-layer cloud optical depth (τ'_{VIS}), whereas in Figure 3b the two optical depths for single-layer cirrus clouds are very similar. More details of the retrieval algorithm and radiative transfer modeling are given in the paper by Chang and Li (2005).

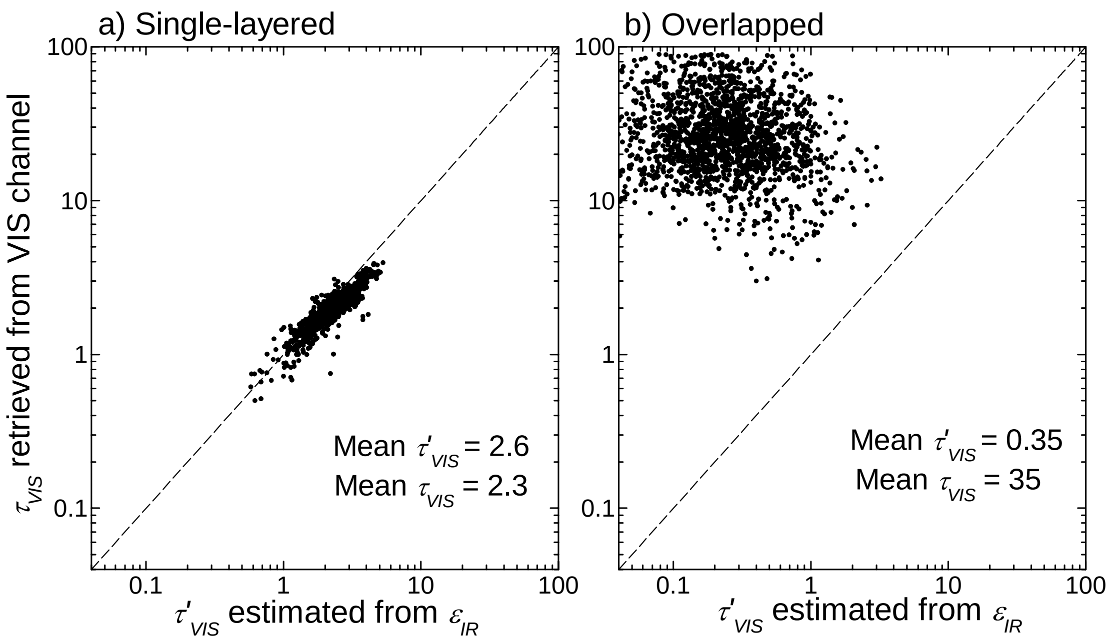

Figure 3. Comparisons of MODIS-retrieved τ_{VIS} versus τ'_{VIS} for a) a single-layer cirrus cloud system observed on 2 April 2001 and b) a cirrus-overlapping-stratus cloud system observed on 31 May 2001.

Comparisons of Cloud Layers

The method of Chang and Li (2005) classifies all high clouds with PC < 500 hPa into three categories of 1) High1: single-layer cirrus cloud (cirrus optical depth < 4), 2) High2: overlapped cirrus cloud (cirrus optical depth < 4), and 3) High3: thick high cloud (high-cloud optical depth > 4). The method is validated for the MODIS data obtained over the ACRF SGP site between March and November 2003. The overcast scene selections are based on the MODIS retrievals that have a cirrus TC < 500 hPa. In our analyses, we found a total of 20 single-layer cirrus cases, 21 overlapped cirrus cases, and 13 thick high cloud cases. In verifying our cloud classifications, we found that three of our 20 single-layer cirrus cases had overlapped cirrus and low clouds as identified by the ARSCL, while 17 of our 21 overlapped cases are confirmed by the ARSCL with overlapped cases. For our four other overlapped cirrus cases, the ARSCL identifies one as single-layer low cloud while the other three as single-layer high cloud only. This difference can be caused by the different spatial domain “seen” by the MODIS (~5 km area) and a vertical point “seen” by the ARSCL. Also, 5 of our 13 thick-high cloud cases contained single-layered high clouds and the other eight contained overlapped high and low clouds.

Comparisons of Cloud Top Pressures and Temperatures

For the overlapped cirrus-and-low cloud cases, Figure 4 shows the comparisons of our MODIS retrievals against the ARSCL mean values and standard deviations in terms of high-cloud PC (P_{hc}) and low-cloud Pc (P_{lc}) as shown in Figure 4a and in terms of high-cloud Tc (T_{hc}) and low-cloud Tc (T_{lc}) as shown in Figure 4b. Note that for ARSCL, P_{hc} and T_{hc} are calculated for the topmost layer while P_{lc} and T_{lc} are calculated for all underlying clouds below the topmost layer. In general, our overlapped retrievals from the MODIS data are on average biased lower in both high- and low-cloud top heights (i.e., larger in Pc and Tc) in comparisons with the ARSCL data. However, the overall comparisons of mean cloud top height exhibit reasonable agreements for both high and low clouds.

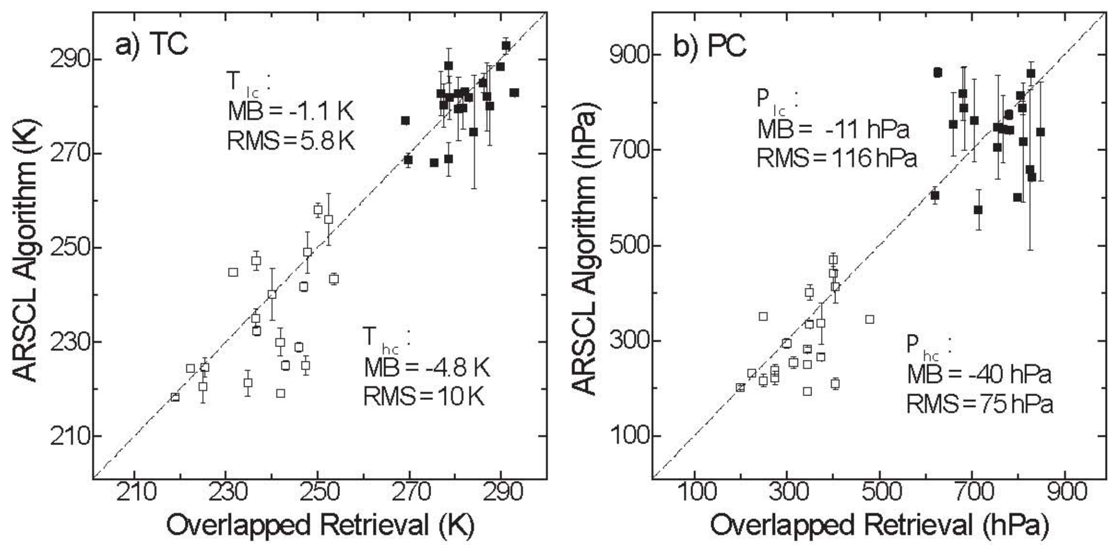

Figure 4. Comparisons of a) Tc and b) Pc for overlapped high (open squares, T_{hc} and P_{hc}) and low (solid squares, T_{lc} and P_{lc}) cloud cases observed at the ARM SGP Cloud and Radiation Testbed site.

Figure 5 compares our MODIS retrievals (red) and the ARSCL data (blue) for the composite statistics of frequency occurrence of cloud top height obtained during the entire month of April 2001 at the ACRF SGP site. The ARSCL data are collected within ±1 hour of the *Terra*/MODIS overpass time at the SGP site; whereas the MODIS Pc data are collected over a spatial domain of ~(100 km)^2 centered at the SGP site. The differences between the two data platforms are mainly caused by their different temporal and spatial sampling. Even so, both the ARSCL and MODIS data clearly show a bimodal characteristic of high and low cloud Pc distribution. The causes for this distinctive bimodal cloud-top vertical distribution warrant further investigation.

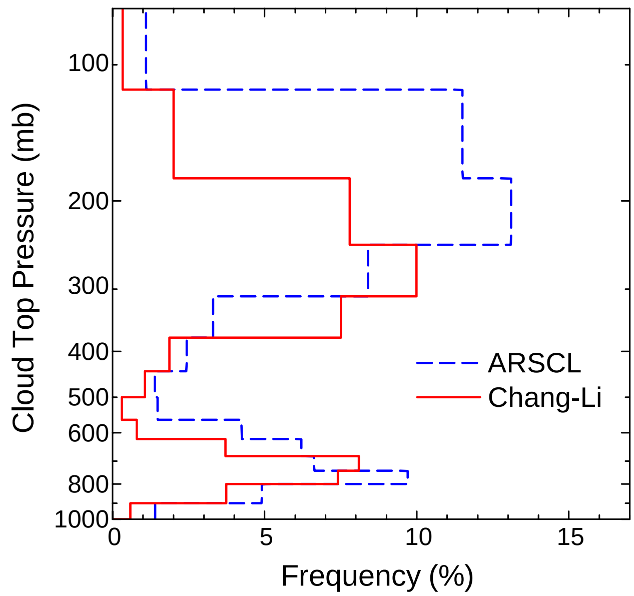

Figure 5. Comparisons of the frequency occurrence of cloud top pressure derived from the ARSCL and the overlapped retrieval based on the Chang and Li method for April 2001 at the SGP site.

Concluding Remarks

Conventional satellite cloud retrieval methods use radiative transfer models that assume a single-layer cloud, which cannot deal with cloud systems having more than one layer. There is high frequency of occurrence of cirrus clouds (optically thin) that are overlapping with lower-level water clouds (often optically thicker). Overlapping the two creates a serious problem for the assumption of a single-layer cloud, which would be forced to place the single cloud top at some inter-median height between the cirrus and lower water clouds. The innovative method of Chang and Li (2005) is developed to resolve this particular cirrus-overlapping-water cloud configuration. One important aspect of the method is that it determines the cirrus cloud top height using the MODIS CO_2-slicing technique. Errors in the CO_2-slicing retrievals would certainly affect our retrievals of the overlapped cloud properties.

Our preliminary validation showed that both cloud top heights of many overlapped cirrus-and-water cloud cases show good agreement in comparisons with the ground-based ARSCL acquired in north-central Oklahoma under the U.S. Department of Energy's ARM Program. This method can overcome or reduce some major shortcomings of the conventional single-layer methods and provide more accurate information on cloud layer structure. Further comparisons between the MODIS-retrievals and ARSCL ground-based measurements will be compared for observations made at other ACRF sites.

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