Detecting Cirrus-Overlapping-Water Clouds and Retrieving their Optical Properties Using MODIS Data

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Introduction

Different methods have been proposed to detect multilayer clouds using passive remote sensing data. Baum et al. (1995) used the CO_2-slicing technique applied to the High Resolution Infrared Radiation Sounder (HIRS) data to determine cirrus cloud heights. The spatial coherence technique (Coakley and Bretherton 1982) was applied to the advanced very high resolution radiometer (AVHRR) data to determine low cloud heights. Ou et al. (1996) presented a threshold test scheme to distinguish AVHRR pixels that contain overlapped clouds and non-overlapped low and high clouds. Baum and Spinhirne (2000) used a bispectral method on moderate-resolution imaging spectroradiometer (MODIS) airborne simulator (MAS) 1.6-µm and 11-µm data to identify areas containing overlapped clouds. All of these methods were focused on detecting overlapped clouds but not on the retrieval of cloud optical depth. Also, no methods have been applied over extensive areas or long time periods. Other algorithms used a combination of microwave, visible, and infrared measurements (Sheu et al. 1997; Lin et al. 1998; Ho et al. 2003) but were restricted to high thick clouds only over the ocean.

Global cloud climatologies over ocean and land have been generated using data from the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999) and the MODIS (King et al. 2003; Platnick et al. 2003). The ISCCP scheme relies essentially on one infrared channel (~11 µm) to retrieve cloud-top height and one visible channel (~0.6 µm) to retrieve cloud optical depth. Both channels are common to all weather satellite sensors. Because cirrus clouds are mostly semitransparent at infrared wavelengths, the measured brightness temperatures are usually warmer than the ambient temperatures of the cirrus clouds but colder than the water clouds. Consequently, using this channel alone would place the cloud-top height between the two layers. To account for the cirrus emissivity, an attempt was made to improve the retrieval of cirrus cloud-top heights using optical depths retrieved from the visible channel (Rossow and Schiffer 1999). This somewhat alleviates the problem but does not solve it because of fundamental limits in the information content. For thin cirrus clouds overlapping thick water clouds, the lower clouds overwhelm the signal in the visible channel.

For MODIS, cirrus cloud-top heights are retrieved using the partially absorbing multispectral infrared channels near the 15-μm CO_2 absorption bands; this retrieval scheme is known as the CO_2-slicing technique. The MODIS cloud optical depth is retrieved from different channels for different surface types, i.e., 0.65 μm over land, 0.86 μm over ocean, and 1.24 μm for ice/snow surface (Platnick et al. 2003). The CO_2-slicing technique was applied to the HIRS data (e.g., Menzel et al. 1992; Baum and Wielicki 1994). Similar to other retrieval methods, the standard CO_2-slicing technique assumes a single-layer cloud. Given a satellite's viewpoint from space, clouds highest in the atmosphere are preferentially detected. Thus, the majority of low clouds underlying high clouds are obscured and neglected. Because the CO_2-slicing method is very sensitive to clouds at the highest altitude, a high thick cloud would be identified based on the retrieved optical depth.

Detection of Overlapped Clouds

Our algorithm is conceptually similar to that of Baum et al. (1995), but it differs technically in many aspects. To identify multilayer cirrus cloud systems, Baum et al. (1995) applied the CO_2-slicing technique to the HIRS data for determining the cirrus cloud-top altitudes and their infrared effective emissivities. They then developed a fuzzy logic technique using AVHRR data to discriminate between single-layer high or low clouds and multilayer clouds. Their method is applicable to an array of pixels but not to individual pixels, and it does not retrieve cloud optical depth. Our cirrus cloud-top altitude is also determined from the CO_2-slicing retrieval. Our low cloud-top altitude is inferred from the average of low cloud-top altitudes identified in neighboring pixels. Overlapping clouds are identified by the difference between the cloud-top temperature, as determined from the CO_2-slicing channel, and the brightness temperature from the 11-μm channel. If there are no adjacent pixels identified with low cloud, a representative mean low cloud-top altitude is determined from a larger neighboring area of ±125 km. If no low clouds are detected within the ±125-km area, the retrieval does not proceed. This could miss an average of approximately 4% (absolute frequency of occurrence) of overlapped cirrus and water clouds around the globe (Chang and Li 2004).

Figure 1 shows an example of the Terra/MODIS images of (a) 11-μm brightness temperature (K), (b) CO_2-slicing-retrieved cloud-top temperature, Tc, (K), and (c) 0.65-μm retrieved cloud optical depth. The parameters shown in the figure were retrieved by the MODIS single-layer cloud retrieval algorithm, which was applied to MODIS radiance data acquired at 1715 Universal Time Coordinates (UTC) on April 2, 2001. The figure shows a geographical area of ~500 km × 300 km over the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) region in north-central Oklahoma. The scene is mostly overcast.

The CO_2-slicing Tc represents the ambient temperature near the top of the highest cloud seen from space, while the 11-μm brightness Tc represents the bulk infrared emission, which is dictated by cloud-top height and optical depth. Note that the brightness temperature is not a physical cloud temperature but a simple transformation of thermal radiance into temperature. Figure 2 shows the comparisons of the two Tc and 0.65-μm cloud optical depth taken from the area within the square box (~50 × 50 km, centered on the SGP central facility) shown in Figure 1. From Figure 2a, about 50% of the CO_2-slicing Tc reveals high clouds (Tc <245 K), while their corresponding 11-μm brightness temperatures are much greater (~270 K). The differences between the warm 11-μm brightness temperatures and cold CO_2-slicing Tc indicate the presence of high transparent cirrus clouds.

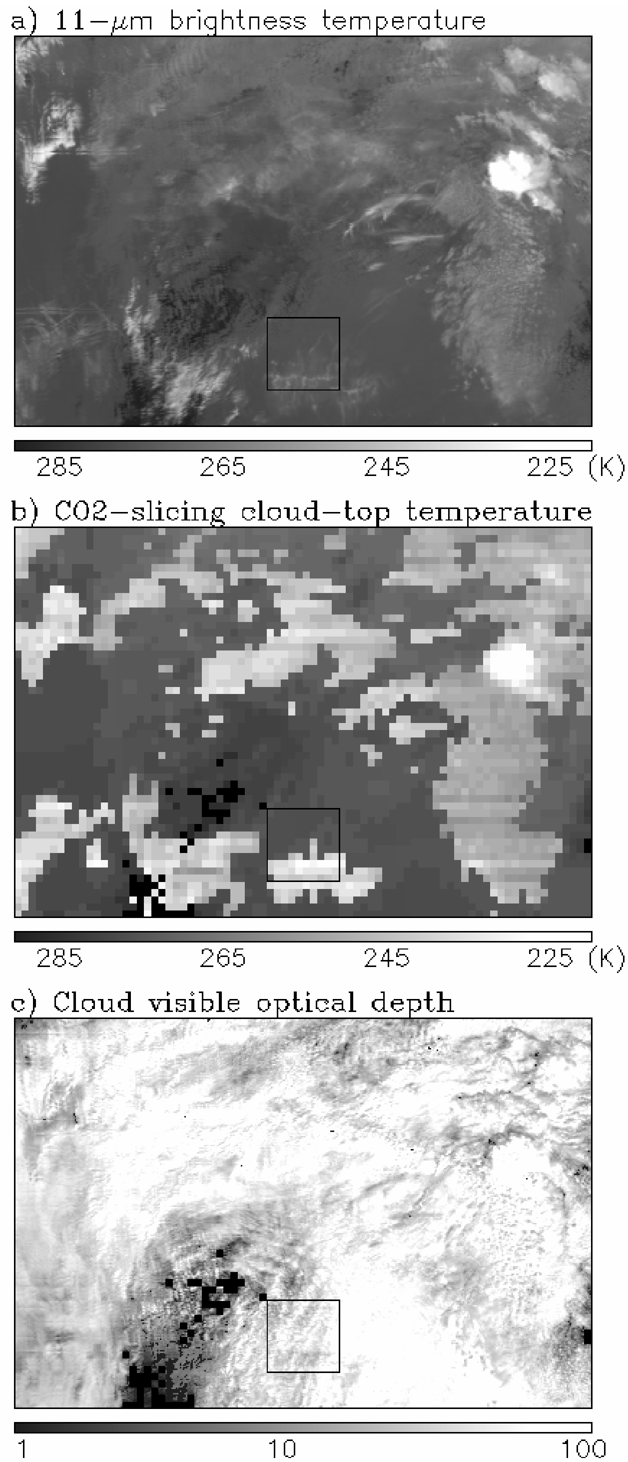


Figure 1. MODIS images of a) 11-μm brightness temperature (K), b) CO_2-slicing-retrieved Tc (K), and c) 0.65-μm cloud optical depth for a geographical area of ~500 km × 300 km obtained on April 2, 2001 (1715 UTC), over north-central Oklahoma. The square box covers approximately 50 km^2 and is centered on the SGP central facilitys.

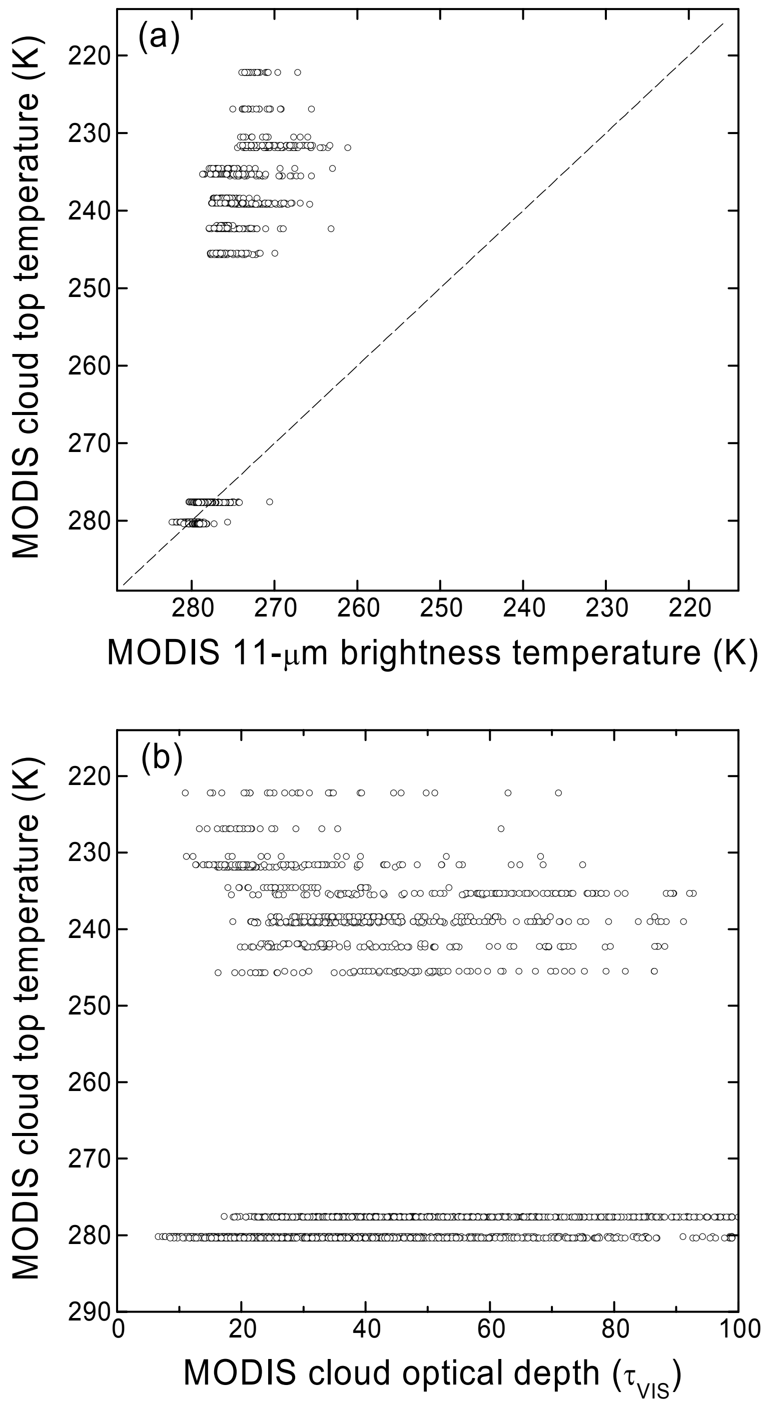


Figure 2. (a) MODIS-retrieved CO_2-slicing Tc as a function of observed 11-μm brightness temperature and (b) MODIS-retrieved CO_2-slicing Tc as a function of τ_{VIS} for the boxed area shown in Figure 1.

The MODIS-retrieved cloud optical depths have very large values (>10) for both high and low clouds, as indicated by the cloud-top temperatures of Tc <250 K and Tc >270 K, respectively. Without other information, the cold cloud-top temperatures associated with large optical depths would be interpreted as high thick clouds, while they are, in fact, low clouds overlapped by thin cirrus clouds. These two cloud configurations have completely different radiative effects and heating profiles. High thick clouds have a small net radiative forcing but a large positive and negative forcing for the longwave and shortwave components, respectively. For thin cirrus clouds overlapping thick water clouds, the shortwave cooling dominates over the longwave warming, so the cloud system has a net strong cooling. Their heating profiles also differ considerably, leading to different thermodynamic and dynamic atmospheric conditions. A global survey of cloud vertical structure obtained from one year of sampled MODIS data indicates that cirrus-overlapping-low clouds account for about 40% of all low clouds and 50% of all high clouds (Chang and Li 2004). Such a high frequency makes the single-layer assumption questionable if they are used for climate-related studies.

Retrieval of the Optical Properties of Overlapping High and Low Clouds

The algorithm first determines the altitude of the high cloud based on the MODIS CO_2-slicing derived Pc. An overlapped or non-overlapped situation is determined only when Pc <500 mb and ε_{hc} <0.85 (τ_{VIS} < ~4) using combined data from the CO_2 slicing channel and 11 µm channel. An automated retrieval procedure determines whether a high-cloud pixel contains single-layer or overlapped high cloud. When an overlapped low cloud is detected, its altitude is inferred from the average cloud-top altitude of the low clouds identified from the neighboring pixels.

For high cloud (ε_{hc} <0.85), the overlapped retrieval begins with a determination of high-cloud infrared optical depth (τ_{IR}) following the method of Minnis et al. (1993a), as given by

$$\tau_{IR} = -\mu \ln(1 - \varepsilon_{hc}), \tag{1}$$

where µ denotes the cosine of the satellite zenith angle. For an overcast pixel, ε_{hc} can be calculated by

$$\varepsilon_{hc} = \frac{R(\upsilon) - R'(\upsilon)}{R_{hc}(\upsilon) - R'(\upsilon)}, \tag{2}$$

except that

$$R'(\upsilon) = \varepsilon_{lc} R_{lc}(\upsilon) + (1 - \varepsilon_{lc}) R_{clr}(\upsilon), \tag{3}$$

where $R(\upsilon)$ is the MODIS-observed 11-µm radiance, $R_{hc}(\upsilon)$ is the 11-µm equivalent blackbody radiance calculated at the MODIS CO_2-slicing-derived temperature, $R_{clr}(\upsilon)$ is the clear-sky 11-µm equivalent blackbody radiance, and ε_{lc} and $R_{lc}(\upsilon)$ denote the low-cloud 11-µm emissivity and equivalent blackbody radiance, respectively. From Eq. 3, if no low cloud is present, then

$$R'(\upsilon) = R_{clr}(\upsilon), \qquad (4)$$

which is essentially the single-layer model used in the MODIS standard retrieval algorithm (Menzel et al. 2002). Note, this has been used for retrievals of both single-layer and overlapped high clouds.

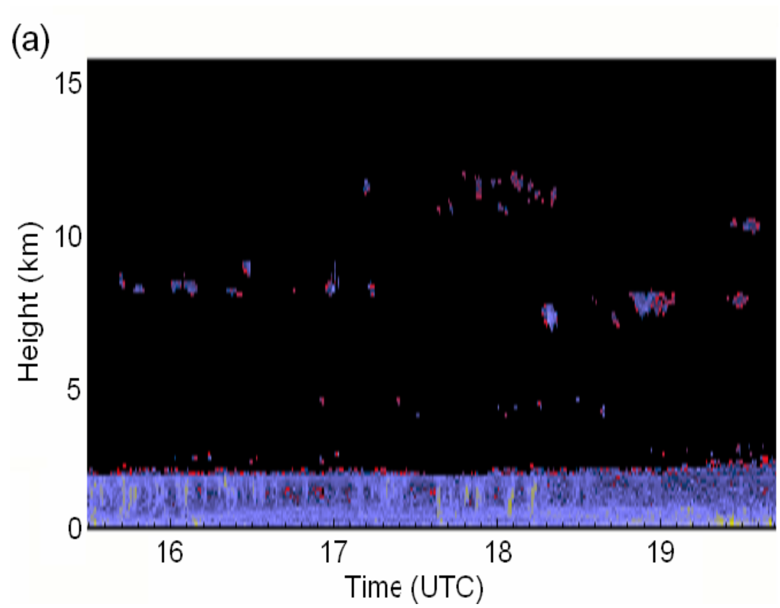
The high-cloud τ_{IR} inferred from Eq. 1 can be related to τ_{VIS} at visible wavelengths (Minnis et al. 1993a) by

$$\tau_{VIS} = \xi \tau_{IR}. \qquad (5)$$

Equations (1-5) constitute the essential components of our two-layer retrieval algorithm. For the determination of high-cloud τ_{VIS}, τ_{VIS} for the low cloud is required and vice versa. To offset this mutual dependence, single-layer low clouds in neighboring pixels are first sought to estimate the cloud-top temperature of the lower clouds. If no nearby single-layer cloud is found within the neighborhood of ± 125 km in all directions, no retrieval is performed, but the pixels are included in determining the statistics of overlapping clouds.

Comparisons of the Retrieved Cloud Vertical Structures with Ground-Based Observations

The 35-GHz millimeter wave cloud profiling radar (MMCR) deployed at the SGP site can detect the simultaneous presence of thin cirrus clouds overlaying low clouds; time-height cross sections of the ground-based radar reflectivity factors during a 4-hour span are shown in Figure 3a (for the April 2 case) and Figure 4a (for the April 18 case). The satellite overpass time for the Terra/MODIS is approximately 1715 UTC. Figures 3b and 4b show the frequency distributions of cloud-top heights (blue) derived from the ARM active remote sensing cloud layer locations (ARSCL) value-added product (VAP) (Clothiaux et al. 2000) for the two days at the SGP site. The ARSCL VAP retrieves cloud boundaries from a combination of MMCR and ground-based vertically pointing laser ceilometer, microwave radiometer, and micropulse lidar measurements. Also shown in Figures 3b and 4b are the frequency distributions of cloud-top heights obtained from the overlapped retrieval scheme (red). Note, the cloud-top heights for the overlapped retrievals are based on a conversion from Pc to height (km). Pc values in pressure are also indicated (the right y-axis). When comparing the satellite retrievals and ground-based measurements, the overlapped retrievals are collected from a spatial domain over an area of about 1.5°-latitude × 1.5°-longitude centered at the SGP site. The cloud-top heights from the ARSCL VAP are collected from 3-hour time series data within ±1.5 hours of the MODIS overpass time. Despite the uncertainties that may be incurred by matching data sampled from two different platforms, both sets of measurements clearly show a similar two-layer cloud vertical structure consisting of a high cloud layer (>6 km) and a low cloud layer (<3.5 km). There are some differences in the frequency of occurrence in terms of cloud-top heights, but this is mainly attributed to the ground point measurements being sampled every 10 seconds and the MODIS retrievals being sampled at a 5-km scale.



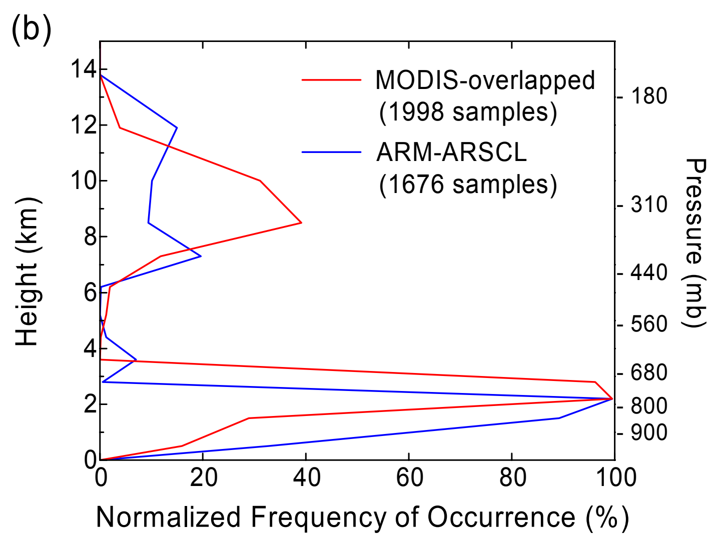


Figure 3. (a) Time-height cross section of the MMCR reflectivity measured on April 2, 2001, at the SGP site. (b) Cloud-top heights/pressures from the ARSCL VAP (blue) and MODIS overlapped retrievals (red).

To put the differences in cloud vertical structure retrieved by different algorithms in context, we compare the Pc and τ_{VIS} from the overlapped retrievals to those derived from the MODIS standard product (MOD06) and those derived from conventional retrievals like the bispectral visible-infrared method employed by the ISCCP. For the ISCCP-like visible-infrared bispectral method, we applied the retrievals to the 0.65-µm and 11-µm radiances observed by MODIS. Figure 5 shows the frequency distributions of Pc and τ_{VIS} from the three retrieval algorithms (overlapped on the left, MODIS product in the middle and ISCCP-like on the right). The different intervals are like those used in ISCCP

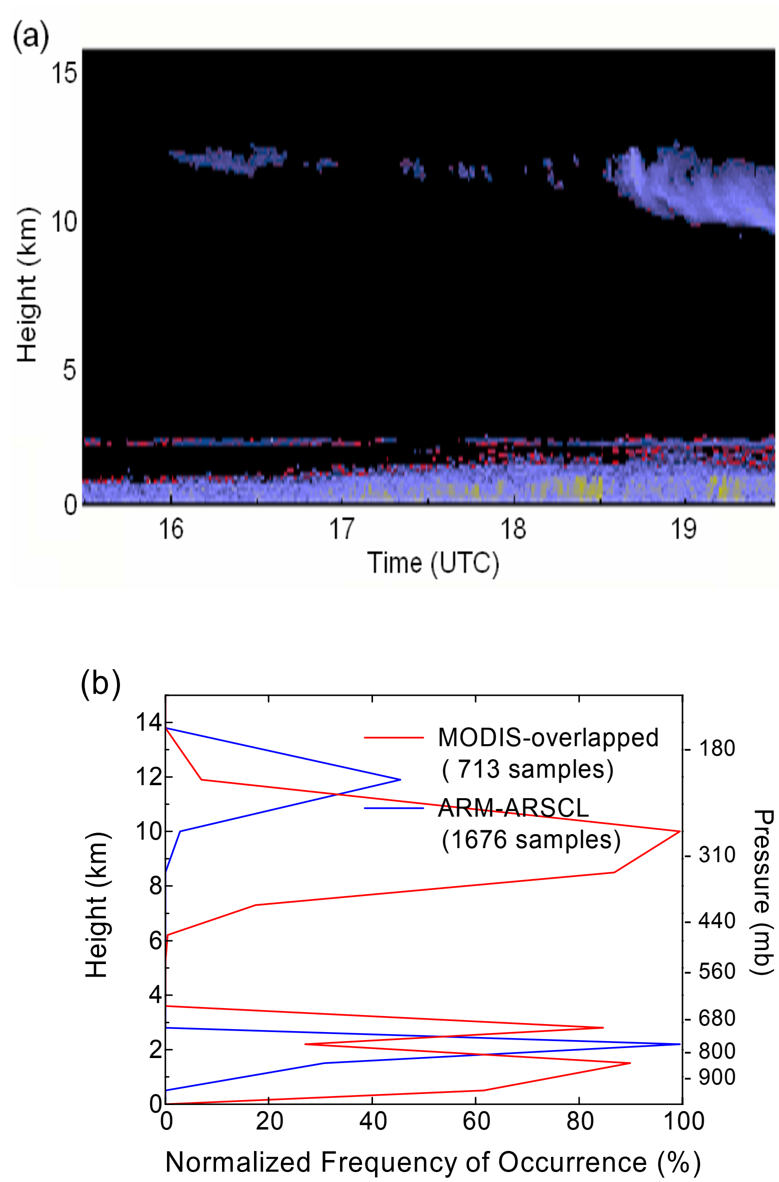


Figure 4. Same as in Figure 3, except for April 18, 2001 (1715 UTC).

(Rossow and Schiffer 1999). All overcast pixels falling within the area of 1.5°-latitude × 1.5°-longitude centered on the SGP central facility are processed by the three algorithms on the two days shown in Figures 3 and 4. The results are compared separately for three overcast conditions found within the region: (a) cirrus overlying low clouds that account for about 45% of the clouds, (b) single-layer high clouds (both thin and thick) that account for about 5.2% of the clouds, and (c) single-layer low clouds that account for about 49.8% of the clouds.

Figure 5a shows the differences for the cirrus-overlying-low-cloud cases. The CO_2-slicing technique employed by MODIS can accurately detect the high clouds, but none of the lower clouds are identified because a single-layer cloud is assumed in the MODIS cloud retrieval

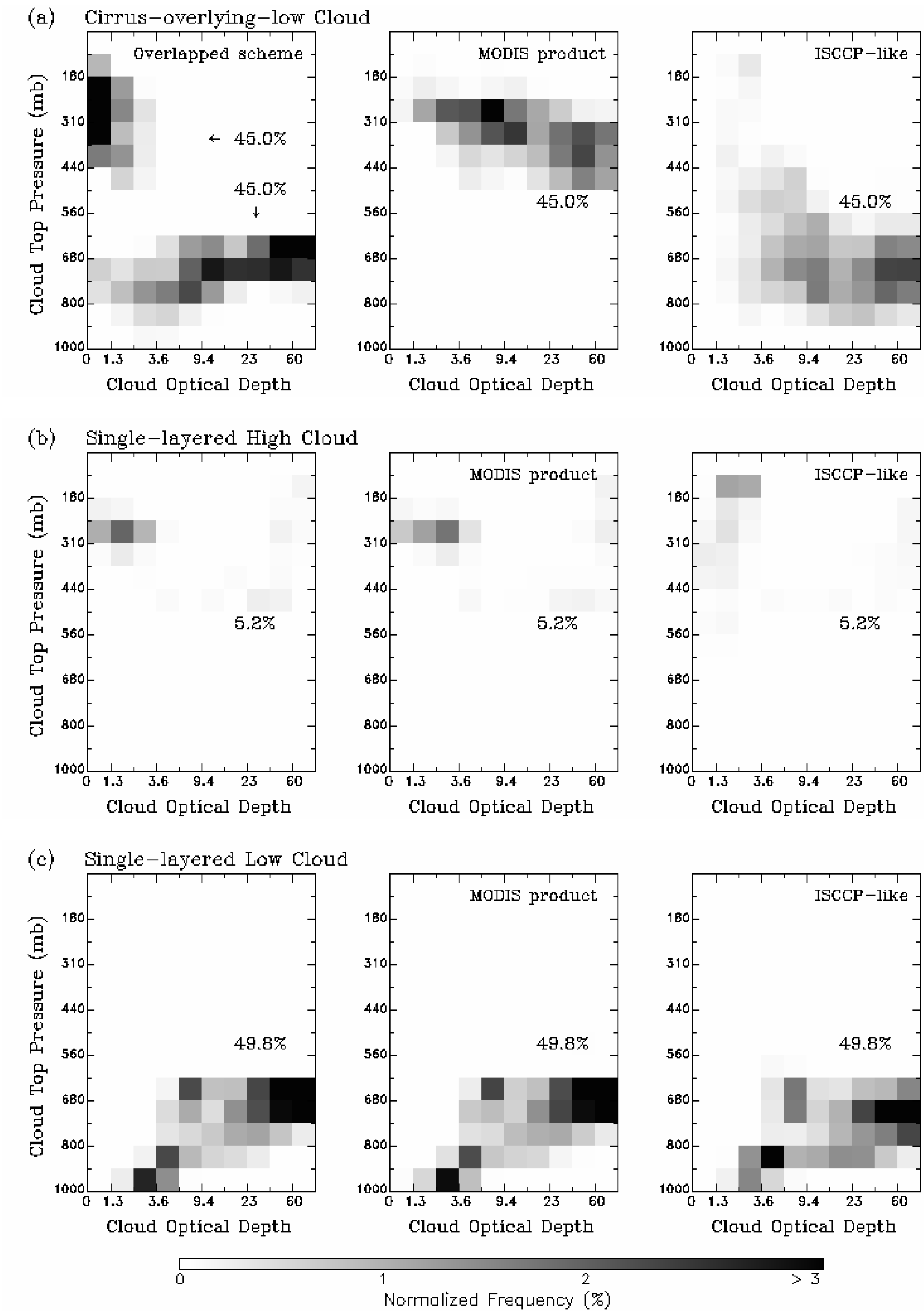


Figure 5. Comparisons of three satellite-retrieved frequency distributions of cloud-top pressure (Pc) and optical depth (τ_{VIS}) from the overlapped (left column), the MODIS-standard (middle column), and an ISCCP-like (right column) retrieval schemes. Comparisons are shown for three cloud types (a) cirrus-overlapping-low cloud, (b) single-layer high cloud, and (c) single-layer low cloud, obtained over an area of 1.5°-lat × 1.5°-lon centered on the SGP site on April 2 and 18, 2001 (UTC 1715).

algorithm. It basically misidentifies the low thick clouds as high thick clouds. Use of the bispectral method simply cannot determine the altitudes of the overlapped cloud system. Instead, it misplaces them as mid-level clouds somewhere in between the high and low cloud altitudes. For the single-layer high clouds (Figure 5b), the two MODIS-based algorithms produce identical results, while higher cloud-top heights are retrieved by the ISCCP-like bispectral method. This is due to an overcorrection in the 11-μm Pc retrieval resulting from the small τ_{VIS} retrieved at 0.63-μm. For single-layer low clouds (Figure 5c), all three methods generate consistent results, as expected.

Conclusion

This study is motivated by surface and aircraft observations that showed a large probability of high cirrus clouds coexisting with low stratus clouds. Because cirrus clouds are optically thin, and low stratus clouds are generally optically thicker, overlap of the two poses a major challenge for the detection of this cloud configuration and the retrieval of the associated optical properties by satellite remote sensing. To date, all operational satellite cloud retrieval algorithms employ radiative transfer models, which assume a single-layer cloud. Serious problems in the retrievals of several cloud properties, such as height, temperature, optical depth, and emissivity, can occur from using these algorithms due to the ubiquitous presence of cirrus-overlapping-low clouds. In this paper, a new satellite retrieval algorithm is proposed that can cope with overlapping clouds. It is designed to take advantage of the wealth of information found in MODIS data. The algorithm can: (1) detect the presence of cirrus-overlapping-low clouds and (2) estimate their individual optical depths, cloud-top altitudes, and emissivity for the upper thin clouds. It first utilizes 11-μm radiances to obtain a first guess of the cirrus cloud optical depth. It then utilizes 0.65-μm visible radiances to determine the low cloud optical depth beneath the cirrus cloud. Next, an iterative procedure follows to adjust the high and low cloud optical depths to match modeled radiances with MODIS-observed radiances at the visible (0.65-μm) and infrared (11-μm) channels. The physical height of the cirrus cloud is determined by the CO_2-slicing technique, while the physical height of the low cloud is determined from neighboring MODIS pixels where single-layer low clouds are identified.

The results presented in this study highlight the importance of determining the presence of overlapped clouds when applying any satellite retrieval algorithm and the uncertainties in satellite-retrieved cloud optical and microphysical properties estimated by the single-layer conventional algorithms. Large errors are found for cirrus-overlapping-water clouds if they are treated as single-layer water or ice clouds. Preliminary comparisons are made of the cloud vertical structures retrieved from the new algorithm, MODIS and ISCCP-like algorithms, and the ground-based cloud radar and lidar deployed in north-central Oklahoma under the ARM Program. The comparisons show that the two-layer overlapping algorithm more correctly identifies cloud layers, and this algorithm estimates the cloud optical properties more accurately than the other two algorithms.

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