VALIDATION OF CLOUD PROPERTY RETRIEVALS FROM MTSAT-1R IMAGERY USING MODIS OBSERVATIONS

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Abstract

A cloud property retrieval algorithm optimized for five channels (centered at 0.6, 3.7, 6.7, 10.8, and 12.0 μm) has been explored for application to onboard meteorological radiometers on geostationary satellites; however, its validity remains to be established. Here, we present validation results for the cloud properties retrieved by the developed algorithm from the full-disk imagery of the Multi-functional Transport Satellite (MTSAT-1R) for August 2006. The considered cloud properties include the cloud phase (CP), cloud optical thickness (COT), effective radius (ER), and cloud top pressure (CTP). Their one-month averages, daily variations, and respective collocated values are compared with the Moderate Resolution Imaging Spectroradiometer cloud data. Our validation results show that an additional 6.7-μm brightness temperature test in CP retrieval identifies water and ice phases that may be overlooked in the 10.8- and 12.0-μm bands. Our method to extract cloud-reflected radiances at the 0.6- and 3.7-μm bands contributes to the accuracy of the COT for values between 5 and 60, and the ER for values less than 40 μm. Estimating high-cloud top pressure from the radiance ratio in the 6.7- and 10.8-μm bands remarkably reduces (by up to 70%) large uncertainties in the CTP, which may be found in the presence of high thin cirrus clouds.

1. INTRODUCTION

To create a weather service with a higher temporal resolution using the Communication, Ocean and Meteorological Satellite (COMS) imager scheduled to be launched in 2009 in Korea, a new cloud analysis algorithm (CLA) was explored on the basis of five channels (centered at 0.6, 3.7, 6.7, 10.8, and 12.0 μm) from weather imagers in geosynchronous earth orbit (Choi et al. 2007). The algorithm introduces the following retrieval methods: (i) CP based on spectral absorptivity in the 6.7-μm band in addition to the 10.8- and 12.0-μm bands; (ii) COT and ER using a combination of cloud-reflected radiances in the 0.6- and 3.7-μm bands through thermal correction; and (iii) CTP using the brightness temperature in the 10.8-μm band for optically thick clouds (COT > ~10), and the radiance ratio in the 6.7- and 10.8-μm bands for optically thin high clouds (CTP ≤ 400 hPa). These three methods were developed based on RT theory.

The retrieval methods have been previously validated by comparing the MODIS cloud data and the collocated cloud properties from the CLA by using the MODIS level-2 calibrated radiances (Choi et al. 2007); however, these validation results may indicate only the uncertainty induced by RT modeling. Because the MODIS radiances have spectral information within finer bandwidths than those of most five-channel meteorological imagers, the results may not indicate the substantial physical uncertainties that would emerge from the coarser bandwidths of these imagers. The Japanese Advanced Meteorological Imager (JAMI) onboard the Multi-functional Transport Satellite (MTSAT-1R) is also a five-channel weather imager and has been in operation since June 28, 2005. JAMI has almost the same response functions as the COMS imager, and its orbit and field-of-view (FOV) are similar to those of the COMS satellite. Therefore, the imagery of JAMI can be used as an input for the CLA, which produces the cloud properties to be validated. The present paper attempts to validate the pre-performed CLA algorithm by using the hourly MTSAT-1R imagery via comparison with the MODIS cloud data.
2. DATA AND METHODS

2.1. MTSAT-1R radiance and MODIS cloud products

We used the hemispheric full-disk images of hourly JAMI/MTSAT-1R calibrated radiance (or converted brightness temperature) for August 2006 as inputs for the CLA developed by Choi et al. (2007). The spatial resolution of the JAMI radiances is 4 km × 4 km. The five JAMI onboard spectral channels are centered at 0.725 (hereafter VIS), 10.8 (IR1), 12.0 (IR2), 6.75 (IR3), and 3.75 μm (IR4).

To compare with the cloud products from the JAMI imagery on the pixel level, we used the MODIS cloud product (MOD06, collection 5) data that contain various retrieval results of cloud properties such as the CP and CTP (COT and ER) at a 5 km × 5 km (1 km × 1 km) nadir resolution (Platnick et al. 2003). In this study, we selected the MOD06 granules in the Northwestern Pacific (10°–30°N, 113°–149°E) during August 5–11, 2006. In MOD06, we used the MODIS CP data derived from the bispectral IR test. The MODIS gridded level-3 daily atmospheric product (MOD08, Collection 5) is also collected for the analysis period. MOD08 contains the 1° × 1° gridded values calculated from the MOD06 cloud properties. We used MOD08 to calculate the averages for the analysis period and the time-series of the cloud properties for the given grids.

2.2. Cloudy scene identification

We identified “cloudy” pixels from the images by a bispectral test using the VIS and IR1 channels before using the CLA to retrieve the cloud properties. The bispectral test for cloud detection is based on the International Satellite Cloud Climatology Project (ISCCP) algorithm (Rossow and Garder 1993), but it is simplified as in the following relations:

\[
\begin{align*}
\text{Clear: } & BT_{IR1}^{\text{clr}} - BT_{IR1} \leq \text{IRTHR} \text{ and } L_{VIS} - L_{VIS}^{\text{clr}} \leq \text{VISTHR} \\
\text{Cloudy: } & BT_{IR1}^{\text{clr}} - BT_{IR1} > \text{IRTHR} \text{ or } L_{VIS} - L_{VIS}^{\text{clr}} > \text{VISTHR}
\end{align*}
\]

where \(BT_{IR1}^{\text{clr}}\), \(L_{VIS}\), and \(L_{VIS}^{\text{clr}}\) are, respectively, the IR1 total-sky brightness temperature, the VIS total-sky radiance, and the VIS clear-sky radiance. Note that \(L_{VIS}\) is a scaled radiance in percentage, as used in the ISCCP algorithm. The values of IRTHR and VISTHR are 12.0 K and 6.0% for land (3.5 K and 3.0% for ocean), respectively. In this work, \(BT_{IR1}^{\text{clr}}\) (\(L_{VIS}^{\text{clr}}\)) is obtained as the maximum (minimum) observed value for each UTC for the 31 days of August 2006. At night, only the IR conditions in Eq. (1) are used. The underlying uncertainties in the cloud mask may exist in the derived MTSAT-1R cloud properties; however, the thin clouds overlooked by our simple thresholds will have little impact on COT and ER.

2.3. Algorithm description and adjustment

The CP algorithm consists of brightness temperature (BT) threshold tests using the IR1, IR2, and IR3 channels. Choi et al. (2007) noted that the IR3 band is a useful alternative when the 8.7-μm band is absent; this should be validated in the present study. Our RT modeling for the MTSAT-1R spectral response function reveals that some clouds with a mixed phase can have a BTIR3 between 228 K and 239 K. Thus, the IR3 threshold for ice phase discrimination is changed to the more rigorous values of 228 K and 239 K from the original 234 K and 250 K in order to prevent false identification of an ice phase from the MTSAT-1R radiance (compare with table 2 in Choi et al. 2007). The changed criteria and test logic for determining a cloud phase are shown in Table 1.

<table>
<thead>
<tr>
<th>Required tests for cloud phase</th>
<th>Ice</th>
<th>Mixed</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTIR1 &lt; 238 K or</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BTIR1−BTIR2 ≥ 4.5 K or</td>
<td>For no ice</td>
<td>238 K ≤ BTIR1 &lt; 268 K and</td>
<td>For no ice/mixed</td>
</tr>
<tr>
<td>BTIR3 &lt; 228 K</td>
<td></td>
<td>BTIR1 ≥ 285 K or</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BTIR3 ≥ 239 K</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Criteria for determining cloud phase.

The COT and ER values are derived simultaneously by using the cloud-reflected radiance components in the VIS and IR4 channels—the sun reflection method. The desired cloud-reflected
components can be decoupled from the undesired ones such as the ground-reflected components, and the cloud and ground thermal radiances can be resolved by the rapid method using only one lookup library, which should also be validated in this study. The COT and ER lookup library comprise the VIS and IR4 radiances, various geometric angles (0°, 20°, 40°, 60°, and 80°), and ground albedo ($A_g = 0$ and 0.5). Theoretically, the ground-reflected radiance changes almost linearly in proportion to $A_g$ under the assumption of very small multiple reflections between the ground and the upper layer (Choi et al. 2007). Once the angular variables and $A_g$ are known for a given pixel, the simulated thermal-free radiance (i.e., the sum of the cloud- and ground-reflected radiances) for $A_g = 0$ is subtracted from that for $A_g = 0.5$ in the lookup table and multiplied by a given $A_g$. In this study, the $A_g$ database used for individual pixels is the space-dependent (in 2.5°) one-month average from European Center for Medium-Range Weather Forecasts.

The CTP is retrieved by a combination of two methods: the IR-window channel (simply IR1) estimate and the radiance ratioing method. The IR1 estimate is a typical method in which the BTIR1 value is compared with the vertical temperature profile in the area of interest. This method is valid only for thick clouds (COT $\geq 10$) (Choi et al. 2007). In the radiance ratioing method, the observed radiance ratio defined by $(L_{IR1} - L_{IR1, cr})/(L_{IR3} - L_{IR3, cr})$ is compared with the simulated radiance ratio. Since the radiance ratio is a function of the CTP regardless of the optical depth, the method compensates for the limitation of the IR1 estimate for thin clouds (COT < 10). The radiance ratioing method using the IR1 and IR3 bands must be validated in this study. The CTP library that includes the relation between the radiance ratio and the CTP is calculated for the standard profiles of the tropics, midlatitude summer, and midlatitude winter and applied to the ranges of latitudes 30°S–30°N, 30N°–60N°, and 30S°–60S°, respectively.

2.4. Validation methods

Since we wish to validate the methods, two types of cloud products are retrieved, namely, base products and final products, in a stepwise manner from the previous or conventional algorithm and the present algorithm, respectively. The terms of the products used in this analysis are summarized in table 2.

<table>
<thead>
<tr>
<th>Term</th>
<th>Unit</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base CP</td>
<td>unitless</td>
<td>Cloud phase is determined by BTIR1 and BTIR1-BTIR2 tests in table 1.</td>
</tr>
<tr>
<td>Final CP</td>
<td>unitless</td>
<td>Cloud phase is determined by BTIR1, BTIR1-BTIR2, and BTIR2-BTIR3 tests in table 1.</td>
</tr>
<tr>
<td>Base COT/ER</td>
<td>unitless/μm</td>
<td>Cloud optical thickness and effective radius are roughly retrieved by using measured VIS and IR4 radiances that remain to include both thermal and reflected components.</td>
</tr>
<tr>
<td>Final COT/ER</td>
<td>unitless/μm</td>
<td>Cloud optical thickness and effective radius are retrieved by the sun reflection method that uses the decoupled radiances, i.e. cloud-reflected components.</td>
</tr>
<tr>
<td>Base CTP</td>
<td>hPa</td>
<td>Cloud top pressure is retrieved by the IR1 window estimate.</td>
</tr>
<tr>
<td>Final CTP</td>
<td>hPa</td>
<td>Cloud top pressure is retrieved by both the IR1 window estimate and the radiance ratioing method using IR1 and IR3 radiances.</td>
</tr>
</tbody>
</table>

Table 2: Definitions of terms used in this analysis.

We compared the base, final, and MODIS products by the following fourfold procedure: (i) scene analysis, (ii) large-scale climatology comparison, (iii) time-series comparison, and (iv) pixel-by-pixel comparison.

3. RESULTS

3.1. Scene analysis

Figure 1 shows the cloud properties retrieved by the CLA for 0333 UTC August 7, 2006. Overall, noticeable differences exist between the base and final products. The final CP shows more water clouds and less uncertain clouds (white) over the globe than the base CP (the first panel). The final COT (ER) values in the centers of tropical cyclones and ITCZ are larger than the base COT (ER) (the second and third panels). More clouds have low CTP (i.e., higher top) in the final product in the East Pacific than in the base product (the fourth panel). These differences indicate that the features inferred from the radiance scenes are more noticeable in the final products than in the base products. Namely, very high and thick clouds are found more clearly in the tropical West Pacific in the final products than
in the base products. Although the optical properties of some clouds are not retrieved due to high geometric angles, the final CTP and COT more obviously show the high thin clouds in the East Pacific and the branch-shaped high thick clouds over the southwestern seas of Australia than the base products.

![Figure 1: Cloud properties derived by the CLA. Cloud phase (Panel A), cloud optical thickness (Panel B), effective radius (Panel C), and cloud top pressure (Panel D) are shown. Base products (a) are the results of conventional methods or without correction methods, and final products (b) from improved methods or with the correction methods developed in the present study.](image)

### 3.2. Large-scale climatology comparison

The retrieved cloud properties are compared quantitatively with the MODIS retrievals for August 2006. Table 3 shows the one-month climatology of the final, base, and MODIS CP. Overall, there are large differences between the derived CP and the MODIS CP. Water and ice clouds are noticeably more prevalent in the final CP than the base CP, and their proportion is closer to that in the MODIS CP. This indicates that the additional water and ice clouds in the final CP are identified by adding the IR3 test to the conventional IR1 and IR2 tests. Without the IR3 test, a large amount of cloudy pixels remain undecided. This improvement is actually seen regardless of the local time and region, as shown in table 3. Meanwhile, mixed clouds are relatively smaller in the final CP than in the base CP. This reduction in mixed clouds should be due to the additional IR3 test. Despite these improvements in the final CP, a large amount—up to the extent in the MODIS CP (roughly 15%)—of clouds remain unknown.

The relative frequency of the one-month climatology of the COT is examined for all the clouds for various conditions (figure 2). The dotted, solid, and thick solid lines indicate the base, final, and MODIS products, respectively. The derived COT is generally underestimated in comparison with the MODIS COT. The highest frequency is seen in the bins 4–9 and 0.5–25 in the final and the MODIS COT, respectively. The frequency of “COT < 4” is greater in the derived data than in the MODIS COT data, while the frequency of “COT = 9–25” is less in the derived data than in the MODIS COT data in all cases. This systematic bias may result from the modeling calculation, and it should be minimized by tuning the COT library.

<table>
<thead>
<tr>
<th>Domain</th>
<th>MTSAT CP (Final)</th>
<th>Base</th>
<th>MODIS CP (Final)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>39.4/24.6/20.5/15.5</td>
<td>20.9/19.1/29.2/30.8</td>
<td>50.3/29.5/5.6/14.7</td>
</tr>
<tr>
<td>Day</td>
<td>34.2/28.2/18.2/19.4</td>
<td>20.9/21.6/26.0/31.4</td>
<td>53.2/26.7/5.1/15.0</td>
</tr>
<tr>
<td>Night</td>
<td>34.5/29.2/21.1/15.2</td>
<td>16.0/20.4/32.9/30.8</td>
<td>46.1/33.4/6.4/14.2</td>
</tr>
<tr>
<td>Northern Hemisphere</td>
<td>30.2/29.1/22.3/18.3</td>
<td>21.8/23.7/29.4/25.1</td>
<td>48.1/32.4/4.4/15.1</td>
</tr>
<tr>
<td>Southern Hemisphere</td>
<td>50.6/19.0/18.2/12.2</td>
<td>19.9/13.5/29.0/37.6</td>
<td>52.5/26.5/6.7/14.2</td>
</tr>
<tr>
<td>Polar</td>
<td>0.7/54.8/36.3/8.2</td>
<td>0.8/31.5/59.8/8.5</td>
<td>28.4/40.3/14.1/17.4</td>
</tr>
<tr>
<td>Midlatitude</td>
<td>28.9/19.6/29.8/21.7</td>
<td>8.8/12.9/40.4/37.9</td>
<td>52.7/23.8/6.8/16.7</td>
</tr>
<tr>
<td>Tropical</td>
<td>46.1/25.7/15.3/12.9</td>
<td>27.7/21.6/22.5/28.2</td>
<td>55.1/30.6/20.1/12.3</td>
</tr>
</tbody>
</table>

Table 3: Comparison of cloud phases from the JAMI/MTSAT-1R and the MODIS algorithm in August 2006. The numbers indicate the percentage of cloud phase (water/ice/mixed/uncertain) over the total cloud fraction. All results are calculated in the FOV of JAMI.
The bias can be also induced by the different reflectivity between liquid and ice clouds. In figure 2, the bias is much larger for liquid clouds than for ice clouds. Water droplets reflect solar insolation more effectively than ice crystals; consequently, the reflected radiance from the liquid clouds is greater than that from the ice clouds for the same COT. Accordingly, the CLA can underestimate the COT if ice clouds are falsely identified as liquid clouds. This indicates the important role of the CP classification result in the COT retrieval.

Our derived ER is also slightly less than the MODIS ER (figure not shown). However, the bias between them is relatively small in comparison with that of the COT. In comparison with the liquid and ice phases, the frequency of ER in both the data sets shows consistently smaller liquid particles with ER between 2 μm and 30 μm and larger ice crystals with ER between 5 μm and 64 μm. The highest frequency is shown in the bins 0–20 μm and 20–30 μm for liquid and ice clouds, respectively. On the other hand, no noticeable difference is found between the ER values of the Northern and Southern Hemispheres. While the bias is relatively large in the tropics, we note that in the midlatitudes, the relative frequencies in the final and MODIS data show fairly good agreement. Since ER retrieval is highly sensitive to the IR4 reflected radiance, the results show that our method may be particularly effective in the midlatitudes to decouple the thermal and surface-reflected components from the observed IR4 radiance (Choi et al. 2007).

With regard to the comparison between the final and the base products, the one-month climatology of the COT and ER agrees with those of the MODIS products to some extent due to the decoupling method employed in the algorithm (compare the dotted and solid lines). By using the decoupling method, the frequency of thin clouds (COT < 4) decreases and that of thick clouds (COT ≥ 4) increases, except for ice clouds (figure 2). Similarly, the frequency of clouds of small particles (ER < 10) decreases and that of clouds of large particles (ER ≥ 10) increases (figure not shown).
Figure 3: Relative frequency distribution (in %) of MODIS CTP (a), base CTP retrieved by the IR1 estimate only (b), and final CTP corrected by the radiance ratioing method (c) for the total clouds. The results are shown for August 2006, daytime, nighttime, Northern and Southern Hemispheres, and the polar, tropical, and midlatitude regions.

The one-month climatology of the CTP is also compared with the MODIS CTP for the analysis period (figure 3). It is noted that our CTP and the MODIS CTP are produced in the units of 50 and 25 hPa, respectively. In the analysis of the MODIS CTP (figure 3a), the CTP frequency is highest at the 300–400, 700–800, and 900–1000 hPa levels in August. This distribution varies between day and night, Northern and Southern Hemispheres, and tropical and polar regions. The base CTP from the IR1 estimate reveals a similar shape of CTP distribution to that of MODIS. However, no high frequencies at the high- and mid-levels are found, and low clouds (CTP = 900–1000 hPa) are more frequent in the IR1-estimated CTP (figure 3b). When the CTP is corrected by the radiance ratioing method, the frequency of high clouds (300–400 hPa) increases by 4% and that of low clouds (900–1000 hPa) decreases by 7% (figure 3c). Consequently, the values from the final CTP at both levels become fairly close to those of MODIS (23.5% versus 20.7% at the low level, 12.2% versus 12.2% at the high level). Interestingly, the regional characteristics of the CTP distribution are present in both the final CTP and the MODIS CTP data; in the tropics, very high (200–300 hPa) and very low clouds (≥1000 hPa) are the most common, while middle clouds (600–800 hPa) are the most common in the polar regions. Therefore, the radiance ratioing method using the IR1 and IR3 channels is found to be useful in identifying high clouds above 400 hPa that are falsely flagged as low clouds using the IR1 estimate alone. It should be noted that some middle clouds identified by the MODIS CO2 slicing method cannot be discriminated by our method, since the radiance ratioing method is valid only above 400 hPa.

3.3. Time-series comparison

We examine the time series of cloud properties in the nine selected regions (figure not shown). The time series of the ratio of ice clouds to the total clouds in the base CP and the final CP includes large hourly fluctuations, indicating a rapid change in the cloud properties in nature. The time series of the ratios in most regions shows that the derived and the MODIS data are nearly in phase. The ratios become higher when the IR3 test is incorporated; therefore, the ratios in the final CP are more close to the MODIS daily values.

Better agreement with the MODIS data is found for the final COT/ER data in most regions than for the base data. This improvement in the COT and ER retrievals via the decoupling method is seen regardless of the region. However, large hourly variations in the COT and ER retrievals exist. This is perhaps related to the influence of the change in the solar zenith angle on the retrieval; large bias must occur around sunrise or sunset.

The time series of the derived CTP generally follow that of the MODIS values in all the analysis regions. The effect of applying the ratioing method may be to change the overestimated base CTP values into more realistic, lower final CTP values. In comparison with the MODIS values, the final CTP values may be underestimated to some extent in Seoul, the northeast China plain, the East Pacific, and the Bering Sea. There are several reasons for this underestimation: (i) middle clouds are not commonly identified; (ii) the radiance ratio library for the midlatitudes is applied to the 30°–60° latitudes, while the atmospheric conditions over the Bering Sea (located between 59°–60°N) may be
far from the model profile; and (iii) in the midlatitudes, the radiance ratio is not distinctly sensitive to the CTP (refer to figure 7 of Choi et al. 2007). Despite these several sources of uncertainties, the final CTP agrees fairly well with the MODIS values in the other regions, including the Gobi desert, Tibetan plateau, South China Sea, Philippine Sea, and Antarctic region.

3.4. Pixel-by-pixel comparison

Figure 4 shows the relative frequency of the differences between the derived MTSAT and the MODIS retrievals to the maximum values, and the errors in the retrievals with respect to the corresponding MODIS values. The error is expressed in terms of the ratio (in percentage) of the difference between the MTSAT and MODIS retrievals to the MODIS retrievals.

Most (90%) of the final CTP and MODIS CTP values are in agreement with each other (figure 4). A large difference in CTP over 300 hPa also occurs for about 0.1% of the total pixels. This uncertainty may result from a number of factors such as the discrepancies in the retrieval resolutions, radiance ratios, constructed clear-sky radiances, and the numerical atmospheric profiles employed. A comparison of the base and final CTP values clearly reveals that our correction method (i.e., the radiance ratioing method for high-cloud top pressure) is effective particularly when the MTSAT CTP is higher than the MODIS CTP (figure 4a). Large errors for low clouds (CTP ≥ 700 hPa) are dramatically decreased by this method (figure 4b).

The final COT and the MODIS COT values are mostly identical to within a difference of ±5. Only a few pixels (~2% of the total pixels) are in disagreement with the MODIS COT (figure 4c). The disagreement and the error in the final COT values are much lower than those for the base COT.
values, especially for clouds with COT < 60 (figures 4c and 4d). The errors in both the base and the final COT values are very small for very (optically) thick clouds with COT ≥ 60.

Unlike the COT, the final ER values still have large uncertainty when compared to the MODIS values. The disagreement between the final and MODIS ER values occurs for a considerable portion of the pixels, and it is likely to have originated from the relatively large ER values (>40 μm) (figures 4e and 4d). This uncertainty probably results from the insensitivity of IR4 radiance to large-sized cloud particles (Choi et al. 2007). Therefore, reliable ER retrieval from MTSAT-1R images can be guaranteed only up to a value of approximately 40 μm. We note that the ER from MODIS provides estimates for liquid (ice) clouds only up to 30 (90 μm).

4. SUMMARY

We have presented validation results of the CLA (Choi et al. 2007) by comparing the base, final, and MODIS cloud properties. The base and final cloud properties are defined as the products from the hourly MTSAT five-channel imagery by the previous and present algorithm, respectively (Table 2). For the validation, we carried out scene analysis, large-scale climatology comparison, time-series comparison, and pixel-by-pixel comparison. Based on our analysis, the final CP, COT, ER, and CTP values are consistently closer to the MODIS reference data than the base products. This indicates that the present developed schemes for the CLA are, in effect, of merit despite the limitation of the channel number. The major results are summarized as follows:

- The final CP has considerably more water and ice clouds (or less mixed and unknown clouds) than the base CP, which indicates the role of the additional IR3 test. Compared with the MODIS CP, however, the proportion of water (mixed) clouds across the globe is still very low (high); it is lower (higher) by about 11% (15%). This uncertainty between the water and mixed phases remains as the limitation of the present IR CP algorithm due to the absence of the 8.5-μm channel in the MODIS algorithm. It is noted that the proportion of ice clouds is comparable with that in the MODIS CP data, but is very high (by about 15%) only in the polar region.

- The final COT and ER values have less bias against the MODIS values than the base products, particularly in the midlatitudes, which indicates the effect of the radiance decoupling method to extract cloud-reflected radiances in the VIS and IR4 channels. When the decoupling method is incorporated, the bias is dramatically reduced for 5 ≤ COT < 60 and for ER < 40 μm. The large uncertainty in the COT and ER retrievals due to high solar zenith angles and very large COT (»60) and ER values (» 40 μm) remains to be resolved.

- Reliable CTP values can be retrieved by correcting the high-cloud top pressure (<400 hPa) via the radiance ratio obtained from the clear-sky radiance, which is defined as the maximal radiance in the domain of 12 km × 12 km. The accuracy of CTP retrievals largely depends on the accuracy of the obtained clear-sky radiance. Bias against the MODIS CTP still exists in the mid-troposphere between the 700 and 800 hPa levels.

REFERENCES

