**Improvement of Cirrus Cloud-Top Height Estimation Using Geostationary Satellite Split-Window Measurements Trained with CALIPSO Data**

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Abstract

We developed a method for the estimation of cloud-top height using only split-window channels of infrared observations from geostationary satellites. Lookup tables (LUTs) were constructed based on regression of them with direct observations of cloud top height from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and Cloud Profiling Radar onboard the CALIPSO and CloudSat satellites, respectively. Our previous estimation scheme using cloud radar underestimated the top heights of cirriform cloud. In this study, using CALIOP data, we succeeded in reducing the underestimation of the height of cirriform clouds. Although CALIOP can detect optically thin clouds around the tropopause, their top heights cannot be estimated well using split-window observations. By defining the altitude at which the optical depth from the top had a specified value $\tau_{\text{crit}} (= 0.2)$ as the cloud-top height, we could create a practical LUT. In the LUT, the underestimation of the heights of cirriform cloud was corrected substantially, while reducing the effect of the low sensitivity of split-window observations to thin tropopause cloud.

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1. Introduction

Since 2006, direct observations of almost the entire geometrical cloud profile and of cloud tops have been available from the Cloud Profiling Radar (CPR) onboard CloudSat and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO, respectively. However, these observations are limited to a small footprint near the nadir of the satellites and they are temporally very sporadic. Therefore, it is not possible to obtain information on any cloud systems beyond the nadir footprint or to trace specific cloud systems continuously using such direct observations alone. Observations performed by geostationary satellites have high temporal resolution and wide spatial coverage. Although cloud-top height is not observed directly by such platforms, it is estimated from infrared (IR) and/or visible radiances. To exploit these merits of geostationary satellites effectively, some methods have been proposed for estimating cloud parameters from geostationary satellite data alone, as reviewed in Hamada and Nishi (2010), hereinafter referred to as HN10. In HN10, they regressed IR split-window observations from MTSAT satellites with CPR data, and they created empirical lookup tables (LUTs) of cloud-top height and optical depth (http://database.ish.kyoto-u.ac.jp/arch/ctop/index_e.html). The split-window method is based on the premise that difference of two brightness temperatures at different wavelengths in the atmospheric window range is large for semi-transparent clouds like cirriform clouds (e.g. Inoue 1985, 1987). Their dataset based on the LUT in HN10 has been used in studies of tropical cirrus (e.g. Suzuki et al. 2010) and in real-time monitoring of cloud systems in some observational campaigns.

However, this LUT has one primary shortcoming, i.e., underestimation of cloud-top heights of cirriform clouds. The original version of the product is effective for monitoring the activity of mesoscale convection and dense anvil clouds because the cloud-top heights obtained from the CPR are close to the actual tops of precipitating clouds and/or the surrounding dense stratus clouds. However, cirriform clouds generally have lower optical depths but may be geometrically thick; thus, the cloud-top heights observed by the CPR can be considerably different to the actual cloud-top heights, which can cause bias in the LUT. An example of the cloud distribution in the tropical upper troposphere along the track of the orbit of the CPR and CALIOP is shown in Fig. 1. Figure 1a shows effective radar reflectivity observed by the CPR and Fig. 1b shows the extinction coefficients observed by the CALIOP. A large cloud cluster with penetrative convective clouds is evident around 86.8°E–85.4°E. In this region, the CPR cloud top is about 1–3 km lower than the CALIOP cloud top shown by the upper bound of the shading in the figure, except for the penetrative convective clouds. In the region 84.6°E–84.0°E, very high cloud tops (17–18 km) are observed by the CALIOP, whereas small amount of clouds are detected by the CPR. The CPR has sufficient sensitivity to detect large ice particles but not the small ice particles comprising the upper parts of cirriform clouds. In contrast, the CALIOP has sufficient sensitivity to detect such small particles and thus, the cloud-top heights of cirriform clouds observed by the CALIOP are much closer to the heights of actual cloud top: the upper bound of hydrometeors. If the LUTs were based on lidar data rather than on cloud radar data, the bias in estimated cloud-top heights would be reduced.

There is a known problem regarding the use of lidar data as the training dataset for the construction of the LUTs. Most upper-tropospheric clouds observed by cloud radar comprise penetrative convective clouds, deep stratiform anvils, and cirriform clouds extending from anvil clouds. These are known as clouds related directly to tropical convection. In contrast, a lidar observes another type of optically thin cirriform clouds. These clouds, which extend around the tropopause, have various origins and they are not necessarily direct extensions of cumulus clusters (Sassen et al. 2009). Radiation observation in the atmospheric window range from geostationary satellites might not have sufficient sensitivity to detect such very thin clouds. Moreover, the split-window method is inadequate for clouds extending around the tropopause because the vertically monotonic decrease of temperature is lost at such altitudes, which prevents accurate estimation of cloud-top heights. In this study, we constructed LUTs using CALIOP data and we evaluated their efficacy by comparison with LUTs based on CPR data.

2. Data and method

We utilized the 2B-GEOPROF and 2B-PLUS products version 4 (Marchand et al. 2008; Polonsky et al. 2008) of the CPR ob-
where no cloud was observed by the CPR from HN10. In HN10, a height of 0 km was assigned to pixels determined as reflecting cloud-free conditions or having cloud-top heights < 3 km and such pixels were incorporated in the calculation of the regression. In this study, such pixels were excluded from the calculations.

We calculated the regressions separately for some concentric geometric rings centered at the nadir point and having different zenith angles to the geostationary satellites. While all were included in our products, only the results for zenith angles < 15° are described in this article.

3. LUT of cloud-top height using CALIOP data

Figure 2 shows the frequency distributions of cloud-top heights of tropical clouds within 20°N−20°S observed by the CALIOP and the CPR for almost two years as a function of the optical depth of the highest cloud layer. For CALIOP, we calculated optical depth by integrating the extinction coefficient from the top of each cloud layer downwards. In the CALIOP observations (Fig. 2a), the largest frequency is found just below the tropopause height (16 km). It should be noted that the altitude of maximum frequency does not depend on the optical depth of the first cloud layer from the top. Many clouds that have a wide range of visible optical depth (τ) properties, i.e., from subvisible (τ < 0.03) through thin (0.03 < τ < 0.3) to opaque (0.3 < τ), have their tops at this altitude. (Note, this classification is traditional, e.g., Sassen et al. (2009).) Figure 2b shows the results of the CPR. The largest frequency is found at 13.5 km, far below that of the CALIOP. The CALIOP cloud tops are considered much closer to the actual cloud tops.

We attempted to construct LUTs of cloud-top heights using CALIOP data and to evaluate them against those created using CPR data (hereafter, LUT_CPR) (Fig. 3a), as in previous versions and in HN10. We also used the level 2 cloud profile (version 3) of CALIOP data (Winker et al. 2009) obtained from NASA Langley Research Center, which has horizontal resolution of 5 km and vertical resolution of 60 m.

We used the IR split-window data of three geostationary satellites: MTSAT-1R, MTSAT-2, and Himawari-8. These data were obtained from the Center for Environmental Remote Sensing, Chiba University, Japan. Because the important properties in the results were common to all three geostationary satellites, we describe the results for the Himawari-8 satellite (July 2015–June 2017) in the following. The data were processed to 0.04° grids, and the observation time interval was 10 min. We selected the brightness temperature at 10.4 µm (T_{10.4}) and 12.4 µm (T_{12.4}) from three wavelengths in the atmospheric window (Murata et al. 2015; Bessho et al. 2016), and we calculated the difference ΔT = T_{10.4} − T_{12.4} for each pixel.

Lookuptables (LUTs) were constructed according to the procedure described in HN10. A brief outline is given here for the case of the LUT based on CPR data. We regressed the cloud-top height observed by the CPR with the T_{10.4} and the ΔT observed by the geostationary satellites. We changed the condition of positional matching between CPR and geostationary satellites from HN10, i.e., at least one CPR observation was within a 0.04° box from the center of each pixel of the geostationary satellites in the time difference smaller than 5 min. The regression was applied for each 1.0 × 0.1 K point in the phase space of T_{10.4} and ΔT. A simple average within the 10 × 1 K area in the phase space was used in the calculation of the regression. Although a sophisticated weighted average method was applied in HN10, we found that the results obtained using both methods were similar because of the large number of samples from Himawari-8; thus, we chose the simpler area averaging method in this version. The similar matching mentioned above was also applied to the CALIOP data. The extra operations required to define cloud tops in CALIOP data are discussed in Section 3. We also changed the treatment for pixels where no cloud was observed by the CPR from HN10. In HN10, a height of 0 km was assigned to pixels determined as reflecting cloud-free conditions or having cloud-top heights < 3 km and such pixels were incorporated in the calculation of the regression. In this study, such pixels were excluded from the calculations.

We calculated the regressions separately for some concentric geometric rings centered at the nadir point and having different zenith angles to the geostationary satellites. While all were included in our products, only the results for zenith angles < 15° are described in this article.

3. LUT of cloud-top height using CALIOP data

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We attempted to construct LUTs of cloud-top heights using CALIOP data and to evaluate them against those created using CPR data (hereafter, LUT_CPR) (Fig. 3a), as in previous versions and in HN10. First, we simply used the cloud-top heights observed by the CALIOP in the regression of the geostationary satellite data. The obtained LUT is shown in Fig. 3b. (We call the
When compared with the LUT_CPR, the estimated cloud-top heights in LUT_0.0 are, as expected, significantly higher, particularly in the high $T_{10.4}$ ranges. However, the estimated heights are within 15−17 km in most of the region in the LUT.

Such a uniform distribution shown in Fig. 3b is further examined. Figure 4a shows cloud-top height versus the $\Delta T$ distribution of the samples observed by the CPR, their probability density, and the estimated cloud heights and standard deviations of the samples (hereafter, SD) along the line $T_{10.4} = 250$ K ± 5.0 K in the LUT (Fig. 3a). The samples are concentrated in a relatively small vertical range. Figure 4b shows the same parameters for the CALIOP cloud tops. In contrast to the CPR data, there are many samples near the tropopause (16−18 km) at most of $\Delta T$ values. The largest
probability density appears at around 16 km, far above the average of most of the ΔT range, which results in a much larger SD than in Fig. 4a. Such thin cirriform clouds around the tropopause are distributed over most of the LUT domain (not shown), whereas they have almost constant cloud top height as we see in Fig. 4b. It shows that the combination of $T_{10.4}$ and $\Delta T$ is insufficient to distinguish these thin high clouds.

To avoid the effects of optically thin cloud layers positioned near the tropopause, we defined the height of a specified optical depth from the top ($\tau_{\text{min}}$) as “cloud top”. Of course, this height is somewhat lower than the actual cloud top. In some cases, the height is located in the first cloud layer from the top, and in others, it is in or lower than the second cloud layer. The LUT when $\tau_{\text{min}} = 0.2$ (hereafter LUT 0.2) is shown in Fig. 3c. This choice of $\tau_{\text{min}}$ is not objectively decided one, but one of the practical choices. The sensitivity of the results on $\tau_{\text{min}}$ will be discussed later. One example of the relationship among this height of $\tau_{\text{min}} = 0.2$ and CPR and CALIOP cloud tops is shown in Fig. 1. As anticipated, in Fig. 4c showing the $\tau_{\text{min}} = 0.2$ results, the probability density at altitudes > 15 km is clearly smaller than for the case of $\tau_{\text{min}} = 0.0$ (Fig. 4b), particularly in the $\Delta T < 4$ K range, and this causes the smaller SD.

The difference between the estimated cloud top heights of the original scheme $\tau_{\text{min}} = 0.0$ (Fig. 3b) and those in the scheme with $\tau_{\text{min}} = 0.2$ (Fig. 3c) is exhibited in Fig. 5a. Within most of the region in the LUT, the estimated height in the $\tau_{\text{min}} = 0.2$ scheme is lower than in the $\tau_{\text{min}} = 0.0$ scheme. The difference is largest in the region with high $T_{10.4}$ and small $\Delta T$. Comparison of the SDs is shown in Fig. 5b. The SD is smaller when $\tau_{\text{min}} = 0.2$ than when $\tau_{\text{min}} = 0.0$, except for the region with high $T_{10.4}$ and large $\Delta T$, where the samples are clearly separated into two height ranges (over 10 km and within 4–8 km) (Fig. 4d). For the improvement in this range, we should consider the use of other wavelengths like IR absorption band (Heidinger et al. 2010).

The LUTs of the CALIOP estimation with $\tau_{\text{min}} = 0.2$ (Fig. 3c) and that of the CPR (Fig. 3a) show similar patterns. We intended to correct the underestimation of the cloud-top heights of cirriform clouds in LUT CPR (Fig. 3a) by introducing CALIOP data, and this aim was achieved in the cirrus parameter regions with large $\Delta T$ (Fig. 5c). The correction is remarkable in the region with high $T_{10.4}$ and large $\Delta T$. However, in the region with small $\Delta T$, the estimated height based on the CALIOP data with $\tau_{\text{min}} = 0.2$ is rather lower than that of the CPR data, contrary to our intention. This small $\Delta T$ region in the LUT corresponds approximately to precipitating clouds such as cumulonimbus and nimbostratus (HN10). We suspect that this reversal of the height estimation is caused by the presence of large ice particles in the upper parts of such precipitating clouds (Rickenbach et al. 2008). Cloud radar has high sensitivity to such large particles; thus, the underestimation of cloud-top heights might possibly be very small in these types of cloud. In comparison, the height with $\tau_{\text{min}} = 0.2$ is considerably lower than the actual cloud-top height because the lidar is not particularly sensitive to the large particles. Figure 5d shows the difference in the SD and in most of the region, no systematic difference is evident.

To see the difference according to the $\tau_{\text{min}}$ value, we prepared Fig. 6, which shows the dependency of the estimated height on $\tau_{\text{min}}$ for some combinations of $T_{10.4}$ and $\Delta T$. As $\tau_{\text{min}}$ increases, the estimated cloud-top height decreases rapidly. Small $\tau_{\text{min}}$ values ($\leq 0.1$) lead to serious effects associated with tropopause clouds to which IR observations are insensitive (not shown), while large $\tau_{\text{min}}$ values cause serious underestimation of height. Therefore, it is imperative that the value of $\tau_{\text{min}}$ be chosen carefully. Since our choice of $\tau_{\text{min}} = 0.2$ is close to the border of traditional ‘thin’ and ‘opaque’ clouds ($\tau = 0.3$), the target of this LUT is roughly opaque cirriform clouds, at least from the viewpoint of CALIOP, and other precipitating clouds including nimbostratus and cumulonom-
bus whose tops are in the upper troposphere. As shown above, our choice of the threshold $\tau_{\text{min}} = 0.2$ is not perfectly objective and not uniquely decided. Obtaining objective threshold is an important future work.

Seasonal dependence was found to be small in the LUT with the CPR data (HN10), which might reflect the small seasonal variation of the temperature profile in the tropical troposphere. However, both the temperature and the height around the tropopause have distinct seasonal changes (Yulaeva et al. 1994). The LUT based on the CALIOP, which has greater sensitivity than the CPR to clouds around the tropopause, might have significant seasonal change. In our preliminary research, considerable seasonal change was detected in the estimated height in the LUT; however, our Himawari-8 record is too short to discuss any seasonal difference quantitatively. Once we have accumulated sufficient Himawari-8 data, we will consider creating seasonal LUTs.

Although the adoption of LUT$_{0.2}$ corrects the underestimation of the heights of cirriform cloud, it introduces the unwanted side effect of underestimation of the cloud-top heights of cumulonimbus and nimbostratus. We might propose a combination of the two LUTs to create a single practical LUT. In such a hybrid scheme, for each point in the LUTs, the higher of the values in the LUT$_{\text{CPR}}$ and the LUT$_{0.2}$ should be chosen.

4. Conclusions

We developed a method for the estimation of cloud-top heights using only split-window channels of IR observations from
three geostationary satellites. We created LUTs by regression of them with direct observations of cloud top height from the CALIOP onboard the CALIPSO satellite and the CPR onboard the CloudSat satellite. In our previous estimation scheme using cloud radar, the heights of cirriform clouds had been underestimated. In this study, using CALIOP data, we succeeded in reducing the underestimation of the heights of cirriform clouds. Although the CALIOP can detect optically thin clouds around the tropopause, their top heights cannot be estimated well based on split-window observations. By defining the altitude at which the optical depth from the top was a specified value \( \tau_{\text{min}} (= 0.2) \) as the cloud-top height, we created a practical LUT to estimate the cloud top height even for the cirriform clouds. In the LUT, the underestimation of the heights of cirriform clouds were corrected substantially, while reducing the effect of the low sensitivity of split-window observations to thin tropopause cloud. We intend future works on this scheme. For example, the adoption of hybrid regression with CPR and CALIOP data to correct the underestimation of cloud-top height of precipitating clouds, creation of seasonal LUTs using CALIOP data, and utilization of the extra information from CALIOP observations such as the depolarization ratio. We are now extending our dataset to mid-latitude areas by estimating cloud-top temperature instead of cloud-top height as in the tropics. We also plan to extend the dataset to the period before the launch of CloudSat and CALIPSO by comparing the radiance of many geostationary and polar-orbiting satellites one by one.

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