Cloud Type and Top Height Estimation for Tropical Upper-Tropospheric Clouds Using GMS-5 Split-Window Measurements Combined with Cloud Radar Measurements

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Abstract

Cloud types of tropical upper-tropospheric stratiform clouds (UTSCs) were estimated using split-window brightness temperatures (Tb) measured by a geostationary satellite. For non-precipitating high clouds, cloud-top heights were estimated. Observation-based estimation tables in terms of 10.8 µm Tb(T₁₁) and the difference between T₁₁ and 12 µm Tb(ΔT = T₁₁ − T₁₂) were presented using ship-borne cloud radar measurements conducted during three months in the tropical warm-pool region. After defining the cloud types and cloud-top height using radar measurements, their detectabilities were shown as the function of T₁₁ and ΔT. The detectability of non-precipitating UTSCs is higher in regions with T₁₁ between 220 and 275 K and higher ΔT. Surface precipitation is more detectable in regions with low T₁₁ and small ΔT. The estimated cloud-top height of non-precipitating UTSCs tends to rise with decreasing T₁₁ and increasing ΔT. The variation in the cloud-top estimates with ΔT reached a few kilometers at T₁₁ of ~250 K.

1. Introduction

Tropical deep convective activity is known to be accompanied by large stratiform clouds extending in the upper troposphere (e.g., Houze 1997). These stratiform clouds (hereafter referred to as upper-tropospheric stratiform clouds or UTSCs) generally consist of nimbostratus with precipitation and cirriform clouds without precipitation (non-precipitating UTSCs).

Non-precipitating UTSCs often extend up to more than a thousand kilometers, and play a key role in maintaining the water vapor content in the upper troposphere. To clarify how tropical cloud systems influence the moisture content in the tropical troposphere, knowledge about the spatial and temporal evolution of the vertical location and ice content of the non-precipitating UTSCs is required. The non-precipitating UTSCs also play an important role in the Earth’s radiative budget. They heat the atmosphere by absorbing terrestrial radiation, and simultaneously cool it by reflecting solar radiation. The degree to which the atmosphere is heated or cooled depends on the UTSCs’ geometrical and radiative characteristics, such as the cloud-top height and optical thickness (e.g., Hartmann 2001). However, global distribution of the cloud-top height and optical thickness of the non-precipitating UTSCs is estimated only roughly.

Infrared brightness temperatures (Tb) measured by geostationary satellites are often used to detect the convective activity that generates the UTSCs (e.g., Udelhofen and Hartmann 1995). However, a threshold adopted in previous studies uses only a single infrared Tb and has difficulty discriminating between precipitating UTSCs and optically thick non-precipitating UTSCs. Geostationary satellites are most effective for observing large, long-lived tropical cloud systems. In the tropics, diurnal cloud variation dominates (e.g., Chen and Houze 1997), and the non-precipitating UTSCs often persist for up to a day. Therefore, to describe the temporal evolution of the UTSCs, a data and analysis method applicable during both daytime and nighttime, is preferred.

The split-window method (Inoue 1985, 1987) using two Tb measurements at infrared window wavelengths, e.g., 10.8 (T₁₁) and 12 µm (T₁₂), can be used during both daytime and nighttime, and it is applicable to recent geostationary satellites. In a simplified radiative transfer model of the ground surface and a single-layer “cloud” without geometrical thickness (hereafter referred to as the simplistic model), the height and optical thickness of the cloud is expressed in terms of T₁₁ and ΔT = T₁₁ − T₁₂ (e.g., Cooper et al. 2003). Using this fact, extensive algorithms have been developed to classify clouds (e.g., Luo et al. 2002) and estimate the cloud-top height and optical thickness (e.g., Inoue 1985), using split-window Tb measurements. However, the simplistic model is highly sensitive to other parameters such as the effective radius and shape of cloud ice (Stephens and Kummerow 2007). Validation using observational data is required.

Validation of the split-window methods using in-situ observational data has been limited to small areas and/or short periods because of the difficulty in observing the non-precipitating UTSCs. Recently, datasets have become available with observations using instruments, such as cloud radar and lidar, which can probe the internal structure of the non-precipitating UTSCs. The purpose of this study is to present an estimation table of the cloud type and cloud-top height using split-window Tb measured by a geostationary satellite. The table is validated using ship-borne cloud radar measurements conducted during three months.

2. Data and analysis method

We used two brightness temperature (Tb) measurements at infrared split-window wavelengths observed by the fifth Geosynchronous Meteorological Satellite...
The occurrence rate of each cloud type in T11-ΔT space was computed by the maximum-likelihood estimation method (Silverman 1986). Smoothing parameters for PDF estimation were obtained by linear spatial interpolation, using four grids around the vessel. For each cloud radar profile, cloud layers were defined as at least three consecutive vertical bins, where the radar signal was 0.1 dB above the noise level (Okamoto et al. 2003). The precipitation flag was set when the radar profile had any vertical bin with Z > -16 dBZ (Wang and Geerts 2003) and V比利 ≤ 1 m s” below 3 km.

The samples were classified into five categories (hereafter referred to as cloud types) using cloud layer and precipitation flag information: 1) Non-precipitating high clouds that has echo top height (z1) higher than 7 km (H-NR-type), 2) Non-precipitating low clouds that has echo top height lower than 7 km (L-NR-type), 3) Surface precipitating clouds with non-precipitating clouds 3 km higher than them (M-type), 4) Surface precipitating clouds with non- accompanying non-precipitating clouds (R-type), and 5) Clear sky (C-type). Note that some of R-type samples may be C-type, because the cloud radar signal is heavily attenuated by precipitation particles. There were 508, 27, 42, 143, and 597 samples of H-NR, L-NR, M-, R-, and C-type, respectively.

We defined the occurrence rate of each cloud type in T11-ΔT space as follows. First, the bivariate probability density function (PDF) in T11-ΔT space was computed for each cloud type using a two-dimensional Epanechnikov kernel in both the T11 and ΔT dimensions (Silverman 1986). Smoothing parameters for PDF estimation were computed by the maximum-likelihood cross-validation technique. The computed smoothing parameters for each dimension were (2.97, 0.39), (3.92, 0.62), (9.07, 0.43), (4.44, 0.39), and (2.87 K, 0.27 K) for H-NR, L-NR, M-, R-, and C-type, respectively. Next, each PDF was multiplied by the ratio of the number of corresponding samples to that of all samples. Finally, the occurrence rate of each cloud type in T11-ΔT space was calculated as the ratio of the corresponding PDF to the sum of PDFs for all the cloud types.

For estimating the cloud-top height using GMS-5 split-window T比利 measurements, we used the value of z比利 as the index of the cloud-top height, which was estimated by nonparametric regression of z比利 over T比利 and ΔT. We adopted the Nadaraya-Watson estimator (Scott 1992) with the same kernel and T比利-ΔT space, as well as the common logarithm of the respective samples to that of all samples. Finally, the occurrence rate falls in the region with T比利 > 280 K, mainly due to the higher number of samples belonging to the C-type, because the cloud radar signal is heavily attenuated by precipitation particles. There were 508, 27, 42, 143, and 597 samples of H-NR, L-NR, M-, R-, and C-type, respectively.

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of surface precipitation higher than 60%. As a result, more than 7-km thick stratiform cloud layers were observed in about two-thirds of all samples (not shown). It is believed that these dense cloud layers originated from nimbostratus with deep convective activity in the tropics. Therefore, even where the occurrence rate of surface precipitation is ~60%, it is very likely that convective activity exists close to GMS-5 observation point.

3.2 Cloud-top height estimation for non-precipitating UTSCs

In the simplistic model, the relationship between \( T_{11} \) and \( \Delta T \) when the height and effective radius of the “cloud” remains constant shows an upward arch in \( T_{11}-\Delta T \) space (e.g., Cooper et al. 2003). The arched distribution of the H-NR-type samples in \( T_{11}-\Delta T \) space (Fig. 1) is reminiscent of the curves of \( T_\text{top} \) versus \( \Delta T \) for the cloud-top heights expected from this model. Figure 4 shows the result of cloud-top height estimation for the H-NR-type samples, obtained by regressing \( z_\text{t} \) over \( T_{11} \) and \( \Delta T \). The estimated \( z_\text{t} \) (solid lines) generally increases with decreasing \( T_{11} \) and increasing \( \Delta T \). Isopleths mostly tend to tilt rightward from the vertical, except in the region with high \( T_{11} \) and small \( \Delta T \). The variation in the cloud-top estimates varies significantly with \( \Delta T \), and reaches a few kilometers at \( T_{11} \) of ~250 K. The standard deviations of \( z_\text{t} \) (dashed lines) tend to be small, as the \( z_\text{t} \) estimate increases. They peak at most ~2.0 km when the estimated \( z_\text{t} \) is higher than 12 km. The above results demonstrate that GMS-5 split-window TB effectively estimates the cloud-top height of the non-precipitating UTSCs.

It is interesting to compare the results shown in Fig. 4 with the following two estimation methods based on the simplistic model. The first is a single infrared channel method, where the value of \( T_{11} \) is considered to be equal to the cloud-top temperature. This method may significantly underestimate the cloud-top height, particularly for clouds with \( T_{11} \) of ~250 K and large \( \Delta T \). The second is a two-channel method using split-window measurements. Curves of \( T_{11} \) versus \( \Delta T \) for \( z_\text{t} \) are largely consistent with those for cloud-top heights expected from the simplistic model, while the estimated \( z_\text{t} \) at around \( \Delta T = 0 \) shows a notable feature. In the simplistic model, zero \( \Delta T \) means that the cloud has infinitely large optical thickness, and is located at a height where the temperature just equals \( T_{11} \). However, even in regions where \( T_{11} \) is low enough to neglect the water vapor effect, \( z_\text{t} \) estimated using cloud radar measurements is still higher than expected from the mean temperature profile computed from the ERA-40 objective analysis data over the analysis period (not shown). For example, a temperature of 220 K corresponds to ~12.5 km in the tropics, whereas the estimate of \( z_\text{t} \) at \( T_{11} = 220 \) K and \( \Delta T = 0 \) K is ~1.5 km higher. This discrepancy is of interest for future studies.
Cloud-top height estimates of the H-NR-type samples generally rise with decreasing $T_{11}$ rather than being constant. The inclination of isopleths in the region $T_{11} < 265$ K suggests that the threshold value of $T_{11}$ for H-NR-type samples is broadly distributed in $T_{11}$-$\Delta T$ space. After calculating the bivariate PDF for each cloud type, the occurrence rate in $T_{11}$-$\Delta T$ space was determined for non-precipitating UTSCs and surface precipitation. Samples of non-precipitating UTSCs (H-NR-type) are broadly distributed in $T_{11}$-$\Delta T$ space, while samples of precipitating clouds (R-type) occur in the region where $\Delta T$ is small. Distributions of H-NR- and R-type samples differ particularly in the region with $T_{11}$ between 220 and 275 K, resulting in a high occurrence rate of non-precipitating UTSCs in this region. Occurrence rates of non-precipitating UTSCs generally tend to increase with increasing $T_{11}$ and $\Delta T$. The variation along $\Delta T$ reaches a few kilometers at $T_{11}$ of $\sim 250$ K, indicating that information about $\Delta T$ is important for the estimation of cloud-top heights of the non-precipitating UTSCs. The shape of isopleths for estimated $z_t$ is largely consistent with those for cloud-top height expected from the simplistic model. Observation-based quantitative results were shown in the present study.

Spaceborne cloud radar measurements can estimate the cloud-top height, regardless of precipitating or non-precipitating conditions. We are currently undertaking an analysis using cloud radar measurements from the CloudSat satellite. Using this radar measurements, the analysis method employed in the present study can be applied easily to data from other geostationary satellites that perform split-window $T_b$ observations. Records of more than one year would clarify the regional, seasonal, and diurnal variation of UTSC properties.

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References


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