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 (T_B) measured by a geostationary satellite. For non-precipitating high clouds, cloud-top heights were estimated. Observation-based estimation tables in terms of $10.8\ \mu\text{m}\ T_B$ (T_{11}) and the difference between T_{11} and $12\ \mu\text{m}\ T_B$ ($\Delta T = T_{11} - T_{12}$) 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 T_{11} and ΔT . The detectability of non-precipitating UTSCs is higher in regions with T_{11} between 220 and 275 K and higher ΔT . Surface precipitation is more detectable in regions with low T_{11} and small ΔT . The estimated cloud-top height of non-precipitating UTSCs tends to rise with decreasing T_{11} and increasing ΔT . The variation in the cloud-top estimates with ΔT reached a few kilometers at T_{11} 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; 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 (T_B) 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 T_B , 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 T_B measurements at infrared window wavelengths, e.g., $10.8\ \mu\text{m}$ (T_{11}) and $12\ \mu\text{m}$ (T_{12}), 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 T_{11} and $\Delta T = T_{11} - T_{12}$ (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 T_B 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 T_B 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 (T_B) measurements at infrared split-window wavelengths observed by the fifth Geosynchronous Meteorological Satellite

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(GMS-5). Response functions for two channels are centered at 10.8 (T_{11}) and 12 μm (T_{12}), respectively. The horizontal resolution of the original data is ~ 4 km at nadir (140°E , 0°N); hourly data on a 0.05° grid is used in this study. The temperature resolution is ~ 0.4 K at 300 K, and it is slightly coarser at lower temperatures, ~ 1.4 K at 210 K. To define the cloud types and estimate the cloud-top height, radar reflectivity (Z) and Doppler velocity (V_D) measurements obtained from the millimeter-wave (wavelength 3.16 mm) cloud radar developed by National Institute of Information and Communications Technology (NICT) were used. This radar was installed on *Mirai*, which is a research vessel of the Japan Marine Science and Technology Center (JAMSTEC), and made vertical observations in the tropical warm-pool region from September to December 2001. In this study, we used data between 90°E – 140°E and 15°S – 15°N . The vertical and temporal resolutions were 82.5 m and 10 s, respectively.

We obtained 1317 samples with paired cloud radar and GMS-5 measurements during the analysis period, as described below. The vertical profiles of Z and V_D were averaged within 2 minutes centered at the time when GMS-5 observed the location of the vessel. Corresponding values of T_{11} and ΔT 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 $V_D \leq -1$ m s $^{-1}$ 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 (z_T) 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 no accompanying non-precipitating clouds (R-type), and 5) Clear sky (C-type). Note that some of R-type samples may be M-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 T_{11} - ΔT space as follows. First, the bivariate probability density function (PDF) in T_{11} - ΔT space was computed for each cloud type using a two-dimensional Epanechnikov kernel in both the T_{11} 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 T_{11} - 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_B measurements, we used the value of z_T as the index of the cloud-top height, which was estimated by nonparametric regression of z_T over T_{11} and ΔT . We adopted the Nadaraya-Watson estimator (Scott 1992) with the same kernel as used in PDF estimation. The smoothing parameter was computed again by the least-square cross-validation technique, and was (6.98 K, 0.39 K). In this study, we show the results only for H-

NR-type samples, because the value of z_T could not be defined by ground-based cloud radar observations under precipitating conditions.

3. Results

3.1 Distribution and occurrence rate of each cloud type in T_{11} - ΔT space

Figure 1 shows the distribution of all samples in T_{11} - ΔT space, as well as the common logarithm of the bivariate PDF for H-NR- (solid lines) and R-type (dashed lines) samples. The H-NR-type samples (green) are distributed broadly in the T_{11} direction. PDF for H-NR-type shows that the center of distribution along the ΔT axis varies with T_{11} . It peaks near 3 K at around $T_{11} = 270$ K, and drops with both increasing and decreasing T_{11} . The R-type samples (red) are also distributed broadly in the T_{11} direction. However, the distribution along the ΔT axis differs substantially from that of the H-NR-type. The center of R-type distribution along the ΔT axis tends to remain at ΔT lower than 1 K in the region where $T < 270$ K. The M-type samples (yellow) tend to have a larger ΔT than the R-type samples. The centers of distribution along the ΔT axis are at ~ 2.5 K between 230 and 260 K, and ~ 1.5 K elsewhere (not shown). The distributions of both C- (blue) and L-NR-type (light blue) samples concentrate in high- T_{11} regions, with minor exceptions.

The observed difference in the distributions of the H-NR- and R-type samples indicates the detectability of the non-precipitating UTSCs using GMS-5 split-window T_B . We calculated the sum of H-NR- and M-type occurrence rates for examining the occurrence rate of the non-precipitating UTSCs, regardless of the precipitation from the underneath cloud. The results are shown in Fig. 2. The occurrence rate basically increases with ΔT when $T_{11} < 270$ K. The highest value, which is over 80%, is found in the region with T_{11} between 220 and 270 K and large ΔT . Since the H-NR-type samples tend to show a high value of ΔT in this region, as mentioned above (Fig. 1), this demonstrates that the high value of ΔT can effectively detect the non-precipitating UTSCs. The occurrence rate falls in the region with $T > 280$ K, mainly due to the higher number of samples belonging to the C- or the L-NR-type. It is noteworthy that isopleths between 50 and 70% in Fig. 2 tend to rise with decreasing T_{11} when $T_{11} < 265$ K. Constant values of ΔT with respect to T_{11} have been used as a threshold value to detect cirrus clouds by the split-window T_B (e.g., Luo et al. 2002). However, the observation-based results (Fig. 2) indicate that threshold values of ΔT for cloud classification are dependent on T_{11} rather than being constant.

Next we examined the detectability of surface precipitation using GMS-5 split-window T_B measurements, by showing the sum of R- and M-type occurrence rates (Fig. 3). Note that the sum of the values shown in Figs. 2 and 3 exceeds 100% in some regions. Higher values are found in regions with lower T_{11} and smaller ΔT . In the region with $T_{11} > 220$ K, the occurrence rate increases with decreasing ΔT , indicating that split-window T_B can estimate tropical rainfall more effectively than a single infrared channel method such as the GOES Precipitation Index (GPI; Arkin and Meisner 1987).

It is noteworthy that the occurrence rate of non-precipitating UTSCs is still up to $\sim 50\%$ in the region with very low T_{11} and small ΔT , since the single-channel threshold of T_{11} around 210 K has been believed to detect the precipitating core of tropical deep convective activity (e.g., Chen and Houze 1997). We examined the time-height cross section of Z for all H-NR- and M-type samples located in the region where an occurrence rate

Fig. 1. Distribution of samples of all cloud types defined by cloud radar profiles. Ordinate and abscissa indicate T_{11} and ΔT , respectively. H-NR, L-NR, M-, R-, and C-type samples are indicated by green, light blue, yellow, red, and blue marks, respectively. Solid and dashed lines indicate the sum of bivariate PDFs for H-NR- and R-type samples, respectively. The PDF is shown as a common logarithm and the contour interval is 0.5 from -3.5 .

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 $\sim 60\%$, 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 ΔT when the height and effective radius of the “cloud” remains constant shows an upward arch in T_{11} - ΔT space (e.g., Cooper et al. 2003). The arched distribution of the H-NR-type samples in T_{11} - ΔT space (Fig. 1) is reminiscent of the curves of T_{11} versus ΔT 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_T over T_{11} and ΔT . The estimated z_T (solid lines) generally increases with decreasing T_{11} and increasing ΔT . Isopleths mostly tend to tilt rightward from the vertical, except in the region with high T_{11} and small ΔT . The variation in the cloud-top estimates varies significantly with ΔT , and reaches a few kilometers at T_{11} of ~ 250 K. The standard deviations of z_T (dashed lines) tend to be small, as the z_T estimate increases. They peak at most ~ 2.0 km when the estimated z_T is higher than 12 km. The above results demonstrate that GMS-5 split-window T_B 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

Fig. 2. Occurrence rates of non-precipitating UTSCs as the sum of H-NR- and M-type occurrence rates in T_{11} - ΔT space (see text for details). The contour interval is 10%. Contours and shadings are omitted where the $\log_{10}(\text{PDF})$ in Fig. 1 is less than -3.3 .

Fig. 3. Same as Fig. 2, but for surface precipitation as the sum of R- and M-type occurrence rates.

significantly underestimate the cloud-top height, particularly for clouds with T_{11} of ~ 250 K and large ΔT . The second is a two-channel method using split-window measurements. Curves of T_{11} versus ΔT for z_T are largely consistent with those for cloud-top heights expected from the simplistic model, while the estimated z_T at around $\Delta T = 0$ shows a notable feature. In the simplistic model, zero ΔT 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_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_T at $T_{11} = 220$ K and $\Delta T = 0$ K is ~ 1.5 km higher. This discrepancy is of interest for future studies.

Fig. 4. Estimates (shading) and standard deviations (dashed contours) of z_T for H-NR-type samples obtained by regression of z_T over T_{11} and ΔT (see text for details). The contour intervals are 1 km and 0.5 km for the estimates and standard deviations, respectively. No contours are shown where the $\log_{10}(\text{PDF})$ in Fig. 1 is less than -3.3 .

4. Concluding remarks

An estimation table of types of tropical upper-tropospheric clouds determined by GMS-5 split-window brightness temperature (T_B) measurements was shown. For non-precipitating high clouds, the cloud-top height was also estimated using split-window T_B . The estimation table shown here is validated using ship-borne cloud radar measurements conducted during three months.

Distribution of cloud types defined from cloud radar measurements is shown in T_{11} - ΔT space. After calculating the bivariate PDF for each cloud type, the occurrence rate in T_{11} - ΔT space was determined for non-precipitating UTSCs and surface precipitation. Samples of non-precipitating UTSCs (H-NR-type) are broadly distributed in T_{11} - ΔT space, while samples of precipitating clouds (R-type) occur in the region where ΔT 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 UTSC generally tend to increase with increasing ΔT . The inclination of isopleths in the region with $T_{11} < 265$ K suggests that the threshold value of ΔT for cloud classification should be dependent on T_{11} rather than being constant.

Cloud-top height estimates of the H-NR-type samples generally rise with decreasing T_{11} and increasing ΔT . The variation along ΔT reaches a few kilometers at T_{11} of ~ 250 K, indicating that information about ΔT 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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