Classification of precipitating clouds using satellite infrared observations and its implications for rainfall estimation

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Percipitation estimates from satellite infrared (IR) radiometers are typically based on cloud top temperatures. However, these temperatures are weakly related to surface rainfall, particularly for shallow or warm clouds. This study classifies precipitating clouds into five cloud groups. The classification uses three brightness temperature differences (BTDs) and one BTD difference (ΔBTD) from Himawari-8 Advanced Himawari Imager (AHI): BTD1 (6.2–11.2 \(\mu\text{m}\)), BTD2 (8.6–11.2 \(\mu\text{m}\)), BTD3 (11.2–12.4 \(\mu\text{m}\)), and ΔBTD (BTD2 − BTD3). BTD1 is found to be effective for separating shallow and non-shallow clouds in reference to the Global Precipitation Measurement Dual-frequency Precipitation Radar (DPR) level 2 data. Once this separation is complete, non-shallow clouds are further classified. The negative and positive values of ΔBTD usually indicate more water and more ice in clouds, respectively, distinguishing non-shallow clouds with tall and taller cloud heights. Subsequently, BTD1 is applied to non-shallow-tall/taller clouds. Because these clouds can be considered as optically thick, BTD1 identifies the relative coldness of the cloud top based on the extent of water vapour over the cloud top. The final classification yields four non-shallow cloud types: non-shallow-tall-cold, non-shallow-tall-colder, non-shallow-taller-cold, and non-shallow-taller-colder clouds. The relationships between IR brightness temperatures and surface rainfall obtained from the classified cloud groups over four latitude bands reveal clear differences, implying that separating cloud types and accounting for regional differences are desirable to improve the accuracy of IR-based precipitation measurements.

KEYWORDS
brightness temperature difference, cloud classification, infrared-based precipitation estimation

1 | INTRODUCTION

Precipitation estimates based on infrared (IR) observations from geostationary weather satellites have been widely used as fundamental information for climate studies, hydrological applications, and the monitoring and prediction of severe weather events. In particular, observations of clouds and precipitation from geostationary satellites are extremely beneficial for the continuous tracking of evolving hazardous weather systems because geostationary satellite observations have strong advantages with respect to their temporal resolutions (e.g. Griffith et al., 1978; Arkin and Meisner, 1987; Adler and Negri, 1988). However, precipitation estimates from IR data have a significant disadvantage...
originating from the indirect relationships between cloud top properties and surface rainfall. It is well known that the validity of these relationships depends greatly on the precipitating cloud types. In general, shallow or warm clouds may suffer from weak relationships between cloud top temperature and surface rainfall, whereas the cold cloud top temperatures of tall or cold clouds tend to have better relationships with surface rainfall. For this reason, information on cloud types is considered an important element for better IR-based rainfall estimates.

Several methods have been developed to classify cloud types and cloud phases by using IR radiometer observations. For example, Ackerman et al. (1990), Strabala et al. (1994), and Thies et al. (2008) reported that the brightness temperature difference (BTD) between 8.7 and 10.8 μm [BTD (8.7–10.8 μm)] is useful to identify the cloud phase as ice or water. BTD (6.2–10.8 μm) has also been examined as an effective discriminator for high- and mid-level clouds (Lutz et al., 2003). Inoue (1987) used a threshold technique to classify four types of clouds based on two-dimensional histogram sets with brightness temperature at 11 μm and BTD (11–12 μm). In this method, when BTD (11–12 μm) is greater than 2.5 K, clouds are identified as cirrus. The physical background of these BTD methods is primarily based on the fact that the imaginary part of the complex refractive index is related to the attenuation or absorption of the amplitude of the oscillatory electromagnetic field. That is, absorption increases with the imaginary index for a given wavelength. The spectral differences in the imaginary indices of refraction for water and ice have been calculated by several authors, such as Downing and Williams (1975), Warren (1984), and Warren and Brandt (2008). These authors reported that the imaginary indices of refraction for water and ice in wavelengths in the atmospheric window region between 8 and 13 μm tend to increase monotonically with wavelength. However, one of the most significant spectral differences between water and ice for IR radiation in the wavelength range between 8 and 13 μm resides in wavelengths greater than approximately 10 μm. The imaginary indices of refraction for water and ice are similar to each other over the wavelength range of 8–10 μm, whereas the imaginary index for ice is significantly larger than that for water over the wavelengths ranging from 10 to 13 μm.

Based on the characteristics of BTD for water and ice clouds and thick clouds, it may be possible to discriminate shallow and non-shallow precipitating clouds using BTDs. That is, the BTD between a wavelength smaller than 10 μm and that larger than 10 μm may be used to discriminate between shallow and non-shallow clouds. One expects that shallow clouds are primarily composed of water in the liquid phase, suggesting negative values of BTD. Meanwhile, non-shallow clouds are assumed to be optically thick such that BTD may be insignificant with values near zero.

In this article, the results of using various BTDs to separate precipitating cloud types are examined. The data used in this study are explained in section 2. The physical backgrounds and results of classifying the precipitation clouds are presented from sections 3 to 5. The summary and conclusions are provided in section 6.

2 | DATA AND METHODS

2.1 | Data

IR brightness temperature (TB) data from the Advanced Himawari Imager (AHI) on board Himawari-8 operated by the Japan Meteorological Agency are used. The AHI employs 16 channels to capture images from the visible to IR spectral regions. This study uses TB data from one water vapour channel and three thermal IR channels whose central wavelengths are located at 6.2, 8.6, 11.2 and 12.4 μm, respectively. To obtain physical information concerning the precipitating clouds, the level 2 data of the Dual-frequency Precipitation Radar (DPR) carried by the Global Precipitation Measurement (GPM) satellite are used. The DPR data contain various rain characteristics. This study uses the shallow rain flag, the near-surface rain rate, and the height of the storm top (or the storm height).

This study compares the IR data from AHI and the level 2 data from DPR (DPR algorithm). The datasets have different spatial resolutions: 2 km for AHI IR data and 5 km for DPR data at nadir. The datasets are collocated at DPR resolution. There is also a difference in the coverage of the Himawari and GPM satellites. The observation area of Himawari-8 ranges from 80°S to 80°N and from 60°E to 220°E, while the GPM satellite can reach latitudes of approximately 70°S and 70°N. For this reason, the experiment area is limited to 70°S–70°N in latitude and 60–220°E in longitude. All experiments are performed for the period of August 1–31, 2015.

2.2 | Methods

The discrimination of types of precipitating clouds is based on threshold techniques with various BTDs, including three BTDs and one BTD difference. The BTDs are defined as follows:

\[
\text{BTD1} = \text{TB}_{6.2\,\mu m} - \text{TB}_{11.2\,\mu m},
\]

\[
\text{BTD2} = \text{TB}_{8.6\,\mu m} - \text{TB}_{11.2\,\mu m},
\]

\[
\text{BTD3} = \text{TB}_{11.2\,\mu m} - \text{TB}_{12.4\,\mu m},
\]

\[
\Delta \text{BTD} = \text{BTD2} - \text{BTD3},
\]

where TB6.2μm, TB8.6μm, TB11.2μm and TB12.4μm are the brightness temperatures at the corresponding subscripted wavelengths. ΔBTD indicates the difference between BTD2 and BTD3. Precipitating clouds are first classified as shallow or non-shallow. Shallow precipitating clouds are characterized by storm heights lower than the height of the freezing level, that is, 1,000 m, as given in the DPR level 2
description. Non-shallow precipitating clouds are then classified into two cloud types based on the relative size of the cloud (or storm) heights. That is, non-shallow clouds are separated into non-shallow-tall and non-shallow-taller clouds. Both types of non-shallow clouds are further classified into cold and colder types based on the difference in the properties at the cloud top and above. As such, the BTD methods classify five precipitating cloud types: shallow, non-shallow-tall-cold, non-shallow-tall-colder, non-shallow-taller-cold, and non-shallow-taller-colder.

Statistical scores such as the Heidke Skill Score (HSS), the Probability of Detection (POD), and the False Alarm Ratio (FAR) are used to obtain the threshold values of BTDs. HSS measures the fractional improvement in the forecast over a random or reference forecast. Negative values indicate that the forecast is worse than the reference forecast. Negative values indicate that the forecast is worse than the reference forecast. HSS = 0 indicates no skill, and a perfect forecast obtains an HSS of 1. HSS is calculated using the following equation:

\[
HSS = \frac{2 \times (A \times D - B \times C)}{(A + C) \times (C + D) + (A + B) \times (B + D)},
\]

where \(A\), \(B\), \(C\) and \(D\) are described in Table 1. The shallow and non-shallow cloud types discriminated via the DPR and BTD-based methods are used for forecast and observation data, respectively. That is, HSS shows how well the cloud types are classified, using the selected BTD thresholds compared to the DPR observations. \(A\) and \(B\) indicate that DPR recognizes two cloud types (shallow and non-shallow clouds); however, the BTD method classifies both as a single cloud type (shallow clouds). \(C\) and \(D\) are classified into shallow and non-shallow clouds, respectively, by DPR, while the cloud type discrimination by the BTD threshold method shows shallow clouds.

FAR is represented by the equation:

\[
FAR = \frac{B}{A + B}.
\]

Similar to FAR, POD indicates the fraction of shallow (or non-shallow) cloud types that are classified as shallow (or non-shallow):

\[
POD = \frac{A}{A + B}
\]

Both FAR and POD range from 0 to 1; however, these two measurements have opposite properties. That is, FAR is perfect when its value equals 0, while POD is perfect when its value equals 1.

### Table 1

A 2 × 2 contingency table for cloud types derived from DPR and BTD

| Shallow (DPR) | Non-shallow (DPR) |
|--------------|-------------------|
| Shallow (BTD) | A                 |
| Non-shallow (DPR) | B               |
| Non-shallow (BTD) | C               |

Additionally, the Proportion Correct (PC) indicating a percentage of correct classifications is calculated by the equation:

\[
PC = \frac{A + D}{A + B + C + D}.
\]

## 3 | Separation of Shallow and Non-Shallow Precipitating Clouds

Shallow and non-shallow clouds may have significantly different characteristics in terms of cloud thickness, cloud phase and rainfall intensity. This section first provides information on the physical background for discriminating shallow and non-shallow cloud types based on BTDs. The results of separating shallow and non-shallow clouds are then discussed.

### 3.1 | Physical background

According to simulation studies (e.g. Chylek and Ramaswamy, 1982) of the emissivity of water clouds as a function of wavelength and cloud thickness, the spectral difference of emissivity tends to diminish with increasing cloud thickness, and eventually, the emissivity values of water clouds at wavelengths between 8 and 14 μm approach unity for a cloud thickness greater than 500 m. This suggests that brightness temperature differences can become small with increasing cloud optical thickness, or equivalently, increasing cloud thickness.

Moreover, water vapour channels, along with channels in the atmospheric window region (8–12 μm), have been commonly used by many authors to discriminate cloud types for water clouds. For example, Kurino (1997a) demonstrated that deep convective clouds tend to have a BTD between 11 and 6.7 μm that is less than or equal to zero. Kurino (1997b) further used three parameters, the brightness temperature at 11 μm, BTD between 11 and 12 μm, and BTD between 11 and 6.7 μm, to calculate the probability of rain and the mean rain rate. Feidas and Giannakos (2012) developed two schemes to classify convective and stratiform precipitation. These schemes use the brightness temperature at 10.8 μm, BTD between 10.8 and 12.1 μm (which is similar to BTD3), BTD between 8.7 and 10.8 μm (which is similar to BTD2), and BTD between 6.2 and 10.8 μm (which is similar to BTD1). Considering the BTD effect on cloud thickness, BTD1, BTD2 and BTD3 are examined to separate shallow and non-shallow clouds.

### 3.2 | Results

Based on the shallow rain flag from the DPR level 2 data, frequency distributions of shallow and non-shallow clouds as a function of BTD1, BTD2 and BTD3 are shown in Figure 1. The separation of frequency distributions for shallow and non-shallow clouds appears to be more obvious with BTD1...
than with BTD2 or BTD3, suggesting that BTD1 is an effective parameter to distinguish clouds by thickness. Meanwhile, BTD2 and BTD3 may be marginally used in the shallow and non-shallow cloud classification. In fact, BTD2 and BTD3 are generally used to discriminate the cloud phase.

More cloud information from the DPR level 2 data, that is, the occurrence of rain, storm height and surface rainfall rate, is investigated in terms of BTD1 and BTD2 for each cloud type in Figure 2. BTD1 and BTD2 are negative for most shallow clouds, whereas for most non-shallow clouds BTD1 is close to zero and BTD2 is smaller than approximately 5 K (Figure 2a,b). In terms of storm height (Figure 2c,d), shallow clouds tend to have relatively low storm heights of approximately 1–3 km, while non-shallow clouds are distributed at relatively high altitudes greater than approximately 4 km. Figure 2e,f shows the near-surface rain intensities for each cloud type. It is seen that shallow clouds tend to have weaker rainfall intensities, while non-shallow clouds have stronger rainfall intensities with a maximum rain rate of over 10 mm/h. This is more clearly shown in Figure 3. Shallow cloud is distributed where the storm height is less than 6,000 m while non-shallow cloud is distributed over 12,000 m. In terms of near-surface rainfall, weak rainfalls seems to appear more frequently in shallow clouds than non-shallow clouds, while strong rainfalls are more frequent in non-shallow clouds.

In summary, shallow clouds tend to occur in regions where the values of BTD1 and BTD2 are negative, while non-shallow clouds are found when both BTDs are close to zero. The frequency distributions show that BTD1 is the best discriminator to distinguish between shallow and non-shallow clouds, and BTD2 is also a good discriminator, though not as much as BTD1. The different distributions of BTD1 and BTD2 demonstrate the possibility of shallow and non-shallow cloud discrimination based on properly selected BTD thresholds.

Based on the foundation from the DPR and BTD observations, the threshold values of BTDs as discriminators for shallow and non-shallow clouds are estimated by finding the maximum value of HSS. Table 2 shows the thresholds of each BTD along with the maximum values of HSS. The maximum values of HSS are approximately 0.82, 0.26 and 0.0 for BTD1, BTD2 and BTD3, respectively. This suggests that shallow and non-shallow clouds are better separated by BTD1 than by BTD2 or BTD3. The results concur with those shown in Figure 1, which displays the different frequency distributions of each BTD for shallow and non-shallow clouds.

The three possible pairs of BTDs are also evaluated to check if the additional information from BTD2 and BTD3 can improve the cloud classification in Table 3. The BTD pairs are BTD1/BTD2, BTD1/BTD3, and BTD2/BTD3. The cases containing BTD1 show values of HSS similar to that of BTD1 alone, while BTD2/BTD3 produces a significantly lower HSS.

Statistical scores including HSS, POD, FAR and PC for each BTD set are also summarized in Table 3. The skill score for these pairs showed the same statistical scores but we selected the BTD1/BTD2 pair since it showed better statistical scores than others in the previous research with the Spinning Enhanced Visible and Infrared Imager (SEVIRI) data. The first cloud classification for shallow and non-shallow precipitating clouds is based on the threshold values obtained from the BTD1/BTD2 pair. Therefore, the BTD threshold values to discriminate shallow and non-shallow cloud types are −39.8 K for BTD1 and 4.9 K for BTD2. That is, precipitating clouds are classified as shallow clouds when BTD1 is less than −39.8 K and BTD2 is less than 4.9 K. The other cases are classified as non-shallow clouds.

Shallow clouds can be considered as thin clouds that usually appear near the surface. The cloud top temperature of shallow clouds can then be similar to the surface temperature. Therefore, it is difficult to connect brightness temperature with surface rainfall for shallow clouds. In contrast, non-shallow clouds are thick and brightness temperature at the cloud top can be low. Furthermore, it is certain that non-shallow clouds have stronger rainfall intensities than shallow clouds (Figures 2 and 3). It may be useful to investigate the relationship between rainfall rate and brightness temperature for each cloud type. The rainfall rate and
FIGURE 2  Distributions of (a,b) rainfall occurrence (%), (c,d) storm height (m), and (e,f) near-surface rainfall (mm/h), with two variables (BTD1 and BTD2). The cases for shallow and non-shallow clouds are displayed separately in the left (a,c,e) and right (b,d,f) columns, respectively. Lines indicate the threshold values of the selected BTD1 and BTD2.

FIGURE 3  Relative frequency of (a) storm height (m), and (b) near-surface rain (mm/h) for shallow and non-shallow clouds.
4 | CLASSIFICATION OF NON-SHALLOW PRECIPITATING CLOUDS (TALL VERSUS TALLER)

The previous section introduced a method to classify clouds into shallow and non-shallow clouds based on cloud thickness. However, clouds classified as non-shallow may vary significantly in terms of cloud top temperature and storm height. One can expect that non-shallow clouds have different proportions of water and ice particles depending on the cloud height. That is, the taller the non-shallow clouds are, the more ice particles the clouds likely have. This section examines an additional classification of non-shallow clouds based on BTDs that are sensitive to water and ice clouds.

4.1 | Physical background

The spectral differences in the IR radiometric responses to the different phases of water due to their different refractive indices have been widely used to detect water and ice clouds. As mentioned above, Inoue (1987) used a threshold technique with split-window data to generate a cloud type classification map. Moreover, tri-spectral combinations of IR bands were suggested by Ackerman et al. (1990) and Strabala et al. (1994). They used BTDs between 8 and 11 μm and between 11 and 12 μm to classify cloud types. Baum et al. (2000) performed radiative transfer calculations for water and ice clouds using a model-based tri-spectral method and showed that the BTD between 8.5 and 11 μm is clearly different for water and ice clouds. The BTDs are characterized by negative and positive values for water and ice clouds, respectively.

Based on the spectral features of 8–12 μm for ice and water particles, BTD2 and BTD3 can be used to separate the cloud phases into water and ice. That is, BTD2 for ice particles is greater than BTD3, and the opposite is true for water particles. The BTD difference between BTD2 and BTD3, or ΔBTD, can then have positive values for ice particles and negative values for water particles. The different spectral characteristics from BTD2 and BTD3 for water and ice particles are examined as parameters for an additional classification of non-shallow clouds in the next section.

4.2 | Results

Figure 5 presents scatter diagrams of rainfall occurrence, storm height, and near-surface rainfall with BTD2 and BTD3 for non-shallow clouds. The diagonal lines indicate the point where ΔBTD = 0. The upper and lower triangular regions divided by the diagonal lines are characterized by negative and positive values of ΔBTD, respectively. The rainfall occurrences appear to be similar for both triangular regions, as shown in Figure 5a,b. Meanwhile, the storm heights and near-surface rain rates averaged over the two triangular regions are significantly different (Figure 5b,c). That is, the non-shallow clouds contained in the lower triangular region tend to have higher cloud heights and stronger surface rainfalls than the clouds in the upper triangular regions. Based on the different characteristics of non-shallow clouds depending on the magnitude of ΔBTD, the non-shallow clouds appear to be additionally classified into two types of clouds. The two types of non-shallow clouds can be referred to as non-shallow-taller and non-shallow-tall clouds for the lower and upper triangular regions, respectively. The results demonstrate that ΔBTD (BTD2 – BTD3) discriminating ice and water phases of clouds can be used for the regrouping of non-shallow clouds. In short, if ΔBTD is larger than zero, then the non-shallow clouds tend to be composed of more ice and have taller cloud heights. On the other hand, if ΔBTD is smaller than zero, then the non-shallow clouds have more water particles and lower cloud heights.

The R–TB relationships introduced in the previous section are also presented to compare the non-shallow-tall and non-shallow-taller clouds. Figure 6 represents the R–TB relationships in the same way as Figure 4 but for shallow, non-shallow-tall, and non-shallow-taller clouds at 11.2 μm. The R–TB relationships clearly show that stronger rainfall rates tend to be associated with taller clouds. It is also clear

| TABLE 2 | Threshold and HSS values for each BTD |
|----------|-------------------------------------|
|          | BTD1  | BTD2  | BTD3  |
| Threshold (K) | −39.8 | −1.7  | 8.5   |
| HSS       | 0.819 | 0.256 | 0.00002 |

| TABLE 3 | Threshold, HSS, POD, FAR and PC for BTD1 alone and each set of BTDs. POD and FAR for shallow cloud are in brackets |
|----------|-------------------------------------|
|          | BTD1 alone | BTD1, BTD2 | BTD1, BTD3 | BTD2, BTD3 |
| Threshold (K) | −39.8 | −39.8, 4.9 | −39.8, 11.3 | −1.7, 7.1 |
| HSS       | 0.819 | 0.819 | 0.819 | 0.257 |
| POD (SH)  | 0.983 (0.860) | 0.983 (0.860) | 0.983 (0.860) | 0.960 (0.240) |
| FAR (SH)  | 0.012 (0.190) | 0.012 (0.191) | 0.012 (0.190) | 0.181 (0.377) |
| PC        | 0.973 | 0.973 | 0.973 | 0.803 |
FIGURE 4  R–TB relationships for (a,c,e,g) shallow and (b,d,f,h) non-shallow clouds in four latitude bands: (a,b) 80–30°S, (c,d) 30–0°S, (e,f) 0–30°N, and (g,h) 30–80°N. Black dots are the mean rainfall rate and black solid lines are ±1 standard deviation.

FIGURE 5  Scatter diagrams of (a) rainfall occurrence (%), (b) storm height (m), and (c) near-surface rainfall (mm/h) with BTD2 and BTD3 for non-shallow clouds. The diagonal lines indicate the point where ΔBTD equals zero.
that the initial brightness temperatures at the first bin of rainfall rate in the R–TB relationships differ depending on the cloud types. That is, taller clouds are usually associated with colder TBs.

5 | FURTHER CLASSIFICATION OF NON-SHALLOW PRECIPITATING CLOUDS (COLD AND COLDER)

In the previous sections, precipitating clouds were classified into three types: shallow, non-shallow-tall, and non-shallow-taller clouds. The classifications were primarily based on cloud thickness and cloud height. For a further consideration of moisture conditions above the cloud top, an application of BTD is examined in this section.

5.1 | Physical background

The final classification is primarily performed by considering the amount of water vapour above the cloud top. BTD1, defined by the TB difference between 6.2 and 11.2 μm, is different for optically thick clouds such as non-shallow clouds depending on the presence of water vapour above the cloud top. Figure 7 schematically illustrates the relative intensity of BTD1 depending on the amounts of water vapour above the cloud top. Figure 7a presents the case where a thick water vapour layer extends high above the cloud top, making the TB of the water vapour channel much colder than that of the window channel, while a relatively thin layer existing above the cloud top is shown in Figure 7b. Based on this diagram, BTD1 will have larger negative values for the case with a
thicker water vapour layer than for the case with a thinner water vapour layer above the cloud top.

In fact, BTD1 has been considered a useful indicator for discriminating between high- and mid-level clouds. BTD1 has large negative values for mid-level clouds due to the absorption from water vapour above the cloud (Lutz et al., 2003; Giannakos and Feidas, 2013). Again, it is expected that BTD1 has larger negative values when a thick water vapour layer exists above the cloud top compared to the BTD1 values with a thin water vapour layer above the cloud top. However, for some opaque clouds, which are occasionally found above the tropical tropopause, the TB at the water vapour channel tends to be warmer than that from the window channels. Then the BTD between the water vapour channel and window channel may have positive values. Radiation from troposphere to space can be blocked when the top of the deep convective cloud reaches the tropopause. As a result, radiation from cloud top and stratosphere is the only component that consists of the radiation at the top of the atmosphere. At the stratosphere, the temperature increases with height and the water vapour channel detects the warm stratospheric water vapour causing BTD1 to be positive. The clouds are so-called warm water vapour pixels (Fritz and Laszlo, 1993; Tjemkes et al., 1997) and also included in the colder cloud types in this study.

5.2 | Results

The threshold values of BTD1 to discriminate cold and colder clouds are empirically assumed based on the investigation of the relationships between surface rainfall and BTD1 (Figure 8). Figure 8 shows only one day of August 2015 but the experiment considered the whole month of August 2015. The R–TB relation of non-shallow-tall/taller in Figure 8 shows the possibility of another separation for tall and taller clouds. The assumed thresholds of BTD1 are −20 K and −5 K for non-shallow-tall and non-shallow-taller clouds, respectively. After applying the thresholds, the R–TB relationships for four types of non-shallow clouds are presented in Figure 9. When BTD1 is greater than assumed thresholds, that is, BTD1 > −20 for non-shallow-tall, BTD1 > −5 for non-shallow-taller clouds, minimum value of TB is much colder than the other case. Here, we define non-shallow-tall/taller-colder clouds as non-shallow-tall/taller clouds that have relatively colder minimum TB in the R–TB relationship and non-shallow-tall/taller-cold for the other case which shows relatively cold minimum TB. Therefore, non-shallow-tall clouds are further classified into two cloud types: non-shallow-tall-cold clouds with BTD1 ≤ −20 K and non-shallow-tall-colder clouds with BTD1 > −20 K. Non-shallow-taller clouds are similarly regrouped into two cloud types: non-shallow-taller-cold clouds with BTD1 ≤ −5 K and non-shallow-taller-colder clouds with BTD1 > −5 K. After separating the non-shallow clouds into four different types, it is clear that the R–TB relationships appear to be different for each type. In general, tall-cold/colder clouds have more linear R–TB relationships over the tropical and subtropical regions. In addition, it is suggested that significantly weaker relationships can be associated with clouds having cold cloud tops, and these relationships may depend on the region.

Figure 10 displays an example of TB distribution and the classified cloud types using the BTD methods for 20 August 2015 at 1850 UTC. Sub-classes of non-shallow clouds are presented in a blue colour scale, while the shallow cloud type is shown in an apricot colour. Non-shallow clouds are primarily located in areas of low TBs and near the centre of a typhoon where strong rainfall rates can occur. Tall clouds are located outside the eyewall of the typhoon, while taller clouds are more frequently observed over larger areas including the region near the eyewall of the typhoon.

6 | SUMMARY AND CONCLUSIONS

The discrimination of shallow and non-shallow clouds and the further classification of non-shallow clouds into four cloud types, non-shallow-tall-cold/colder and non-shallow-taller-cold/colder clouds, were performed based on the threshold values of three BTDs and one BTD difference. The threshold values of the BTDs were determined by referring to the best HSS statistics with DPR level 2 data of the shallow rain flag.

BTD1 was found to be an effective parameter for the separation of shallow and non-shallow precipitating clouds. The simultaneous use of BTD2 added a slight improvement in the shallow and non-shallow cloud separation. The relative proportion of water and ice in the non-shallow precipitating clouds was examined by checking the sign of ΔBTD. The negative and positive values of ΔBTD, which are expected
to result from the presence of more water and more ice, respectively, classified the non-shallow precipitating clouds into two types of non-shallow clouds having different cloud heights. That is, the parameter $\Delta BTD$ was used to find non-shallow-tall and non-shallow-taller clouds. A further separation of non-shallow-tall/taller cloud types was based on the thickness of the water vapour layer over the cloud top. Based on an examination of $BTD_1$, clouds with a thick water vapour layer above the cloud top were found to be associated with colder clouds. Applying this classification to the non-shallow-tall/taller clouds produced four types of non-shallow precipitating clouds.

The thresholds for shallow clouds and the four different types of non-shallow clouds are summarized as

$BTD_1$ $(T_{6.2} - T_{11.2}) \leq -39.8$ and

$BTD_2$ $(T_{8.6} - T_{11.2}) \leq 4.9$ for shallow clouds;

tall if $BTD_2$ $(T_{8.6} - T_{11.2}) - BTD_3(T_{11.2} - T_{12.4}) \leq 0$,

tall – cold if $BTD_1$ $(T_{6.2} - T_{11.2}) \leq -20$,

tall – colder if $BTD_1$ $(T_{6.2} - T_{11.2}) > -20$,

taller if $BTD_2$ $(T_{8.6} - T_{11.2}) - BTD_3(T_{11.2} - T_{12.4}) > 0$,

taller – cold if $BTD_1$ $(T_{6.2} - T_{11.2}) \leq -5$, and

taller – colder if $BTD_1$ $(T_{6.2} - T_{11.2}) > -5$.

The R–TB relationships for the classified cloud groups were also examined. As expected, shallow or warm clouds tended to have significant indirect associations between surface rainfall and IR brightness temperature. Moreover, some types of non-shallow clouds showed weak relationships between surface rainfall and IR brightness temperature depending on the region. The R–TB relationships depend on the cloud types and regions and may have a significant impact on IR-based precipitation estimations. For example, by separating shallow cloud from non-shallow-tall/taller-colder type
FIGURE 9  Same as Figure 6, but for four different cloud types: (a,e,i,m) non-shallow-tall-cold, (b,f,j,n) non-shallow-tall-colder, (c,g,k,o) non-shallow-taller-cold, and (d,h,l,p) non-shallow-taller-colder clouds. The four latitude bands here are (a–d), (e–h), (i–l) and (m–p).

FIGURE 10  Example of classification of the precipitating clouds on 20 August 2015, 1850 UTC: (a) 11.2 μm brightness temperatures of AHI, and (b) five cloud types.
which usually related to heavy rainfall, retrieving rainfall rates from IR TB can be improved. The results suggest that proper separations of precipitating clouds based on thermal and physical characteristics can improve the accuracy of precipitation estimates from IR observations.

**ACKNOWLEDGEMENT**

This work was supported by “Development of Cloud/Precipitation Algorithms” project, funded by ETRI, which is a subproject of “Development of Geostationary Meteorological Satellite Ground Segment (NMSC-2017-01)” programme funded by NMSC (National Meteorological Satellite Centre) of KMA (Korea Meteorological Administration).

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How to cite this article: So D, Shin D-B. Classification of precipitating clouds using satellite infrared observations and its implications for rainfall estimation. *Q J R Meteorol Soc* 2018;144 (Suppl. 1):133–144. https://doi.org/10.1002/qj.3288