1. Introduction

Since 1997, the Tropical Rainfall Measuring Mission (TRMM) satellite has observed the Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible and InfraRed Scanner (VIRS), and Lightning Imaging Sensor (LIS). These measurements have increased our scientific understanding of precipitating clouds significantly for over 20 years. For example, continental precipitation regions typically experience maximum precipitation in the late afternoon, when radiative heating from the sun, and the resulting atmospheric instability, are at their peak. Oceanic regions exhibit increased rainfall at night or dawn due to radiative cooling in an already humid environment (Takayabu 2002; Nesbitt and Zipser 2003; Yang and Smith 2006; Liu and Zipser 2008). Continental precipitation clouds are characterized by higher storm height (SH) and larger radar reflectivity inside the clouds than oceanic clouds (Liu et al. 2008; Xu and Zipser 2012). Furthermore, the TMI Polarization Corrected Temperature (PCT) at 85 GHz is relatively low in continental precipitation clouds because large scattering occurs due to ice crystals in the upper layer, along with frequent lightning flashes from LIS observation in continental
regions (Nesbitt et al. 2000). Zipser et al. (2006) reported that the central African continent, which is located in tropics, exhibits the clearest continental precipitation characteristics, demonstrated by a lower TMI PCT, higher PR 40-dBZ height (an indicator of vigorous convection), and frequent LIS lightning flashes. In a follow-up study, Liu et al. (2007) analyzed the characteristics of deep convective clouds in the Congo and the northwestern (NW) Pacific Ocean. They found that the Cloud Top Height (CTH), estimated by VIRS, was similar in both regions (due to a similar level of neutral buoyancy); however, the altitude with PR 40-dBZ reflectivity values of over 20 dBZ or 40 dBZ was relatively low in the North Western (NW) Pacific region than in Central Africa (Here, the term refers to the middle part of the African continent, not the Economic Community of Central African States). They inferred that the weaker vertical velocity in the NW Pacific caused this difference in reflectivity altitude.

Furthermore, in a study of middle latitude regions, Sohn et al. (2013) emphasized that heavy rainfall in the Korean peninsula is accompanied by relatively low CTH, radar reflectivity of the upper layer, and ice water content, in contrast to Oklahoma in the United States, and argued that warm-type heavy rain (in contrast to cold-type) dominates the Korean peninsula’s precipitation system. Subsequently, Song and Sohn (2015) reported that warm-type heavy rain, classified from PR reflectivity profiles, is not limited to the Korean peninsula, but is a common precipitation structure shown in the NW Pacific and East Asia monsoon environments. This feature has led to significant problems for satellite-based precipitation estimating (Ryu et al. 2012; Shige and Kummerow 2016) and determining microphysical parameters for numerical models (Song and Sohn 2018; Song et al. 2019) over these monsoon areas. Active collision and coalescence of raindrops in a humid environment are a major cause of warm-type heavy rain (Song et al. 2017). Hamada et al. (2015) also reported a surprisingly low correlation between very high-altitude vertically developed clouds and clouds with heavy precipitation, which highlights the importance of warm-rain processes for producing heavy rainfall. Hamada and Takayabu (2018) further noted that extreme rainfall events around Japan were produced by a huge supply of water vapor from the southwest, similar to studies over South Korea (Sohn et al. 2013; Song and Sohn 2015).

In another approach, Song et al. (2019) and Kim et al. (2019) classified heavy rain types in the Korean peninsula based on the frequency distribution of infrared-based CTH by rainfall intensity. Here, as with SH, heavy rain systems with relatively low CTHs are also considered warm-type heavy rain events. Moreover, Liu et al. (2007, 2008) investigated the occurrence frequency of deep convective clouds, in which the VIRS brightness temperature, at 10.8 μm (TB11), is less than 235 K or 210 K. The results demonstrated that most of these clouds are concentrated in tropical regions, such as the Western Pacific Ocean, Central Africa, and the Amazon. Furthermore, Liu et al. (2007) investigated the differences between the PR 20-dBZ height, the CTH estimated from TB11, and reanalysis data for rain clouds with TB11 of 210 K or less. They discovered a very large difference between the two heights, predominantly in tropical regions. Additionally, the Mesoscale Convective System, which has an extremely cold cloud top temperature and a large horizontal area, predominantly occurs in tropical regions (Yuan and Houze 2010). Based on the above results, it is clear that there are large contrasts in CTH between tropical regions and middle latitudes, including the Korean peninsula. This result, from a CTH/SH point of view, shows differences from the conclusion of Song and Sohn (2015), who stated that the vertical structures of heavy rain around the NW Pacific Ocean and the Korean peninsula display a similar structure in radar reflectivity profiles. This implies that fundamental differences exist between the CTH obtained by TB11 and the SH derived from reflectivity profiles. Based on this concept, many previous studies have analyzed the joint probability density function (PDF) of TB11 and SH in order to understand cloud characteristics and evaluate cloud parameterization in numerical weather prediction models (Masunaga and Kummerow 2006; Matsui et al. 2009, 2016; Roh and Satoh 2014). However, because this framework targets all clouds, there has been little emphasis on the characteristics of heavy rain clouds, which occur with relatively low frequency.

Thus, this study aims to achieve a comprehensive understanding of warm-type heavy rain in the middle latitude and continental/oceanic precipitation in tropics. Specifically, this research aims to improve our understanding of the characteristics of heavy rain clouds in Central Africa and the NW Pacific (Liu et al. 2007), Korea, and the United States regions (Sohn et al. 2013), and the NW Pacific and East Asia monsoon regions (Song and Sohn 2015). The TB11 and SH characteristics of these four regions are interesting because SH should be sensitive to the continental and oceanic precipitation systems, and TB11 differs...
between tropical and middle latitude regions. Since regional characteristics should be more distinct for heavy rain clouds than light rain clouds, this study focuses on the characteristics of heavy rain clouds. Instead of using the TB11 data, this study investigates the difference between CTH and SH in terms of the altitude scale by converting TB11 data into CTH format along with reanalysis data. Furthermore, this study discusses the mechanism behind regional differences in CTH and SH.

2. Data and methods

TRMM Multisatellite Precipitation Analysis (TMPA) precipitation data (version 7) for the June–August period of 2002–2013 were used in this study. The final production of TMPA precipitation, scaled by surface rain-gauge observations (3B42), was compared with the uncalibrated 3B42RT data (microwave and infrared merged product) to examine the problem of satellite-based rain retrieval related to precipitation’s regional characteristics (see Huffman et al. 2007, 2010, more detail about precipitation products). In addition, spatiotemporal matching data (2D-CLOUDSAT-TRMM) of the CloudSat Cloud Profiling Radar (CPR) at 94 GHz, with PR reflectivity profiles, were used for the June–August period of 2002–2010 (note that the product was limited within this period). Here, the 50-min window was used for temporal matching between two satellites. The vertical resolution of CPR and PR data was 240 m and 250 m, respectively. Unlike PR, CPR data is limited from the spatial observation aspect because only along-track scanning is performed at 2-km intervals. Additionally, Ice Water Content (IWC) profiles from the CPR 2B-CWC-RVOD product (Austin et al. 2009; P1_R05 version) were used for the period of 2006–2016, which were fully available throughout the period.

This study predominantly used TRMM PR near-surface rain rate and echo top height (or SH), TMI PCT85, and VIRS TB11 instantaneous data (version 7) from June–August of 2002–2013. The TRMM data were available from 1997, but the analysis period was set to 12 years due to changes in spatial resolution and coverage caused by an orbit boost in August 2001. The TRMM ended in April 2015, and VIRS data were available up to March 2014. The PR is a satellite-based radar operated at 13.8-GHz frequency that performs observations for a 247-km swath width at a horizontal footprint of 5.0 km (at the nadir). The VIRS is a visible, infrared imager that makes observations in a cross-track scanning format, like the PR, with a 833-km swath width at a horizontal resolution of 2.4 km (at the nadir). TMI is a conical scanning microwave imager, which performs observations at 10.7, 19.4, 21.3, 37.0, and 85.5 GHz channels, with a 878-km swath and 5-km horizontal resolution. The VIRS and TMI data were spatially matched with nearest PR rain pixels within the PR footprint. Since parallax correction between two sensors is not considered here, it partly includes the potential of spatial mismatch. The PR-VIRS data were matched again with ERA-Interim data (Dee et al. 2011) with 6-h temporal intervals and $1^\circ \times 1^\circ$ horizontal resolution by applying spatiotemporal interpolation to the ERA-Interim data into PR instantaneous data (total 192,869,424 PR rain pixels). The ERA-Interim data included temperature and geopotential height profiles, Convective Available Potential Energy (CAPE), Total Precipitable Water (TPW), and column-integrated moisture flux convergence (ConQ). We admit the current method’s limitations for estimating CTH based on the ERA-Interim temperature profiles with coarse temporal and horizontal resolutions. This issue can be improved by using the recently advanced ERA5 reanalysis products with higher temporal and horizontal resolutions (1 hourly and $0.25^\circ \times 0.25^\circ$ grids) in future studies.

This study attempted to calculate the CTH of precipitation clouds from VIRS TB11 data by referring to the temperature profiles of ERA-Interim data. In the case of opaque clouds, such as precipitation clouds, TB11 can be used to estimate cloud top temperature. Additionally, if the vertical distribution of temperature is known, it can be converted to CTH (Kwon et al. 2010). Under the assumption of a moist adiabatic lapse rate ($6 \text{ K km}^{-1}$), for example, the 1-K error of cloud top temperature measurements can lead a CTH uncertainty of approximately 0.16 km. However, latent heat cooling can occur due to sublimation in the upper part of deep convective clouds; if its magnitude is large, it can lead to lower estimates of cloud top temperature (higher CTH). Lastly, the vertical distribution of air temperature is another factor that generates uncertainty; for example, temperature profiles inside precipitation clouds can differ from those estimated from reanalysis data. In this case, the assumption that the cloud top temperature equals the ambient environmental temperature may no longer be valid, as shown in Luo et al. (2010) and Wang et al. (2014). The CTH of this study was set to be the same or higher than the SH and the same or lower than the tropopause height. The SH is the altitude corresponding to a reflectivity of approximately 15-dBZ and should be physically lower than the CTH because it refers to the height at which larger precipitation particles appear compared
to the clouds. In addition, it is assumed there is no overshooting cloud above the troposphere, so the CTH cannot exceed the tropopause height. Although overshooting clouds are common in the tropics, (e.g., Luo et al. 2008; Liu and Zipser 2005), this study does not consider them. The tropopause height was determined from the vertical distribution of ERA-Interim temperatures by referring to the World Meteorological Organization (1957) method, defined as the lowest level that showed a lapse rate of less than $-2 \text{ K km}^{-1}$.

In the CTH calculation process, when TB11 was lower than the temperature at the ERA-Interim tropopause height, the spatial distribution climate values of the Atmospheric Infrared Sounder (AIRS) and Advanced Microwave Sounding Unit (AMSU) tropopause height (monthly and 1° × 1° grids; doi: 10.5067/Aqua/AIRS/DATA319) were substituted in the analysis. Typically, tropopause heights of 14.5–16.5 km were used for the regions of major interest in this study.

3. Results

The regional differences between heavy rain clouds, revealed in previous studies, can be related to problems with estimating satellite precipitation. For example, Sekaranom and Masunaga (2019) showed that the regional difference of PR and TMI rain products (focusing on oceanic and continental convection) occur because PR tends to detect more organized heavy rain systems under humid environments, whereas TMI rainfall is sensitive to deep convective clouds under relatively dry and unstable conditions. Figure 1a shows the average value of TMPA summer precipitation. In general, substantial precipitation occurs along the Inter Tropical Convergence Zone (ITCZ). Furthermore, among middle latitude regions, Korea and Japan regions show remarkably high precipitation as a result of the East Asian summer monsoon, comparable with that of tropical regions. In the TMPA products, microwave and infrared precipitation estimates are calibrated by ground rain-gauge observations; when precipitation is compared before and after performing this correction, an interesting result is found (Fig. 1b).

A satellite-based precipitation estimation algorithm over land is developed that depends on whether the temperature in the upper part of the clouds is low (infrared method) or is a strong depression due to ice scattering (microwave method). However, if it is adjusted to a certain region, decreased retrieval accuracy for other regions is unavoidable. The regions affected by this phenomenon are shown in red (positive

Fig. 1. (a) TMPA mean precipitation (version 7) and (b) the difference of TMPA precipitation between without and with rain gauges (i.e., uncalibrated 3B42RT and calibrated 3B42 products) over a 12-yr summer (June–August) period (2002–2013).
As positive deviations are found in the United States, the Eurasia continent, and Central Africa, satellite precipitation over the continental region was overestimated compared to ground observations. On the other hand, negative deviations are clearly visible in monsoon regions, such as India, the Indochina Peninsula, the islands of Southeast Asia, Taiwan, Southern China, Korea and Japan, and northern South America, implying a relatively warm brightness temperature at the satellite despite heavy precipitation. In the southern hemisphere, negative deviations are also observed in New Zealand and Chile. In general, the regions showing negative deviations are adjacent to the sea and may be influenced substantially by the humid environment. Since the transition from the TMPA to the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) is underway (Huffman 2019), regional bias in precipitation shown in this study may be mitigated somewhat in the IMERG data.

The regional cloud and precipitation characteristics should be examined more with respect to the importance of satellite precipitation estimation. To accomplish this goal, a suitable candidate is match-up data from the CloudSat CPR and TRMM PR, which are active sensors. The CPR can estimate the CTH and cloud profiles relatively accurately because it is sensitive to relatively small cloud particles. However, the PR is sensitive to relatively large precipitation particles. The height corresponding to the echo top of radar reflectivity can be regarded as the SH, and the vertical structure of precipitation can be observed. After analysis of the spatiotemporal matching data of CPR and PR, the CPR and PR radar reflectivity for PR precipitation intensity, both smaller and larger than 10 mm h$^{-1}$, are presented in Contoured Frequency by Altitude Diagrams in Figs. 2a and 2b, respectively. As the rain rate
increases, higher radar reflectivity is observed in the upper layer, along with increased CTH and SH. The cloud layer corresponding to the zone between CTH and SH can be observed only at the CPR. Because the CPR is strongly attenuated to precipitation particles (Stephens et al. 2008), the radar reflectivity does not increase continuously as the altitude decreases, but decreases below a certain altitude (near melting layer), as in Luo et al. (2017). Therefore, PR reflectivity below the SH shows more realistic conditions. When the precipitation intensity is larger than 10 mm h\(^{-1}\), the difference between CPR and PR reflectivity increases further. However, because the CloudSat observation width is close to a line, its trajectory differs from that of the TRMM satellite, match-up between the two satellites occurs only approximately 27 times per day (Fig. 2c). Even if four years of available data are gathered, this is far from sufficient to study regional cloud and precipitation characteristics (77,963 rain clouds and 6,511 heavy rain clouds with near-surface rain rate larger than 10 mm h\(^{-1}\)). Although the vertical distribution inside the cloud layer could not be investigated, as with CPR, this study investigates the regional CTH and SH characteristics of heavy rain clouds by converting VIRS infrared observation data, which are mounted along with PR on the TRMM satellite, into CTH.

Figure 3 shows the summer spatial distribution of CTH and SH averaged for each rain rate intensity. In Figs. 3a and 3b, the regions with higher CTH and SH values typically correspond to regions with large precipitation. Note that regions with large precipitation in Fig. 1a also exhibit large average rain intensity. In summer, the upward motion in the southern hemisphere is suppressed compared to that in the northern hemisphere; consequently, CTH and SH are not high. Furthermore, CTH and SH are low in the surrounding regions of subtropical high pressure because of the suppressed updraft. Because CTH and SH generally have a proportional relationship with precipitation in-
tensity (Song et al. 2019; Song and Sohn 2020), both CTH and SH increase clearly as the rain rate intensity increases (e.g., $10 > \text{mm h}^{-1}$, $40 > \text{mm h}^{-1}$). The SH of extreme heavy rain, shown in Fig. 3f, is more than 9 km in continental precipitation regions (e.g., Central Africa, China, the United States), and less than 9 km in oceanic precipitation regions (e.g., ocean regions, Korea, Japan, Taiwan, Philippines, the Indochina Peninsula, India, Amazon, and parts of New Zealand and Chile). The majority of maritime continent regions correspond to land regions with negative deviations in Fig. 1b. Specifically, even regions recording average unconditional ($\geq 0 \text{ mm h}^{-1}$) precipitation of over 250 mm month$^{-1}$ in Fig. 1a exhibit an average SH of only 8–9 km. This is in contrast to the SH of 9–12 km observed in continental precipitation regions, which have lower average precipitation than oceanic precipitation regions (Fig. 1a). The CTH of extreme heavy rain clouds shows different characteristics to the SH of those (Fig. 3e). In continental precipitation regions, maximum CTH is approximately 15 km, which is higher than SH because the SH is already high. The average CTH is high (13–14 km) in the ITCZ, similar to the average precipitation (Fig. 1a), and the maximum value (14–15 km) is found in the NW Pacific Ocean. Conversely, the average CTH of Korea and Japan is approximately 12–13 km, which is very different from the NW Pacific Ocean. This is a very contrasting feature considering the similar SH between these two regions. This implies that the CTH difference between the tropical and middle latitude regions was overlooked in Song and Sohn’s study (2015), which classified the NW Pacific and East Asia monsoon regions as “warm-type heavy rain” based on the similar vertical structure of radar reflectivity. Note that the mean tropopause heights are 15.19 km in the United States, 15.84 km in Korea/Japan, and 16.23 km in tropics (Central Africa and NW Pacific) in boreal summer. Although not all rain cases reach the tropopause, the regional differences of in-tropopause height can also affect the CTH results in this study, especially for the difference between mid-latitude and tropics. It is also noted that Korea and Japan are characterized by lower mean CTH despite a greater tropopause height than the United States.

Figure 4a shows the spatial distribution of the difference between CTH and SH for extreme heavy rain ($> 40 \text{ mm h}^{-1}$). That is, it refers to the cloud layer depth corresponding to between approximately 10 km SH and 15 km CTH shown in Fig. 2b. The regions of interest in previous studies (Liu et al. 2007; Sohn et al. 2013; Song and Sohn 2015), such as the United States, Korea and Japan, Central Africa, and the NW Pacific, are shown by boxes in Fig. 4a. The statistical average values of the four regions are provided in Table 1. Note that the visit frequency of middle latitude regions
is higher than those of tropical regions due to the TRMM satellite orbit’s characteristics. The average precipitation for the United States, Korea/Japan, Central Africa, and the NW Pacific is 94.9, 180.7, 171.3, and 268.1 mm month$^{-1}$, respectively. Specifically, the average inland precipitation of Korea/Japan is 220.9 mm month$^{-1}$, which is 82% of that in the NW Pacific, and the highest level of all middle latitude regions.

First, the United States has an average CTH−SH (difference between CTH and SH) of approximately 2.7 km, which is the lowest value among the four regions, and the CTH and SH are both high (13.2 km and 10.5 km, respectively). In Central Africa, the average SH is 10.4 km, similar to that of the United States; however, because the CTH is rather high at 14.3 km, the average CTH−SH is 3.9 km. In Korea/Japan, the CTH and SH are 12.6 km and 8.3 km, respectively, which are the lowest values among the regions. The SH in the NW Pacific is similar to that of Korea/Japan; however, because the CTH is high (14.2 km), the average CTH−SH is 5.5 km, which is the largest among all four regions. The differences in CTH and SH between these regions can be explained by the different thermodynamic environments. In fact, the CAPE is typically high in tropical regions (Fig. 4b), and the TPW exhibits maximum values in South Asia, NW Pacific, and East Asia monsoon regions (Fig. 4c). Specifically, because ConQ is high around Korea/Japan, the dynamic conditions for producing heavy rainfall are satisfied over those regions (Fig. 4d).

When the average values are examined for the four regions (Table 1), the CAPE is highest (1,503.2 J kg$^{-1}$) in the NW Pacific and lowest (544.5 J kg$^{-1}$) in Korea/Japan. The TPW is highest in the NW Pacific (62.2 mm), followed by Korea/Japan, Central Africa, and the United States. ConQ is highest in Korea/Japan, at 0.38 g m$^{-2}$ s$^{-1}$. In addition, the CAPE and CTH−SH of extreme heavy rain clouds in the Eastern Pacific Ocean are much lower than those in the Western Pacific Ocean. These results are consistent with the relatively suppressed deep convection in the Eastern Pacific in Sekaranom and Masunaga (2019), and can vary with interannual changes of the El Niño Southern Oscillation (Henderson et al. 2018). However, the mean CTH−SH of extreme heavy rain clouds in the Eastern Pacific is still higher than that in Korea/Japan because of relatively high CTH in the EP (Fig. 3e). Therefore, the small difference between CTH and SH of extreme heavy rain clouds found in Korea and Japan seems to be unique.

For a more detailed analysis, Fig. 5 shows the PDF distributions for CTH and SH, as well as the thermodynamic environment variables of extreme heavy rain. First, in the CTH distribution (Fig. 5a), double peaks appear in every region. Among them, the peak located at the lower height corresponds to a location below the tropopause height during the process of allocating the VIRS TB11 to the vertical distribution of ERA-Interim temperatures. The peak, located at a higher altitude, corresponds to the case in which the peak is outside the ERA-Interim data; thus, the climatology of AIRS/AMSU tropopause height is substituted. Note that different treatment of tropopause height will not much change the regional difference tendency in CTH.
although it can affect the statistics. It is confirmed that there are many cases where the CTH is 15 km or higher in the NW Pacific and Central Africa, with the NW Pacific exhibiting more cases where CTH values are close to 17 km. Meanwhile, in Korea/Japan, the proportion of cases with a CTH of less than or equal to 13 km is 48.7 %, which is the largest among the four regions. The CTH condition of less than or equal to 13 km, required for classification of warm-type heavy rain in the Korean peninsula, has also been discussed by Song et al. (2019) and Kim et al. (2019). For the PDFs of SH, the results between the NW Pacific and Korea/Japan are very similar (Fig. 5b), which is consistent with the results from Song and Sohn (2015). Compared to these regions, the United States and Central Africa exhibit many cases where SH is greater than or equal to 10 km. In particular, in the United States, the SH is often in the 10–15 km range, and in Central Africa, the SH is often greater than or equal to 15 km. The average SH is similar between these two regions (Table 1).

The resulting CTH−SH distribution is the largest in the NW Pacific, followed by Korea/Japan, Central Africa, and the United States (Fig. 5c). For example, the proportion of CTH−SH cases with a thickness of greater than or equal to 4 km in the NW Pacific, Korea/Japan, Central Africa, and the United States is 74, 59, 51, and 24 %, respectively. The proportion of CAPE cases of greater than or equal to 1,000 K kg⁻¹, which can provide the thermodynamic energy for deep convective clouds to grow in the NW Pacific, Central Africa, the United States, and Korea/Japan is 75, 52, 34, and 17 %, respectively (Fig. 5d). It is determined that the order of CAPE values is closely related to the CTH results. The TPW distribution reveals a stark contrast between humid NW Pacific and Korea/Japan regions and relatively dry Central Africa and United States regions (Fig. 5e). This difference in water vapor is likely the fundamental cause of differences between oceanic precipitation regions and continental precipitation regions, including the SH difference. Furthermore, the substantially lower TPW in the United

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**Fig. 5.** Probability Density Functions (PDFs) of (a) cloud top height, (b) storm height, (c) difference between cloud top and storm heights, (d) CAPE, (e) TPW, and (f) ConQ for extreme heavy rain (> 40 mm h⁻¹) over the United States, Korea and Japan, Central Africa, and western Pacific areas during June–August 2002–2013.
States than in Central Africa is why it has the lowest average precipitation among the four regions (Table 1). Cases where ConQ is higher than 0.5 g m$^{-2}$ s$^{-1}$ appear most frequently in Korea/Japan among the four regions (Fig. 5f), indicating dynamically favorable conditions for heavy rainfall.

Figure 6 shows the joint frequency distribution of IWC, observed from the CloudSat CPR. The occurrence of heavy rain cannot be determined using CPR observations alone. However, the IWC distribution above the SH for heavy rain clouds can be inferred from the fact that the SH of heavy rain is typically higher than 9 km. The proportion of cases where the IWC is greater than 2 g m$^{-3}$ (above approximately 9 km) is 0.38, 0.26, 0.12, and 0.03 % in the United States, Central Africa, the NW Pacific, and Korea/Japan, respectively, in descending order. The fact that the average rain rate is higher, and the PCT85 is lower (i.e., indicating abundant IWC), in the United States than in Central Africa for extreme heavy rain clouds (Table 1) partially explains the proportion of high IWC in the United States. However, since there are similar occurrences of extreme heavy rain clouds in the two regions, despite the relatively frequent TRMM satellite visits for mid-latitudes (more than twice as much as that for tropics), the relative occurrence frequency of heavy rain clouds in the United States is less than half of that in Central Africa, implying more suppressed convection over the United States. Rather, it can be interpreted that clouds accompanied by abundant IWC produce localized heavy rain cases in the United States. The small proportion of high IWC in the NW Pacific and Korea/Japan is consistent with a relatively high PCT85 (Table 1). Because the NW Pacific has a deeper cloud layer above the SH (i.e., CTH-SH) as well as smaller amount of IWC than Central Africa, this is interpreted as lower volumetric ice density for the NW Pacific. Lastly, the CTH–SH
of Korea/Japan is the second largest, behind that of the NW Pacific, but this region contains the smallest amount of ice crystals in the corresponding cloud layer (the proportion of IWC values of 2 g m\(^{-3}\) or greater is only 21% in the NW Pacific and 7% in the United States). In this case, as discussed in Fig. 1b (Ryu et al. 2012; Shige and Kummerow 2016), the microwave-based precipitation algorithm, based on a cold brightness temperature due to ice scattering, will fail in Korea/Japan, resulting in a severe precipitation underestimate.

A comprehensive explanation of the above results can be summarized as follows. The heavy rain clouds of Central Africa and the United States, which are continental precipitation regions, are characterized by higher SH compared to the NW Pacific and Korea/Japan, which are oceanic regions. A strong updraft in a relatively dry environment is thought to be the mechanism for continental precipitation. CTH is large in the NW Pacific and Central Africa, which are located in tropical regions, and this characteristic is related to high atmospheric instability (i.e., CAPE). Although the CAPE of Central Africa is lower than that of the NW Pacific, the fat-type CAPE structure of continental precipitation regions can provide stronger vertical velocity for clouds at the same CAPE than oceanic regions with the skinny-type CAPE structure (Lucas et al. 1994). Heavy rain events in the United States are generated at lower CAPE and TPW conditions than in Central Africa, consistent with lower occurrence frequency and precipitation over the United States. In addition, the United States has the lowest CTH–SH among the four regions. Korea/Japan has high precipitation, comparable to that of the NW Pacific in the thermodynamically near-neutral environment (i.e., lower CAPE condition), with a large amount of total water vapor. As discussed in the numerical analyses of Song et al. (2017), active collision and coalescence processes of raindrops in a humid environment are a major cause of the “warm-type heavy rain” found in Korea and Japan. The CTH–SH of Korea/Japan is the second highest among the four regions, but the amount of ice crystals inside the corresponding layer is insufficient due to the lowest CAPE environment. The NW Pacific has low SH in humid environments, similar to Korea/Japan, but the highest CAPE environment, which is a large contrast to Korea/Japan. Consequently, heavy rain clouds that develop in the NW Pacific region show large average CTH and CTH–SH values. The most typical examples of similar SH and contrasting CTH in Korea/Japan and the NW Pacific are probably the East Asia Summer Monsoon front (called Changma in Korea and Baiu in Japan) and typhoon. Figure 7 provides typical examples of the Changma and typhoons. Despite similarities in the rain rate and SH between the two cases, distinct differences are observed in the VIRS TB11 (i.e., a substantially lower cloud top temperature for typhoon case over the NW Pacific).

4. Summary and conclusions

The results of precipitation deviations in TMPA data before and after rain-gauge adjustment typically showed positive deviations in continental precipitation regions and negative deviations in humid monsoon regions. Therefore, differences in regional precipitation characteristics can cause severe problems in satellite-based precipitation retrieval. Furthermore, this study analyzed the vertical structure of clouds and precipitation, targeting precipitation clouds based on the spatiotemporal matching data of TRMM PR and CloudSat CPR. When rain rate intensity was 10 mm h\(^{-1}\) or higher, the average SH was approximately 10 km, and the average CTH was approximately 15 km, confirming that CPR reflectivity was observed for the layer between the SH and the CTH. However, it was determined that the match-up data of TRMM and CloudSat satellites was highly insufficient for studying the regional characteristics of precipitating clouds.

This study used long-term TRMM PR (near-surface rain rate and SH) and VIRS (TB11 or CTH) data to investigate the regional CTH and SH characteristics of heavy rain clouds. For the analysis, the CTH was calculated for precipitation clouds using VIRS TB11 data and ERA-Interim temperature profiles. As the rain rate intensity increased to 0, 10, and 40 mm h\(^{-1}\), the average CTH and SH increased notably; however, differences were observed between regions. A detailed analysis was performed for the United States, Central Africa, NW Pacific, and Korea/Japan, which were the regions of interest in previous studies. First, the United States showed an average CTH–SH of 2.7 km, which was the lowest among the four regions, whereas CTH and SH were both high (13.2 km and 10.5 km, respectively). In Central Africa, the average SH was 10.4 km, but the average CTH was 14.3 km, which was relatively higher than that of the United States, resulting in a mean CTH–SH of 3.9 km. SH in the NW Pacific was similar to that in Korea/Japan (8.7 km); however, because the CTH was high (14.2 km), the average CTH–SH was 5.5 km, which was the largest among the four regions. The CTH and SH of Korea/Japan were 12.6 km and 8.3 km, respectively, which were the lowest values among the four regions. Moreover,
heavy rain clouds in Korea and Japan regions were characterized by extremely lower IWC.

The heavy rain clouds found in Central Africa and the United States, which are continental precipitation regions, were characterized by higher SH than those in the oceanic precipitation regions of the NW Pacific and Korea/Japan. Strong updrafts in a dry environment are a suggested continental precipitation mechanism. CTH values were large in the NW Pacific and Central Africa, which are located in tropical regions, and this characteristic was related to the high CAPE and tropopause height conditions. Korea/Japan exhibited a large amount of precipitation, comparable to that in the NW Pacific, due to active raindrop collision and coalescence processes in humid environments, despite a thermodynamically neutral condition (i.e., lower CAPE condition). The CTH–SH of Korea/Japan was the second greatest among the four regions, but the IWC inside the corresponding layer was much lower with respect to the low CAPE environment. The NW Pacific also had low SH in humid environments, similar to that in Korea/Japan. However, the highest CAPE environment and high CTH/CTH–SH values caused by this differed from those in Korea/Japan. In conclusion, this study has increased our understanding of the regional cloud height characteristics of heavy rain clouds in continental, oceanic, tropical, and middle latitude monsoon regions. Furthermore, the results of this study could be used to improve satellite-based precipitation estimation or cloud parameterization for numerical weather prediction models.

Acknowledgments

The TRMM, CloudSat, AIRS, and ERA-Interim data were downloaded from https://gpm.nasa.gov/data-access/downloads/trmm, http://www.cloudsat.cira.

Fig. 7. The spatial distributions of (a) PR rain rate, (b) PR storm height, and (c) VIRS brightness temperature at 10.8 μm (TB11) for Changma event (00UTC 22 June 2009) over the Korean peninsula. (d), (e), and (f) Same as (a), (b), and (c), but for Typhoon Chaba (08UTC 24 August 2004) over the northwestern Pacific Ocean.
colostate.edu, http://disc.sci.gsfc.nasa.gov, and http://apps.ecmwf.int/datasets/data/interim-full-daily, respectively. This work was funded by the KMA Research and Development Program “Development of the AI technique for the prediction of rainfall optimized over the Korean peninsula” under Grant (KMA2018-00124).

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