Comparison of Diurnal Variations in Precipitation Systems Observed by TRMM PR, TMI, and VIRS

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ABSTRACT

Tropical Rainfall Measuring Mission (TRMM) data during June–August 1998–2003 are used to investigate diurnal variations of rain and cloud systems over the tropics and midlatitudes. The peak time of the coldest minimum brightness temperature derived from the Visible and Infrared Scanner (VIRS) and the maximum rain rate derived from the Precipitation Radar (PR) and the TRMM Microwave Imager (TMI) are compared. Time distributions are generally consistent with previous studies. However, it is found that systematic shifts in peak time relative to each sensor appeared over land, notably over western North America, the Tibetan Plateau, and oceanic regions such as the Gulf of Mexico. The peak time shift among PR, TMI, and VIRS is a few hours.

The relationships among the amplitude of diurnal variation, convective frequency, storm height, and rain amount are further investigated and compared to the systematic peak time shifts. The regions where the systematic shift appears correspond to large amplitude of diurnal variation, high convective frequency, and high storm height. Over land and over ocean near the coast, the relationships are rather clear, but not over open ocean.

The sensors likely detect different stages in the evolution of convective precipitation, which would explain the time shift. The PR directly detects near-surface rain. The TMI observes deep convection and solid hydrometeors, sensing heavy rain during the mature stage. VIRS detects deep convective clouds in mature and decaying stages. The shift in peak time particularly between PR (TMI) and VIRS varies by region.

1. Introduction

Diurnal variations in precipitation systems are of interest in meteorology. The global distribution of such diurnal variations has been studied with ground-based meteorological observations (Dai 2001) and with observations from meteorological satellites carrying either infrared radiometers (e.g., Janowiak et al. 1994; Nitta and Sekine 1994; Yang and Slingo 2001) or microwave radiometers (Chang et al. 1995). Geostationary infrared radiometers observe clouds hourly, and brightness temperature has been used as a proxy of precipitation in studies of diurnal variation. Tian et al. (2004) examined the relationship between the diurnal phases of clouds and retrieved precipitation using multiple geostationary infrared data. However, precipitation does not always occur corresponding to cloud activity. Microwave imagers detect precipitation more directly. However, temporal sampling is sparse [twice daily at similar local
morning and evening times from the Special Sensor Microwave Imager (SSM/I) and Advanced Microwave Scanning Radiometer (AMSR), etc.]. Relationships between clouds and precipitation and regional differences of diurnal variations using directly observed data are not fully understood.

The Tropical Rainfall Measuring Mission (TRMM) satellite can study the diurnal cycle globally because of its non-sun-synchronous orbit (e.g., Nesbitt and Zipser 2003; Bowman et al. 2005; Collier and Bowman 2004). The Precipitation Radar (PR) uniquely and directly observes precipitation from space at fine resolution (>~5 km), even over complex orography. For example, Bhatt and Nakamura (2005) used TRMM PR data to study diurnal variations over the Himalayas. Rain in that area falls over valleys and lowlands between midnight and early morning. Rain falls during the day over ridges on south-facing slopes. Fujinami et al. (2005) showed that over the Tibetan Plateau daytime precipitation onset over mountain ranges is a few hours earlier than precipitation over valleys. TRMM PR data reveal not only the precipitation amount as used above, but also precipitation characteristics (convective and stratiform) and the vertical structure. Takayabu (2002) used TRMM PR data to show diurnal variations in convective and stratiform precipitation over land and ocean near the equator. Over the ocean, both convective and stratiform precipitation types have a morning peak. In contrast, convective and stratiform rains over land have maxima around afternoon and midnight, respectively. Geerts and Dejene (2005) have investigated diurnal variations in the vertical structure of precipitation over tropical Africa using PR data, showing changes in both storm vertical structure and storm frequency.

In addition to the PR, the TRMM satellite also carries the TRMM Microwave Imager (TMI), the Visible and Infrared Scanner (VIRS), and the Lightning Imaging Sensor (LIS).¹ Regional differences in diurnal variations have also been revealed using various TRMM data, surface and atmospheric conditions, and topography over the globe (Petersen and Rutledge 2001; Nesbitt and Zipser 2003), over Asia (Hirose and Nakamura 2005), over the Maritime Continent (Mori et al. 2004), and over tropical oceans (Imaoka and Spencer 2002).

In spite of the above-mentioned advantages, the TRMM satellite has the disadvantage that the sampling bias that depends on local time because of orbital characteristics (Negri et al. 2002). The bias is largest at high latitudes. However, the long observation period has ameliorated sampling biases (Hirose and Nakamura 2005; Hirose et al. 2008). Hirose et al. (2008) showed that the minimum resolutions, with hourly rain samples from multiple precipitation events for 8 yr, are 0.2° and 0.5° in the yearly mean and the seasonal mean, respectively.

The TRMM simultaneously observes precipitation–cloud systems with the PR and with microwave and infrared radiometers. These three sensors have different sensitivities for cloud and precipitation systems. The PR directly detects radiation backscattered by precipitation particles. The microwave radiometer observes the integrated effects of radiation both emitted from the surface and hydrometeors and scattered by solid hydrometeors. The infrared radiometer detects cloud-top emissions.

Life stages of convective precipitation systems can be determined by combining PR, TMI, and VIRS (Rajendran and Nakazawa 2005; Kondo et al. 2006) or PR and VIRS data (Masunaga et al. 2005). Sensor signatures can be classified as either developing, mature, or decaying. Kondo et al. (2006) statistically related cloud–system evolution, as defined by the Geostationary Meteorological Satellite (GMS) and cloud parameters (minimum brightness temperature, size, and gradient at cloud edge), with precipitation parameters observed by the TRMM.

A systematic disagreement between PR and TMI exists globally for rain estimates (Ikai and Nakamura 2003). Rain rates (RRs) derived from TMI are larger (smaller) than those from PR over the summer tropics (winter midlatitude). Errors arise because of (1) the underestimation of TMI precipitation water path by TMI in midlatitudes, 2) the underestimation of near-surface precipitation water content by PR in tropics (Masunaga et al. 2002), 3) errors of TMI rain estimates depending on storm height and rain type (Furuzawa and Nakamura 2005), 4) errors in the TMI algorithm freezing-level assumption, or inadequate radar-reflectivity factor to rainfall rate (Z–R), or attenuation to rain rate (k–R), relationships in the PR algorithm (Ikai and Nakamura 2003), etc.

The local time of the minimum brightness temperature derived from the geostationary infrared radiometer is delayed by a few hours compared to data derived from ground-based precipitation radars (Houze et al. 1981), rain gauges (Ohasawa et al. 2001), satellite microwave imagers (Janowiak et al. 1994; Garreaud and Wallace 1997), and precipitation radar (Mori et al. 2004; Fujinami et al. 2005). The delay may arise from misinterpreting cirrus clouds in convective precipitation systems because infrared brightness temperature just stopped recording observations in May 2001.

¹ The Clouds and the Earth’s Radiant Energy System (CERES) stopped recording observations in May 2001.
corresponds to cloud-top temperature. Tian et al. (2004) suggested that deep convection serves to moisten the upper troposphere through the evaporation of the cirrus anvil clouds using geostationary satellites data. Comparisons using only TRMM sensor data allow for a clarification of the regional differences in diurnal variations of precipitation–cloud systems.

This study compares diurnal variations of convection observed by the TRMM sensors. Simple indices, which are the peak local time of maximum precipitation–cloud cover and the strength of the diurnal variation, are constructed. In section 2, we describe the data used in this study. The peak local time of precipitation–cloud systems computed using TRMM PR, TMI, and VIRS is compared in section 3a. Section 3b shows further precipitation–cloud parameters such as storm height, the convective–stratiform ratio, and height of cloud. Finally, section 3c describes regional differences among the sensors at the peak local time. The results are summarized in section 4.

2. Data

This study used TRMM version 5 level 2 standard products (instantaneous two- or three-dimensional parameters along the TRMM swath) provided by the U.S. National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) for June–August (JJA) 1998–2003. Kummerow and Barnes (1998) have provided a complete data description. Algorithm 2A25 and 2A23 were used to derive near-surface rain rate (RR-PR), rain type, and storm height from the PR. Algorithms for rain amount and rain type have been described by Iuchi et al. (2000) and Awaka (1998), respectively. “Near surface” is defined as the lowest point in the clutter-free ranges in almost all cases. The near-surface height ranges from 500 m at nadir to 2 km at swath’s edge. “Storm height” in 2A23 is the height of the storm top with high confidence (>18 dBZ; a reflectivity equivalent to about 0.5 mm h⁻¹). In this article, storm-height data are picked up from only “existing rain,” corresponding to the maximum height in 2A25 where more than three continuous range bins with rain exist. Surface rain rates in 2A12 (RR-TMI) were used for TMI. Brightness temperatures (BT) derived from VIRS radiance on 1B01 (BT-VIRS) were used. The VIRS has five channels, but only data from channels 4 (10.8 μm, BT4) and 5 (12.0 μm, BT5) were used here.

TRMM version 6 products have recently become available. There are some differences between versions 5 and 6. For example, for heavy rainfall (>30 mm h⁻¹), RR-PR in version 5 (6) is greater than that in version 6 (5) over land (ocean). However, the authors guess that version 5 data yield acceptable results because the tendency of the diurnal variation may not change between versions 5 and 6, though the absolute values change.

Data were processed as follows to allow comparison among TRMM sensor products. First, raw orbital data were converted to gridded (0.25° × 0.25°) data to reduce differences that arise from differences in spatial resolution among the sensors. Swath widths of the TMI and VIRS were limited to the PR swath width to avoid any sampling errors that would arise from the difference of swath widths. Next, gridded data were placed in time bins for each hour of local time (LT). Finally, the peak local times of maximum RR-PR and RR-TMI and minimum BT4-VIRS were calculated.

3. Results

a. Comparison of peak local time among the sensors

As mentioned in the introduction, there is an issue in a sampling bias for the local time when diurnal variations using TRMM data are investigated (Negri et al. 2002). Compared to the sample numbers in a local time accumulated in a month for 6 yr, temporal biases are few in tropical regions, while significant temporal biases appear in midlatitude regions (Hirose and Nakamura 2005). Hirose and Nakamura (2005) concluded that three consecutive months of data provide hourly samples almost evenly, although uncertainties must be considered over rainy seasons with significant seasonal variations in rainfall. There is also the miss detection of diurnal variations resulting from either few samples with rain rate >0, or small diurnal variations. Over regions with few rain rate >0 samples, hourly rainfall amounts exhibit sharp fluctuations. We adopted the following method of Hirose and Nakamura (2005) to detect a significant peak of diurnal variation: 1) the RRrs (BT4) within 1 h from the local time of maximum RR (minimum BT4) are above (under) mean RR (BT4) for PR and TMI (VIRS), 2) rain frequency, where the sample number with rainfall is divided by the entire observed number, is more than 1% for PR and TMI, and 3) the mean RR is more than 10 mm month⁻¹ for PR and TMI and the mean BT4 is less than 280 K for VIRS. For BT4, we newly defined the threshold of method 3 above, which would reduce contaminations from surface temperature. As noted in Hirose and Nakamura (2005), the term of a significant peak of diurnal variation is not always equal to a conventional sense of a large-amplitude diurnal variation in rainfall; rather, it just indicates smooth temporal variations with a con-
Continuous peak lasting for at least 3 h. Hirose et al. (2008) showed that 43% of the observational region for a 0.2° grid scale showed a significant peak of diurnal signature for the 8 yr of TRMM PR version 6 data. Even for 6 yr of data, the area coverage of significant peaks is almost the same. We only focused on regions where a significant peak of diurnal variation appeared.

Figure 1 shows the significant peak in local time derived from PR, TMI, and VIRS. For all sensors, daytime peaks dominate over the
western United States, the Tibetan Plateau, the Indochina Peninsula, and the coastal regions of the Maritime Continent. Nocturnal peaks appear over the eastern side of the Rocky Mountains, the Deccan Plateau, and mountainous regions of the Maritime Continent. Peak local time shifts occur over the inland region of the northeastern coast of South America, over the southern slopes of the Himalayas, and over oceanic regions, including the Bay of Bengal, the Gulf of Mexico, and the Maritime Continent. These diurnal variations and their shifts are reported in many studies (e.g., Dai 2001; Carbon et al. 2002). In some regions, the peak local time derived from PR, TMI, and VIRS is less prominent, perhaps resulting from small sampling numbers, orography, or surface features, etc. For instance, the nocturnal peak over mountainous regions, such as east of the Rocky Mountains and the Deccan Plateau, and peak time shifts, such as those over coastal northeastern South America and adjacent oceans, are not clear. A late night–early morning peak (0000–0600 LT) appears over land regions such as South Africa, South America, Australia, and the western Tibetan Plateau in the VIRS results. Because cloud-free data are included in the VIRS data analysis, the surface BT can contaminate results in arid regions. Peaks may therefore be due to diurnal variations in surface temperatures. Even though mean BT4s higher than 280 K were removed, the surface effect still remains because of relatively low surface temperatures.

The strength of the diurnal variations was examined using a normalized differential rainfall index (NDRI) and a normalized differential BT index (NDBI), respectively defined as

$$\text{NDRI} = \frac{\text{RR}_{\text{max}} - \text{RR}}{\text{RR}}$$

and

$$\text{NDBI} = \frac{\text{BT} - \text{BT}_{\text{min}}}{\text{BT}}$$

where $\text{RR}_{\text{max}}$ (BT$_{\text{min}}$) is RR (BT) at the peak local time, and $\overline{\text{RR}}$ (BT) is the averaged RR (BT). The indices show the prominence of RR (BT) at the peak local time compared to the average. It should be noted that NDRI is large over regions with small rain amounts because RR$_{\text{max}}$ is likely to be much larger than the $\overline{\text{RR}}$ in arid regions. NDBI also is likely to be large because of surface temperature, tropopause height, and so on. Thus, although NDRI and NDBI do not always represent the conventional sense of the amplitude of diurnal variation, larger NDRI and NDBI generally indicate that stronger diurnal variations exist.

Figure 2 shows the distributions of NDRI derived from RR-PR and RR-TMI and NDBI derived from BT4-VIRS. To exclude the above-mentioned factors (i.e., small rain amount, surface temperature), the NDRI and NDBI are colored in pixels with significant peak of diurnal variations. Large NDRI ($\text{NDRI} > 2.5$) occur mainly over land, for example, over the central and western United States, the Tibetan Plateau, the Maritime Continent, the coastal region of northeast South America, and some islands. The NDRI is small over oceanic regions, such as the center in ITCZ and the northwestern Pacific Ocean, but not over the Gulf of Mexico, the Maritime Continent, or the western Bay of Bengal. NDBI is very similar to the NDRI above-mentioned regions. Over tropical Africa, however, not only the Sahel region, but also the tropical savanna and forest climate zones have large NDBIs ($\text{NDBI} > 0.06$). Over the ocean, NDBIs in the tropics are larger than those in the midlatitudes. This may be due to the large temperature difference between high BT caused by high surface temperature without cloud cover and low BT$_{\text{min}}$ in the tropics, as well as high frequencies with cloud cover by midlatitude precipitation systems.

When the peak local times among RR-PR, RR-TMI, and BT4-VIRS are compared, systematic time differences appear. For example, over the western and eastern United States, and over the Tibetan Plateau, peaks between 1200 and 1600 LT dominate in the PR and TMI, but peaks between 1400 and 1800 LT dominate in VIRS. Over oceanic regions, such as the Gulf of Mexico and the western Bay of Bengal, peaks between 1200 and 1600 LT are more dominant offshore in the VIRS.

Figure 3 shows histograms of differences in peak local time between the sensors, that is, TMI − PR, VIRS − PR, and VIRS − TMI over global oceans, over land, and over different land and ocean regions. Table 1 summarizes the regions and numbers of pixels.

Over the global ocean (Fig. 3a), the frequency (i.e., the percentage distribution) is nearly the same, excluding around the LT difference of zero. This shows that peak local time for RR-PR, RR-TMI, and BT4-VIRS are generally similar. Over land, the peak time difference shows a distribution that shifts to the right (Fig. 3b). In other words, the frequency at +1–2 h is higher than that at −1–2 h, although the difference is quite small, particularly for PR − TMI. The peak local time for VIRS tends to appear later compared with that for PR and TMI. Focusing on specific regions, the peak time differences show different distributions. There is little time lag between PR and TMI over tropical Africa (Fig. 3c), but VIRS frequently lags behind PR and TMI by more than 5 h. In contrast, time differences between
PR and TMI over the Tibetan Plateau and western North America (Figs. 3d,e, respectively) are prominent. The time shifts for TMI – PR and for VIRS – PR (TMI) over the Tibetan Plateau is more outstanding at 1–2 and 2–3 h, respectively. A second maximum of the peak time difference appears around −11 h in VIRS – PR, mainly resulting from a nocturnal peak in the western Tibetan Plateau for VIRS. The frequency of no peak time difference (i.e., zero) on the Tibetan Plateau (20%) is only about half compared with that of other regions (40%–50%). On the Tibetan Plateau, precipitation amounts at the peak local time are relatively low.
small, particularly for TMI, and these small amounts may cause more variable distributions. Over western North America, the time differences of maximum frequency for TMI – PR and for VIRS – PR (TMI) are 2 and 3–6 h, except for no peak time difference, respectively. Over the Gulf of Mexico (Fig. 3f), the peak time difference is relatively outstanding, although the large variation appears because of a small diurnal signature. This region corresponds to the large NDRI region so that this systematic time shift may appear even for an oceanic region.

b. Global distributions of other precipitation/cloud parameters

The previous section presented only the global distributions of peak local time of RR-PR, RR-TMI, and BT4-VIRS. This section will show distributions of the convective fraction, storm height, and peak local times of frequency for the various BT4s-VIRS.

1) Convective and stratiform rain

This subsection highlights the diurnal variations in convective and stratiform RR-PR. Schumacher and Houze (2003a) have shown spatial distributions of convective and stratiform precipitation systems over the tropics in the view of rain amount and frequency. They also suggested that shallow and isolated rain, which frequently occurs over oceanic regions with small rain amounts, should be reclassified as convective (Schumacher and Houze 2003b). As a result, that suggestion was reflected in the version 6 algorithm. Then, diurnal variations in convective and stratiform rain frequency possibly change from versions 5 to 6 over the oceanic regions. However, this study does not deal with this
issue because the regions with small rainfall are excluded.

Figure 4 shows the frequency of convective rain pixels to the total rain pixels derived from PR 2A25. Rain is classified as being convective either if the rain has no bright band and a strong $Z$ factor (>39 dBZ), or if the rain has strong $Z$ factor in the rainy area under the bright band (EOC/NASDA 2001; Awaka 1998). Over land, convective rain frequently occurs over North America, the coastal regions of South America, south of the Amazon, the Maritime Continent, Hindustan and the Indus Plain, and the Sahel. These regions generally show large NDRI (Fig. 2, top) except for the Tibetan Plateau where the convective rain frequency is small despite a large NDRI. Hirose and Nakamura (2005) pointed out that small rain systems classified into shallow stratiform rain frequently occur over the Tibetan Plateau, although most of them would be shallow convection. In spite of reclassification in Schumacher and Houze (2003b), the rain type remains shallow stratiform because of the definition of warm rain using climatological data of temperature (Hirose and Nakamura 2005).

Over the open ocean, where the diurnal variation is generally weak, the convective frequency and NDRI seem to have a small negative correlation. This appears particularly around the edge of the ITCZ and eastern Australia around 25°S. Rain amounts (Fig. 5) and convective frequencies in these regions are fewer and smaller than those in the center of the ITCZ, Maritime Continent, etc. As mentioned in the previous section, NDRI tends to be large over regions with small rain amounts because $RR_{\text{max}}$ is likely to be much larger than $RR$. The convective frequency generally becomes high with a large rain amount because rainfall is intensified by convective precipitation systems. Thus, the NDRI largely depends on the rain amount over the ocean. Although the NDRI also corresponds to rain amount

### Table 1. Regions and number of samples used in this study.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Surface</th>
<th>Latitude</th>
<th>Longitude</th>
<th>No. of all samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global ocean</td>
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<td></td>
<td></td>
<td>287,986</td>
</tr>
<tr>
<td>Global land</td>
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<td></td>
<td></td>
<td>97,386</td>
</tr>
<tr>
<td>Tropical Africa</td>
<td>Land</td>
<td>0°–20°N</td>
<td>15°W–20°E</td>
<td>2897</td>
</tr>
<tr>
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<td>Land</td>
<td>30°–35°N</td>
<td>80°–95°E</td>
<td>1200</td>
</tr>
<tr>
<td>Western North America</td>
<td>Land</td>
<td>20°–35°N</td>
<td>105°–125°W</td>
<td>1293</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td>Ocean</td>
<td>20°–30°N</td>
<td>80°–100°W</td>
<td>1937</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regions</th>
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<th>No. of PR – VIRS</th>
<th>No. of TMI – VIRS</th>
</tr>
</thead>
<tbody>
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<tr>
<td>Gulf of Mexico</td>
<td>1135</td>
<td>846</td>
<td>866</td>
</tr>
</tbody>
</table>

Fig. 4. Ratio of convective rain frequency to total rain derived from PR2A25 for JJA 1998–2003.
over land, the NDRI largely depends on the convective frequency compared with the effect of rain amount. Over the oceans near coastal regions, the relationship between NDRI (NDBI) and convective frequency is obscure except for some regions such as the Maritime Continent and the Gulf of Mexico in which the effects for land-type rain characteristics can be seen.

The peak local times in convective and stratiform rain frequency (Fig. 6) are quite different over land. The peak time in convective rain frequency occurs around noon to early afternoon, while that in stratiform rain frequency appears in the late evening–midnight. Even over regions with a small NDRI and convective frequency, such as north of the Amazon and over the savanna in Africa, the peak time distributions in convective and stratiform rain show the same characteristics. This tendency means that the peak time of diurnal variations in convective and stratiform rain do not depend on regions. Mechanisms of afternoon (late evening) peak rainfall over land were proposed for surface solar radiative heating [cloud-top radiative cooling (e.g., Dai 2001)], which was further reviewed by Yang and Smith (2006). The relationship between these mechanisms and rain types (i.e., convective and stratiform rain) are reasonable. The above-discussed characteristics hold over oceans near the coast with strong diurnal variations, except for the peak time (i.e., early morning peak). Over open oceans, it is difficult to see differences between the peak time of convective and stratiform rain.

2) STORM HEIGHT

As a convective system develops, storm height generally increases. Therefore, storm height has a diurnal variation. Figure 7 shows the distributions of mean storm height above sea level at the peak local time of storm height as derived from PR 2A23.

The distribution of peak storm height resembles the composite distribution of high convective rain frequency (Fig. 4) or large rain amount (Fig. 5) over both land and ocean, except for the Tibetan Plateau. The high storm height over a high convective frequency region corresponds to high NDRI, as mentioned before. Over the Sahel region, relatively high storm height and a small precipitation amount coincide, and a large convective fraction and a large NDRI dominate. This relation can also be seen over other land regions, such as over North America and Pakistan. On the contrary, the high storm height over a large rain amount does not always correspond to high NDRI. For example, over central Amazon and tropical Africa, high storm-height regions correspond to large precipitation amounts, but not to high NDRI values. This may be due to tall rain systems regardless of convective and stratiform rain over these regions. Over tropical Africa, instead of NDRI, high NDBI values appear. The possible causes are discussed in section 3c.

3) DIURNAL VARIATION OF CLOUDS

As a convective system develops, anvil clouds often spread out from the system. The IR rain estimates can therefore erroneously detect heavy rainfall resulting from the high anvil cloud tops. This may affect both rainfall estimates and diurnal variation detection. Inoue (2000) and Inoue and Aonashi (2000) made comparisons between cloud information and rainfall using TRMM, VIRS, and PR in East Asia. They showed that a BT difference (BTD) in the so-called split-window
technique is a good indicator for detecting rain area. For the study on diurnal variations of clouds, BTD45 (BT4 − BT5) is the most suitable because both of the channels can be utilized regardless of time. However, Inoue and Aonashi (2000) showed that unreasonable diurnal variations in BTD45 occur due to unclear reasons. We also confirmed the same tendency; thus, instead of the application of the split-window technique,
we classified BT4s into two categories—convective cloud (BT4 ≤ 235 K), which is often utilized as a proxy for rain area (Arkin and Meisner 1987), and 2) warm cloud (235 K < BT4 ≤ 255 K), as a proxy for no or weak rainfall.

Figure 8 shows that the peak time of maximum frequency in convective cloud and warm cloud has the same criteria as in the significant peak of diurnal variations. Over land, an afternoon peak (1400–1800 LT) appears over the eastern and western United States, the Amazon, the Tibetan Plateau, and the plain areas in Southeast Asia and the Indian subcontinent. In these regions, the peak time of convective cloud is almost the same as, or a few hours earlier than, that of warm cloud and minimum brightness temperature. Particularly over tropical Africa, the peak time difference is distinct (i.e., 2000–2400 LT for convective cloud and 2200–0200 LT for warm cloud). Over oceans, the frequency of the daytime peak (1400–1800 LT) for warm cloud is more outstanding than those for convective cloud mainly over the tropics. In contrast, the clear late-morning peak and peak time shift from inshore to offshore appear over the Gulf of Mexico and the Bay of Bengal. However, it is difficult to see distinct peak time changes over the western Atlantic Ocean.

c. Diurnal variations in rain/cloud systems and their regional differences

We further investigated diurnal variations in rain–cloud parameters and their regional differences. Some regions mentioned in Fig. 3 are picked up again. Fractions of pixel number in peak local time for storm height, RR-PR in convective and stratiform systems, and RR-TMI are shown in Fig. 9. Those with categorized BT4s (convective: 235 K < BT4, warm: 235 K ≤ BT4 < 255 K) are also shown in Fig. 10. The pixels with a significant peak of diurnal variations only are used in the same way as in the previous subsections.

Over the global ocean (Figs. 9a and 10a), the diurnal variations of all parameters are quite small, but a weak morning peak in RR-PR and RR-TMI and double (morning and afternoon) peaks in convective clouds are present. The peaks in convective clouds precede those in warm clouds by about 6 h. The RR-PR in convective
(stratiform) clouds has also a weak early morning (late night) peak.

Over land (Fig. 9b), in contrast, an afternoon peak fraction appears in both RR-PR and RR-TMI. Convective systems have a strong diurnal variation, whereas stratiform systems have a much weaker variation with a late-night peak. The same peak local time of RR-PR in both total and convective systems appears, but the fraction of RR-PR in a convective system is higher than that in total system before the peak local time. The maximum fraction of storm height lags RR-PR by 1–2 h and gradually decreases after the peak local time. The peak fraction for convective clouds (Fig. 10b) lags behind RR-PR and RR-TMI by 2 h, and there are 4-h time lags between RR-PR (or RR-TMI) and warm clouds.

From the results of temporal variations in rain–cloud parameters, we infer that differences in signatures for each sensor at each stage in the evolution of convective precipitation systems cause the differences in peak local time. Figure 11 shows a schematic diagram of convective rain–cloud-system development over land. PR directly detects near-surface rain from the initial to mature stages. TMI mainly observes deep convection and detects heavy rain with solid hydrometeors in the mature stage. VIRS detects deep convective clouds at mature and decaying stages. While the fraction of convective clouds increase with RR-PR and RR-TMI and lasts

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Fig. 9. (top panels) Fraction of the pixel number in peak local time with storm height (thin solid). (bottom panels) The near-surface rain of convective (thin solid), stratiform (thin dashed), total rain (bold solid line) derived from PR 2A25, and the surface rain derived from TMI 2A12 (bold dash-dotted). Areas are (a) ocean and (b) all land, and land regions of (c) tropical Africa, (d) the Tibetan Plateau, (e) western North America, and (f) the oceanic region over the Gulf of Mexico.
for a few hours, the peak local time of warm clouds is behind RR-PR and RR-TMI development. Indeed, the peak time of the frequency of occurrence in convective rain occurs earlier than the peak time of mean RR-PR by 2 h. An initial stage of a rain system generally is convective. By the mature stage, the relative frequency of convective rain decreases because the rain frequency becomes high with stratiform rain.

Focused on the specific regions (tropical Africa, the Tibetan Plateau, and western North America; Figs. 9c–e and 10c–e, respectively), the distributions of rain and cloud parameters are similar to those over global land but appear more prominently. Over tropical Africa, the same peak local time (1600 LT) appears among RR-PR, RR-TMI, and storm height. The peak local time of RR-PR in convective cloud precedes them by 1 h. Compared to the global land region, the higher fractions of RR-PR in convective cloud before the peak local time are more outstanding. The high fractions of RR-PR in stratiform cloud at the early morning peak and of convective and warm clouds in the late-night peak keep for 5–6 h. Over the Tibetan Plateau, the fractions of RR-PR, RR-TMI, and storm height show the same peak local time. However, that of RR-TMI (RR-PR in convective cloud) is higher than that of RR-PR in total cloud after (before) the peak local time. RR-PR in stratiform cloud shows and keeps prominent diurnal variations during midnight–morning. The convective and warm clouds lag behind RR-PR in total by 1 and 2 h, respectively. These time lags are smaller than the other regions. Over western North America, the differences of fraction between RR-PR and RR-TMI are not so large. In contrast, the peak time of RR-PR in convective clouds and of convective and warm clouds largely differ from that of RR-PR in total by −2 and 4 h, respectively. The peak time of convective and warm clouds shows the same time, but the distribution of the fraction of warm clouds shifts to 2 h later.

Over the Gulf of Mexico (Fig. 9f), the first and the second peaks are present at 0800 and 1200 LT for RR-PR, RR-TMI, and storm height, and at 1300 and 1500 LT for convective and warm clouds. Those double peaks may be caused by the peak local time difference between inshore and offshore from the horizontal map.
There are no prominent diurnal variations in RR-PR in either convective or stratiform systems. Several rain properties, such as storm height, RR-PR, RR-PR in convective and stratiform systems, and RR-TMI, are shown in Fig. 12. Cloud properties of various BT4s (deep convective: BT4 < 215 K, convective: 215 K ≤ BT4 < 235 K, warm: 235 K ≤ BT4 < 255 K) are shown in Fig. 13. Hourly mean values without temporal averaging using all data observed in each region are calculated, although only the pixels with significant peak of diurnal variations are used in the previous section. Pixel numbers in 0.25° × 0.25° for each region are shown in Table 1.

Over the global ocean (Fig. 12a), the diurnal variations of mean storm height and rain rate for all properties are small, with a weak morning peak in RR-PR and RR-TMI; RR-TMI is larger than RR-PR throughout. Amounts of convective and stratiform rain are nearly equal. The peak time distributions are quite variable, although some pixels are shaded in Fig. 1 as a significant peak of diurnal variation. Diurnal variations in deep convective and convective clouds (Fig. 13a) are quite small, but a weak early morning peak in deep convective cloud and an early afternoon peak in convective cloud are present. Relatively prominent diurnal variation appears in the early evening for warm clouds in Fig. 13a.

Over land (Fig. 12b), in contrast, an afternoon peak frequency appears in both RR-PR and RR-TMI. Convective systems have a strong diurnal variation, whereas stratiform systems have a much weaker variation. The mean maximum storm height lags RR-PR by...
1–2 h and gradually decreases after the peak local time. As in the global ocean, RR-TMI is larger than RR-PR. However, the difference between RR-PR and RR-TMI increases after rain systems develop [i.e., (RR-TMI)/(RR-PR) are 145% and 194% before and after rain systems develop]. While the TMI algorithm senses emission by liquid hydrometeors over ocean, TMI uses a scattering algorithm that is sensitive to frozen hydrometeors over land. When convective rain systems develop, an updraft makes solid hydrometeors in an upper part of the system. After the systems developed, solid particles remain later while near-surface rain weakens. This characteristic is consistent with the diurnal variations in storm height and has also been shown by Furuzawa and Nakamura (2005). The diurnal variations for deep convective and convective clouds (Fig. 13b) resemble that for RR-PR and RR-TMI from developing to mature stages, although the peak frequencies remain high after 2–3 h. The peak frequency for deep convective cloud lags RR-PR and RR-TMI by 2 h. In addition, the peak frequency appears around 2200 LT for the warm cloud system.

Histogram distributions vary with regions. Over tropical Africa (Fig. 12c), the diurnal variations of RR-PR are relatively small, but those of RR-TMI are distinct. These characteristics agree with results by Geerts and Dejene (2005) for PR and by Mohr (2004) for TMI. This may be because precipitation may not reach the surface because of evaporation (Geerts and Dejene 2005) or because the tropical wet region with weak diurnal variations is dominant in the selected region. Diurnal variation in storm height keeps peak height at 1600 LT until around midnight. As with storm height, deep convective and convective cloud systems (Fig. 13c) remain with high frequencies until late evening. In particular, the frequency for deep convective cloud is higher than other regions. It is reasonable that RR-TMI shows prominent diurnal variations because deep convective clouds contain large amount of solid hydrometeors. The peak frequency for warm cloud lags by 2 h and remains high until early morning.

The Tibetan Plateau is characterized by afternoon peak diurnal variations in RR-PR, RR-TMI, convective rain, and storm height (Fig. 12d). There are two characteristics that appear only over the Tibetan Plateau—one is that RR-PR is larger (smaller) than RR-TMI before (after) peak local time, and the other is that stratiform rain seems to precede the convective rain. Over the Tibetan Plateau, relatively light precipitation systems with small scales prevail (Hirose and Nakamura 2005). Because these systems are usually classified as stratiform, the diurnal variation in stratiform rain appears outstandingly. Diurnal variations in deep convective and convective cloud (Fig. 13d) are quite similar to RR-PR and RR-TMI. Compared to tropical Africa, it is likely difficult for the rain systems to develop anvils. On the contrary, diurnal variations in warm cloud resemble that in stratiform rain.
Compared to the global land (Fig. 12b), afternoon–evening diurnal variations in RR-PR, RR-TMI, convective rain, and storm height occur more outstandingly over western North America (Fig. 12e). Those peak times are 1600 LT, and heavy rainfall is kept until 2000 LT and then slightly weakens. The deep convective and convective cloud (Fig. 13e) shows similar diurnal variations, although the frequencies remain high. The peak time for stratiform rain is small and lags the peak time for convective rain by 4-6 h.

Over the Gulf of Mexico (Fig. 12f), there is a morning peak in diurnal variations of RR-PR and RR-TMI; these peaks are related to convective precipitation type. Storm height and deep convective cloud (Fig. 13f) do not show prominent diurnal variations well, but correspond to RR-PR and RR-TMI. The peak time for convective cloud lags behind RR-PR and RR-TMI by more than 2 h. Moreover, warm cloud shows weak evening diurnal variations.

Some rain parameters of these diurnal variations differ from those of the fractions (Fig. 9). While the fractions of RR-PR in convective rain precede RR-PR in total by 1–2 h over land, mean RR-PR in convective rain synchronizes with those in total. This means that convective rain dominates in the initial stages of the rain system. Over the ocean, with diurnal variations such as the Gulf of Mexico, mean RR-PR in convective rain corresponds to that in total, although the fraction of RR-PR in convective rain is not outstanding. Compared to RR-PR, RR-TMI tends to overestimate prominently after the peak local time of all mentioned regions, except for the global ocean. The TMI algorithms can also affect peak local time differences and rain estimates. Retrieved rain over land is derived from scattering by solid hydrometeors in higher-frequency channels. Thus, it is reasonable that RR-TMI overestimates and lags behind RR-PR after convective systems develop. Over ocean, variations in RR-TMI should be similar to those of RR-PR because of emissions from low-frequency channels. However, the relation of RR-PR and RR-TMI over the near-coastal ocean was similar to that over land. This may be because scattering process may be adopted even over ocean because of high storm height from the high convective frequency.

The temporal differences related to the stage of convective precipitation system are consistent with results derived from the PR and TMI (Furuzawa and Nakamura 2005; Rajendran and Nakazawa 2005) and from cloud-system development (Kondo et al. 2006). Both PR and TMI directly observe rain and hydrometeors, so the peak time difference is relatively small. The VIRS observes the cloud-top height so the peak time difference can be large. The peak time difference depends on regional characteristics, including differences in the precipitation–cloud structure.

4. Conclusions

This study used 6 yr of orbital data from the PR, TMI, and VIRS on the TRMM satellite to investigate relations between diurnal variations in rain–cloud systems as detected by the three sensors. Some indices, such as the NDRI and NDBI, were also examined to identify the prominence of RR (BT) at the peak local time compared to the average, which relates to the strength of the diurnal variation of rain–cloud. Compared to the peak local times among RR-PR, RR-TMI, and BT4-VIRS, we find that systematic peak time differences frequently appear with regional variability, although the diurnal variations among the sensors are apparently similar. The peak time difference between the PR (or TMI) and VIRS is larger than that between the PR and TMI. These regions correspond to large NDRI and NDBI, for example over tropical Africa, the Tibetan Plateau, the Hindustan plain, and western North America. Over the ocean, significant peak shifts are well obscured.

We further investigated the relationships among rain–cloud properties such as convective and stratiform rain, storm height, rain amount, and BT4s categorized by thresholds. The distributions and relationships largely depend on regions. However, we deduced some general characteristics from their properties. Over land, the regions with strong diurnal variation generally correspond to those with high convective frequency except for the Tibetan Plateau, perhaps because of the rain-type classification problem in the PR algorithm for weak rain. The storm height is generally high when high convective rain frequency or large total rain amount appears. The correlation between NDRI and storm height is not clear because high storm height likely appears over regions with high rain totals, where convective rain frequency is not always high. The peak time in convective rain frequency dominates around noon to early afternoon preceding the peak time of RR-PR by a few hours, while that in stratiform rain frequency appears in the late evening–midnight over the regions regardless of NDRI. For clouds, the peak time of convective cloud is almost the same, or a few hours earlier, than that of warm cloud and minimum BT4.

Over the open ocean, high storm height correlates with convective rain frequency or rain totals, similar to over land. However, the relationships among NDRI, the convective frequency, the storm height, and rain totals are not clear. The characteristics over land hold for some oceanic regions near the coast, such as the
Gulf of Mexico, although the peak time of rain and cloud are very different (i.e., late-morning peak).

According to these results, we suggest that sensor signatures that depend on convective precipitation and cloud-system development may cause these time shifts. The PR directly detects near-surface rain from initial to mature stages. The TMI mainly observes deep convection and detects heavy rain with solid hydrometeors in the mature stage. VIRS detects deep convective clouds at mature and decaying stages. Regions where convection dominates are regions with large time shifts. The diurnal variations for deep convective clouds resemble that for RR-PR and RR-TMI from developing to mature stages, although the peak frequencies remain high for 2–3 h. However, the peak frequency of convective clouds persists for longer times compared with rainfall, particularly for warm cloud systems. This tendency is quite distinct over western North America. Over tropical Africa, the duration of high frequencies in BT4 is longer than that of the other regions. On the contrary, convective cloud systems do not last long over the Tibetan Plateau.

This study showed that differences in the diurnal variation of precipitation and cloud systems vary by region. The lag in the diurnal variation between precipitation and clouds may introduce errors resulting from time persistence of deep convective clouds. These results would help to improve precipitation estimates from infrared observations that the time lag and regional information incorporated in previous algorithms. We further investigated the relationships among NDRI, convective frequency, storm height, and rain amount, and found some general characteristics. Over land and over ocean near the coast, the relationships are rather clear, but not over open ocean. We need further investigations to make the general characteristics reliable.

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