Regional Characteristics of Extreme Rainfall Extracted from TRMM PR Measurements

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ABSTRACT

Characteristics and global distribution of regional extreme rainfall are presented using 12 yr of the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) measurements. By considering each rainfall event as a set of contiguous PR rainy pixels, characteristic values for each event are obtained. Regional extreme rainfall events are defined as those in which maximum near-surface rainfall rates are higher than the corresponding 99.9th percentile on a 2.5° × 2.5° horizontal-resolution grid.

The geographical distribution of extreme rainfall rates shows clear regional differences. The size and volumetric rainfall of extreme events also show clear regional differences. Extreme rainfall rates show good correlations with the corresponding rain-top heights and event sizes over oceans but marginal or no correlation over land. The time of maximum occurrence of extreme rainfall events tends to be during 0000–1200 LT over oceans, whereas it has a distinct afternoon peak over land. There are also clear seasonal differences in which the occurrence over land is largely coincident with insolation.

Regional extreme rainfall is classified by extreme rainfall rate (intensity) and the corresponding event size (extensity). Regions of “intense and extensive” extreme rainfall are found mainly over oceans near coastal areas and are likely associated with tropical cyclones and convective systems associated with the establishment of monsoons. Regions of “intense but less extensive” extreme rainfall are distributed widely over land and maritime continents, probably related to afternoon showers and mesoscale convective systems. Regions of “extensive but less intense” extreme rainfall are found almost exclusively over oceans, likely associated with well-organized mesoscale convective systems and extratropical cyclones.

1. Introduction

Heavy rainfall events can trigger natural disasters, such as floods and landslides, and cause severe damage to lives and property. An important concern is whether future climate change will alter the intensity and frequency of extreme rainfall and, if so, how this will affect the characteristics of extreme rainfall. Previous analyses have indicated that the frequency and intensity of extreme rainfall on a daily basis exhibits a positive trend but that there are large regional differences in the level of increase/decrease (e.g., Aguilar et al. 2005; Alexander et al. 2006). CO2-doubling experiments with atmosphere–ocean coupled general circulation models indicate that global-mean precipitation increases with global-mean near-surface temperature. However, such increases are attributed mainly to the uppermost percentile of global rainfall distribution (Allen and Ingram 2002).

Extreme rainfall is associated with a wide variety of weather systems, such as mesoscale convective systems (Houze et al. 2011), orographic precipitation in association with low-level jets (Lin et al. 2001; Monaghan et al. 2010), tropical cyclones (Lau et al. 2008), and other...
mesoalpha to synoptic-scale disturbances (Maddox et al. 1979; Funatsu et al. 2009). Interannual variations in such disturbances affect the annual frequency of extreme rainfall (Ajayamohan et al. 2010). Large-scale environmental conditions are also related to the type and frequency of extreme rainfall in some regions. In the tropics, the El Niño–Southern Oscillation (ENSO) has a major effect on the frequency of extreme events; El Niño and La Niña events are associated with increased frequencies of extreme dry and wet weather, respectively, over tropical land (e.g., Carvalho et al. 2002; Curtis et al. 2007). The latitudinal shift of storm tracks is considered linked to the frequency of extreme events at midlatitudes (Haylock et al. 2006).

What is meant by extreme rainfall differs by region. For example, a few tens of millimeters of hourly rainfall are commonplace in some rainy regions but in arid areas are comparable to the total annual rainfall and may cause serious damage (e.g., Rasmussen and Houze 2012). Geographical distributions of extreme rainfall intensity on shorter time scales have been identified on a regional scale by many authors (e.g., Romatschke and Houze 2010; Romatschke et al. 2010), and many have performed detailed examinations of the weather conditions and/or precipitation systems yielding extreme rainfall within the target region. However, quantitative comparisons of regional extreme rainfall intensity are not straightforward because of the different definitions of extreme rainfall used. With globally homogeneous measurements, the global distribution of extreme rainfall events can be attained by satellite remote sensing. Zipser et al. (2006) showed a map of extremely intense convective events and their seasonal/diurnal cycles measured from instruments onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. They found that extremely intense convective activity reveals a distribution significantly different from that of total rainfall and that it is often found in semiarid regions.

There is a relatively long history of describing the global distribution of intense convective activity from spaceborne measurements (e.g., Spencer and Santek 1985; Mohr and Zipser 1996; Cecil et al. 2005; Cecil and Blankenship 2012). However, there are very few studies on the global distribution of extremely intense rainfall using spaceborne measurements. This is primarily because of the limitations in using passive infrared and microwave measurements as a proxy of surface rainfall. Severe convective activity is unquestionably linked to natural disasters, such as thunderstorms, hailstorms, and tornadoes. However, there are also extreme precipitation systems that yield flash floods, which have a structure distinct from typical severe thunderstorms (e.g., Smith et al. 1996; Petersen et al. 1999). Sohn et al. (2013) indicated that heavy rainfall over the Korean Peninsula is associated more with lower echo-top height clouds than with conventional deep convective clouds. These findings suggest the importance of studying extreme rainfall events in terms of surface rainfall as well as storm intensity.

It would be useful to have a definition that permits a globally unified comparison of the regional characteristics of extreme rainfall. In this study, we introduce a simple method for defining regional extreme rainfall characteristics using the TRMM Precipitation Radar (PR) data. In our analysis, we establish the characteristics of precipitation systems related to extreme rainfall in each region, such as intensity, size, and maximum echo-top height. Section 2 provides a brief summary of the data used in this study and introduces the method for defining regional extreme rainfall. Section 3 describes the global distribution of extreme rainfall characteristics and their regional, diurnal, and seasonal differences. Summary and concluding remarks are given in section 4.

2. Data and methodology

2a. Data

The TRMM satellite has been observing global rainfall from space with five sensors since December 1997. Among these sensors, the 13.8-GHz PR is a unique spaceborne radar that enables the observation of three-dimensional rain structures. The non-sun-synchronous orbit of the TRMM satellite has an inclination of 35°, which allows the collection of rainfall data between ~36.5°S and 36.5°N at all local times. In this study, we use rainfall data derived from the PR 2A25 (Iguchi et al. 2000, 2009) version 7 product. These data include near-surface rainfall rate, which is defined as the rainfall rate at the lowest range (vertical) bin, free from the main lobe clutter. We did not use “estimated surface rainfall rate” (e_SurfRain) in the 2A25 product, which is an estimated rainfall rate at the actual surface. The e_SurfRain is calculated based on an assumption that effective radar reflectivity is constant below the clutter-free level. However, this assumption is not necessarily consistent with many observational facts that the vertical gradient of radar reflectivity below the melting level exhibits significant dependences on region and weather regime (e.g., Szoke et al. 1986; Zipser and Lutz 1994). The 2A25 product also include the vertical rainfall profile from the near-surface level to 20 km, at a resolution of 250 m with a 4.3-km footprint (5 km after a boost in August 2001 extending the mission life), within a swath width of 220 km (247 km after August 2001). Information on the observation time, geographical location, surface type (land, ocean, or coast), and rain type (convective or stratiform) is also obtained.

The overall performance of the 2A25 version 7 product has been improved from the earlier version 6
product, especially in mitigating the known underestimation of rainfall rates over land (e.g., Seto et al. 2013; Kirstetter et al. 2013), although it has been argued that underestimation still remains, especially for extremely intense convective rainfall (Rasmussen et al. 2013). However, the version 7 product has been found to contain unexpected, suspicious data that are likely caused by contamination from surface clutter (Hamada and Takayabu 2014). Such false data are usually related to extremely high near-surface rainfall rates and they significantly affect extreme rainfall statistics. Prior to the analysis, we applied a removal filter for false extreme rainfall data, which has been developed by Hamada and Takayabu (2014). The maximum near-surface rainfall rate is 300 mm h⁻¹ in both the original and filtered 2A25 dataset, because of a ceiling of the rainfall-rate estimates in the original 2A25 dataset.

The TRMM satellite has provided continuous measurements since its launch in November 1997, but its orbiting altitude was changed in mid-August 2001 and, accordingly, the PR sensitivity was decreased (Short and Nakamura 2010; Hirose et al. 2012). Therefore, the analysis period was taken to be the 12 yr from September 2001 to August 2012, to use homogeneous data as long as possible.

The duration of rainfall event is another important variable for producing short-term extreme rainfall related to flash floods. Since the TRMM observation provides only instantaneous rainfall rates, the duration of extreme rainfall event cannot be obtained directly. To this end, we use a high-temporal-resolution version of the Global Satellite Mapping of Precipitation (GSMaP; Kubota et al. 2007; Aonashi et al. 2009) products, GSMaP_MVK version 5, to derive the “mapped rainfall duration” of each rainfall event at the local point of the extreme rainfall. Surface rainfall rate in the GSMaP_MVK is obtained with cloud-top motion derived from two successive infrared images of geostationary satellites and a Kalman filter, which integrates passive microwave radiometer measurements with infrared measurements (Ushio et al. 2009). The spatial and temporal resolutions are 0.1° and 1 h, respectively. The analysis period for deriving the mapped rainfall duration is from September 2001 to November 2010, because of the product’s availability. Note that, in this study, mapped rainfall duration is defined as persistence time of rainfall at a local point rather than a lifetime of the event. The rainfall duration is obtained by consecutive nonzero rainfall rate, which is the average of 3 × 3 grid points of GSMaP_MVK surrounding the location of extreme rainfall event, in a similar way to Liu (2011) but using higher-spatiotemporal-resolution dataset.

b. Definition of extreme rainfall event

In this study, we aim not only to describe extreme rainfall intensities on a regional basis, but also to relate them to precipitation systems that yield extreme rainfall. To this end, we identify individual rainfall events as contiguous rainy pixels in the TRMM PR measurements before defining extreme rainfall. By using a rainfall event as the sampling unit, rather than individual rainy pixels, other characteristic values such as the size of the rainfall event can be obtained for each event.

A rainfall event is defined as a contiguous area of PR footprints where the near-surface rainfall rates are higher than 0.5 mm h⁻¹ and are flagged as “rain certain” in the 2A25 “rain flag” data. The rainfall rate of 0.5 mm h⁻¹ almost corresponds to the minimum detectable PR reflectivity of 17 dBZ. For each rainfall event, the maximum near-surface rainfall rate, its size, the volumetric rainfall, and the maxima of rain-top height and 40-dBZ echo-top height are derived. The maximum near-surface rainfall rate for each rainfall event (R_{max}, units: mm h⁻¹) is defined as the maximum pixel value of near-surface rainfall rate in the rainfall event. The size of each rainfall event (km) is calculated by the square root of the number of pixels in the rainfall event multiplied by the PR footprint size (5 km × 5 km throughout the analysis period). The volumetric rainfall (km³ mm h⁻¹) is calculated as the sum of all near-surface rainfall-rate values in the rainfall event multiplied by the PR footprint size. The maximum rain-top height (km) is defined as the maximum pixel value of rain-top heights (defined as the uppermost vertical bin with a rainfall rate higher than 0.5 mm h⁻¹) in the rainfall event. The maximum 40-dBZ echo-top height (km) is defined in the same way as the maximum rain-top height but using 40-dBZ echo-top height at each pixel in rainfall event. The representative location of each rainfall event is defined as the location at which the maximum surface rainfall rate is observed.

Note that the size and volumetric rainfall are potentially underestimated because some parts of the rainfall event could extend beyond the edge of the PR swath, especially for rainfall events with large horizontal extent. Nesbitt et al. (2006) observed that 9% of rainfall features overall and more than 50% of those larger than 10⁴ km² in the precipitation feature database (Nesbitt et al. 2000) intersect the edge of the PR swath. We have confirmed almost the same circumstance in our rainfall event database.

The rainfall event database developed in this study is basically built on the same concept as the University of Utah TRMM precipitation feature (PF) database (Liu et al. 2008), where both are event oriented and easy to retrieve information on individual rainfall events. The method to define a rainfall event in our database is almost same as that to define a “radar precipitation feature” (RPF) in the PF database, except for the threshold value of near-surface rainfall rate. The overall characteristics of rainfall events, such as size distribution, are, naturally, almost identical to those of PFs. Although the PF database
is even more comprehensive and well informed than ours, we developed our own database for the following two reasons: First, as described above, the 2A25 version 7 product requires the removal of false extreme rainfall rates before aggregating pixel-level information. Second, we need the location of the maximum near-surface rainfall rate in each rain event, which is not included in the RPF database.

Extreme rainfall is defined on a local basis, by dividing the analysis domain into 2.5° × 2.5° longitude and latitude grids. The characteristic values related to extreme rainfall events are defined for each individual grid. Rainfall events are distributed in grids within which the representative locations fall, and then $R_{\text{max}}$ values are sorted in the ascending order within each grid. Figure 1 shows the regional variation of cumulative distribution functions (CDFs) of $R_{\text{max}}$ for grids within the 32.5°–35°N belt. It can be seen easily that the CDFs vary significantly for different grids over both the land and the oceans. The spread of $R_{\text{max}}$ becomes larger at higher percentiles, and the ratio between the maximum and minimum values is about 4 and 3 at the 99.9th percentile over land and oceans, respectively. This shows how the threshold for regional extreme rainfall varies with region. In this study, we employ a percentile-based approach for defining regional extreme rainfall. Extreme rainfall events are defined for each grid as those with $R_{\text{max}}$ larger than its corresponding 99.9th percentile value in the grid. The number of regional extreme event and 99.9th percentile value of $R_{\text{max}}$ in each grid are shown in Figs. 2a,b. By definition, the number of regional extreme events is almost equal to the number of rainfall events divided by 1000 in each grid box. Subsequently, the regional extreme rainfall is calculated for each grid as the average of the $R_{\text{max}}$ values for extreme rainfall events. For other characteristic variables (i.e., size, volumetric rainfall, and maximum rain-top height), their corresponding extreme values are defined as their averages for extreme rainfall events. Note that they are not averages of the values for rainfall events (not limited to extreme rainfall events) with the value larger than its corresponding 99.9th percentile in the grid. It should also be noted that extreme rainfall events in this study are defined from full-year PR data, although we will examine the diurnal and seasonal variations.

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FIG. 1. Cumulative distributions of $R_{\text{max}}$ for 2.5° horizontal-resolution grids along 32.5°N: (a) over land and (b) over oceans. The horizontal and vertical axes represent $R_{\text{max}}$ (mm h$^{-1}$) and its corresponding percentile, respectively. Solid line shows median value, dark shading shows the interquartile range, and light shading indicates range between minimum and maximum values at each vertical bin with size of 0.1 percentile.

FIG. 2. Global distribution of (a) the number of extreme rainfall events, (b) 99.9th percentile value of maximum near-surface rainfall rate (mm h$^{-1}$), (c) regional extreme rainfall defined as the average of $R_{\text{max}}$ values for extreme rainfall events (mm h$^{-1}$), (d) size of extreme rainfall events (km$^2$), (e) maximum rain-top height (km), and (f) maximum 40-dBZ echo-top height (km). Values in (c)–(f) are shown as the average values for all extreme rainfall events at individual grids. Note that the values in (d)–(f) are shown as the average for the extreme rainfall events (see text for details). Colors for grids with less than three extreme rainfall events are not shown.
We have conducted a sensitivity analysis on extreme rainfall, as defined above, using threshold values defining the rainfall event with near-surface rainfall-rate values from 0 (with rain-certain flags) to 1 mm h\(^{-1}\). The results show that the calculated extreme surface rainfall rates are not significantly sensitive to the choice of threshold values used to define the rainfall event (not shown).

3. Results

a. Global view

Figure 2a shows the global distribution of the number of extreme rainfall events. As the number of extreme rainfall events directly reflects the number of detected rainfall events, larger numbers of extreme rainfall events are observed in those regions with more frequent rainfall. Note that there are discontinuities at the latitudes of 32.5°N and 32.5°S because of the characteristics of the TRMM orbit. The number of rainfall events varies significantly by region. Over the oceans, rainfall events are generally more frequent on the western side of the oceans, except over the Indian Ocean. High numbers of rainfall events are observed in the western tropical Pacific, the intertropical convergence zone (ITCZ), the South Pacific convergence zone (SPCZ), the northwestern Pacific, the northwestern Atlantic, and the south Indian Ocean. Over land, the number of rainfall events is generally lower than that over the oceans. The highest numbers are found along the Himalaya and the eastern edge of the Tibetan Plateau; however, there are some other rain-frequent regions, such as the Amazon and East Asia.

Regional differences in the geographical distribution of regional extreme rainfall are evident in Figs. 2b,c and indicate that the consideration of regionality is essential for studying extreme rainfall. Regional extreme rainfall is generally higher over land than over oceans. The world’s greatest regional extreme rainfall are found over land around Meghalaya in eastern India, northern Vietnam, and maritime continents. The regional extreme rainfall in these regions is higher than 220 mm h\(^{-1}\). Over land, high regional extreme rainfall is also observed over equatorial Africa, the sub-Himalayan region, East Asia, vast areas of North America, the Amazon River basin, and the Rio de la Plata basin with rainfall rates in excess of 200 mm h\(^{-1}\) in some regions. Over the oceans, high regional extreme rainfall is observed mainly in coastal regions with intensities around 120 mm h\(^{-1}\). There are also some regions with relatively high regional extreme rainfall within the ITCZ and SPCZ. Regions of high regional extreme rainfall tend to extend from eastern continental coastlines in the subtropics.

The geographical distribution of the size of extreme rainfall events also shows clear regional differences (Fig. 2d). Extreme rainfall events are generally much larger over the oceans than over land. Over the oceans, the largest values are found to the south of Japan, the Bay of Bengal, eastern equatorial Pacific, southern Pacific, and southwestern Atlantic with areas greater than 200 km. Over the subtropical oceans, the pattern of larger values is similar to that of storm tracks in both hemispheres (Blackmon et al. 1977; Trenberth 1991). This feature probably indicates that extreme rainfall within these regions is related to extratropical frontal systems, as shown in previous studies of extreme daily precipitation (Catto and Pfahl 2013). Over land, large values are observed in the Sahel regions, eastern China, Japan, eastern United States, and southeastern South America. Those regions with larger-sized rainfall events tend to have high regional extreme rainfall (Fig. 2c).

The geographical distribution of the volumetric rainfall of extreme rainfall events appears similar to the corresponding size distribution (not shown). These distributions are similar to the locations of precipitation systems with the world’s highest volumetric rainfall (as captured by TRMM PR) (Hirose et al. 2009). This positive correlation between size and volumetric rainfall is consistent with other well-known positive correlations between them (note: not limited to extreme rainfall), as seen in many observational studies (e.g., Richards and Arkin 1981).

There are also significant regional differences in the maximum rain-top height of extreme rainfall events (Fig. 2e), although the variation is small in comparison with the other variables analyzed in this study. The tallest rain-top heights are observed in the Sahel region, Bay of Bengal, and northwestern Australia, where rain-top heights exceed 17 km. Over the oceans, taller extreme rainfall events are distributed broadly over the Pacific warm pool, tropical Indian Ocean, ITCZ, and SPCZ. There is an east–west contrast over the subtropical oceans, in which higher rain-top heights are observed on the western side, partly because of the large-scale subsidence and relatively low sea surface temperature suppressing deep convection in the eastern part of the oceans (Takayabu et al. 2010). Over land, higher rain-top heights are observed in both the tropics and subtropics. In central areas of the United States and southern South America, rain-top heights exceed 15 km in some regions, indicating severe convection reaching the tropopause. In southern East Asia, the rain-top heights are around 12–13 km, although the extreme surface rainfall rates are comparable with those of the central United States.

In contrast to the small difference of the maximum rain-top height between over land and over the oceans, clear land–ocean contrast is observed in the maximum 40-dBZ echo-top height (Fig. 2f). Over the oceans, there is significant discrepancy between the maxima of rain-top height and 40-dBZ echo-top height. These land–ocean differences can be related to different environmental conditions, in which the vertical stratification over the
Ocean is less unstable than over land (Kelley et al. 2010) but their levels of neutral buoyancy are close to each other (Liu et al. 2007). Even over land, the regional variation of the maximum 40-dBZ echo-top height is larger than that of the maximum rain-top height. For example, more than 4-km difference is found for the same 15–16-km rain-top heights between the northern and southern South America.

It is interesting to note that the regions with the world’s highest surface rainfall rates do not necessarily correspond to the regions with the world’s most intense convective activity (Zipser et al. 2006, their Fig. 3). For example, in western equatorial Africa, which is one of a small number of regions with the most intense convection, the regional extreme rainfall is generally less than that in the Amazon River basin, although the rain-top heights of the extreme rainfall events are much lower than those in western equatorial Africa. This regional contrast in the relationship between storm intensity and surface rainfall is consistent with the climatological characteristics highlighted by McCollum et al. (2000). Figure 3 shows joint histograms between $R_{\text{max}}$ and the maximum 40-dBZ echo-top heights for all the extreme rainfall events, separately for the tropics and subtropics, and for land and oceans. The tropics and subtropics are separated at the latitude of 20°. A notable feature is a clear land–sea contrast. Over the oceans, there are clear correlations both in the tropics and in the subtropics with correlations higher than 0.5 (Figs. 3a,c). In contrast, distributions over land are much more scattered both in the tropics and in the subtropics (Figs. 3b,d) and show no correlation. An interesting feature is that, in any of the four regions, the relationship between surface rainfall rate and convective intensity is much reduced for the rainfall rates higher than 100 mm h$^{-1}$. There seems to be two regimes, where one exhibits the highest convective intensity related to the rainfall rate around 100–150 mm h$^{-1}$ and the
other exhibits the highest rainfall rate related to the 40-
dBZ echo-top height around 6–7 km. A possible physical
interpretation on such decorrelation is that many of the
rainfall events that produce extreme rainfall rate from
less intense convection are associated with orographic
rainfall, which exhibits lower strong echo-top height even
for intense rainfall (e.g., Shige et al. 2013; Taniguchi et al.
2013). However, such a decorrelation might be related to
different stages in the life cycle of the same rainfall
events (i.e., the maxima of rainfall rates may follow the
maxima of convective intensity; Leary and Houze 1979),
and to the potential underestimation of TRMM PR-
derived rainfall rate for extremely intense convective
rainfall (Rasmussen et al. 2013). Further investigation is
needed for adequate physical interpretations.

It is also noteworthy that higher regional extreme
rainfall does not necessarily correspond to larger rainfall
event size, especially over land. For example, Meghalaya
has the world’s highest surface rainfall rate, but both the
corresponding rainfall event size and volumetric rainfall are
not that different from other areas of India, where the ex-
treme surface rainfall rate is approximately half that in
Meghalaya. In addition, the Amazon River basin has an
extreme surface rainfall rate that is significantly larger than
that in western equatorial Africa, but the rainfall event size
of the Amazon basin is smaller than that in western equa-
torial Africa. Such regional difference could be attributed to
several factors, such as available moisture and physical
processes for precipitation efficiency and synoptic-scale dy-
namics favorable for organization of precipitation systems
among these regions (e.g., McCollum et al. 2000; Sato 2013).

Looking more closely, in southern South America (Fig. 2)
there is a difference in the locations of extreme surface
rainfall rate, extreme event size, and maximum rain-top
height, probably reflecting the regional characteristics of
precipitation systems in this area (Romatschke and Houze
2010). We examine the relationship between the regional
extreme rainfall and the corresponding event sizes. Figure 4
shows separate joint histograms for the tropics and subtropics and for the land and oceans. The tropics and subtropics are again separated at the latitude of 20°. A notable feature is the clear land–sea contrast between the oceans and the land, as found in the relationship between $R_{\text{max}}$ and maximum 40-dBZ echo-top heights (Fig. 3). Over the oceans, there are linear correlations both in the tropics and in the subtropics with correlation coefficients greater than 0.3 (Figs. 4a,c). This is largely consistent with previous studies (Nesbitt et al. 2006; Cifelli et al. 2007), although they did not focus on extreme rainfall events. Such a positive correlation can be attributed to their mesoscale dynamics that enhance precipitation efficiency.

In contrast, distributions over land are more scattered, both in the tropics and in the subtropics (Figs. 4b,d). There is no significant correlation over topical land. Such a weak correlation is attributed mainly to rainfall event sizes smaller than 100 km, for which the corresponding surface rainfall rates are distributed widely from a few dozen to near 300 mm h$^{-1}$. Such a very little correlation might be related partly to orographic effects (Houze 2012).

There is a clear regional contrast in the extreme rainfall event characteristics, when they are classified into four types based on the extreme rainfall rate and corresponding event size. Figure 5 shows the geographical distribution of classified regional extreme types. Threshold values are set to 120 mm h$^{-1}$ for extreme rainfall rate and 150 km for extreme rainfall event size. These threshold values are chosen so as to be around the upper quartiles for the corresponding characteristic values. Recall that both the extreme rainfall rate and event size are defined as their average for extreme rainfall events. A region in which both the extreme rainfall rate and event size exceed the thresholds is considered as a region of “intense and extensive” extreme rainfall. Regions of “intense but less extensive” and “extensive but less intense” extreme rainfall can be determined in a similar manner.

The regional distribution of each extreme type is only concerned here, as the detailed interpretation will be made in the last part of this section. The intense and extensive extreme rainfall regions, shown in red in Fig. 5, are found mainly over the oceans near coastal areas with the exception of eastern Melanesia. Over land, these regions are found in small parts of equatorial western Africa, central areas of the United States, and southeastern South America. The intense but less extensive extreme rainfall regions, shown in yellow, are distributed widely over land and maritime continents. In contrast, the extensive but less intense extreme rainfall regions, shown in blue, are found almost exclusively over the oceans.

Rainfall duration is another key parameter for causing disasters related with short-term extreme rainfall. Geographical distribution of the median value of mapped rainfall duration for extreme events is shown in Fig. 6. In most regions both over land and over the oceans, more than half of extreme rainfall events produced rainfall for more than 6 h. There are some regions with shorter mapped rainfall durations, such as in West Asia and the Tibetan Plateau over land and in western Africa and South America over the oceans.

Note that regional extreme rainfall events defined in 2.5° × 2.5° grid boxes do not represent all local points included in each grid, especially in such grid boxes with complex terrain (e.g., Nair et al. 2009; Seiler et al. 2013). For example, Fig. 7 shows the locations of extreme rainfall events in the subregion of the Western Ghats. Extreme events are located along the western feet of the mountain ranges except for the northeastern grid box. The representativeness of extreme events is biased toward the western part of these grid boxes, since there is a clear west–east contrast in climatological precipitation characteristics. Although these local extremes affected by complex terrain are important subjects, it is beyond the scope of this study.
b. Diurnal variation

A clear land–ocean contrast in the relation between regional extreme rainfall and the size of extreme rainfall event (Fig. 5) indicates that the characteristics of extreme rainfall events over land and over the oceans are substantially different. We next examine the diurnal variation of regional extreme rainfall characteristics. The 6-hourly occurrence of extreme rainfall events (Fig. 8) shows a clear land–sea difference. Over land, almost all regions have an occurrence peak within 1200–1800 LT. The size of extreme rainfall event within this time interval tends to be smaller than that in the other time intervals (not shown). There are some notable exceptions: for example, probably related to the diurnal migration of rainfall systems in the central United States (Carbone et al. 2002) and northeastern South America (Garreaud and Wallace 1997; Takayabu and Kimoto 2008). Over the oceans, the diurnal variation of the occurrence frequency is much smaller than that over land and it exhibits a broad peak between 0000 and 1200 LT in many regions. In some coastal regions, the diurnal variations are almost in phase with the adjacent land area: for example, in the Bay of Bengal and along the western coast of tropical Africa and North America.

Figure 9 presents joint histograms of the maximum occurrence time (in local time) of extreme rainfall events and the corresponding regional extreme rainfall with bin intervals of 3 h and 30 mm h⁻¹, separately, for the tropics and subtropics and for the ocean and land. Note that the regional extreme rainfall in Fig. 9 has been calculated at each 3-hourly bin using the extreme rainfall events occurring in the time bin. There is a significant difference between the oceans and land both in the tropics and in the subtropics. Over the oceans, other than for a few exceptions, the maximum occurrence of extreme rainfall events tends to be higher during 0000–1200 LT than during 1200–2400 LT (Figs. 9a,c). The amplitude is slightly larger in the tropics than in the subtropics. In contrast, the maximum occurrence of extreme rainfall events over land is concentrated in the afternoon for all extreme rainfall-rate bins (Figs. 9b,d). There is a difference between the tropics and the subtropics for extreme rainfall-rate bins greater than 210 mm h⁻¹, where the occurrence over subtropical land exhibits a secondary maximum during the nighttime.

Diurnal variations in extreme rainfall, shown in Fig. 9, agree with a number of previous observational studies regarding the diurnal variation of mean precipitation using various types of measurements (e.g., Gray and Jacobson 1977; Albright et al. 1985; Nesbitt and Zipser 2003). In the tropics, it is well known that there are clear diurnal variations. Rainfall over land has a significant diurnal cycle with an afternoon maximum, whereas...
rainfall over the oceans has a maximum in the predawn to early morning period. The former is associated with convective activities from the heated land surface (Nesbitt and Zipser 2003), and the latter is attributed mainly to contributions from mesoscale convective systems (Chen and Houze 1997). A nocturnal peak in extreme rainfall over subtropical land (Fig. 9b) might be related to orographic effects with monsoonal flow (e.g., Barros and Lang 2003) or nocturnal low-level jets (Monaghan et al. 2010). The differences in correlations between the regional extreme rainfall and the corresponding event size of land/ocean and tropical/subtropical regions (Fig. 4) are considered to reflect the degree of contribution to extreme rainfall from long-lived cloud systems, such as well-organized mesoscale convective systems. The distinct afternoon peak, observed...
only over land, indicates that extreme rainfall over land arises mostly from short-duration or small-scale precipitation such as afternoon showers, as shown later.

c. Seasonal variation

The occurrence of regional extreme rainfall shows significant seasonal variation (Fig. 10). Over subtropical land, the occurrence frequency of extreme rainfall events is higher in midsummer than in winter, probably coincident with the seasonal variation of insolation. There are some exceptions in West Asia and eastern United States, where the occurrence frequency is highest in springtime. Over land in the deep tropics, the seasonal variation is less apparent than that over subtropical land, although there are some regions that display clear seasonal variation. In eastern equatorial Africa and the northeastern Amazon basin, the occurrence frequencies are highest in March–May (MAM), and northern South America has a peak frequency in June–August (JJA). These three regions are all experiencing the withdrawal of the rainy season at these times (Marengo et al. 2001; Liebmann et al. 2012). There is also a moderate peak in central Africa in September–November (SON), which is when the rainy area migrates southward into this region (Liebmann et al. 2012). It is noticed that the seasonal cycle of extreme rainfall event occurrence is somewhat different from that of average convective intensity in some regions. For example, the Amazon shows the peak occurrence of extreme rainfall event in December–February (DJF), while the average convective intensity and the occurrence of extremely intense convection are highest in SON (Zipser et al. 2006; Liu 2011). Such different seasonal occurrences are probably related to different atmospheric stratification between two seasons.

FIG. 9. Two-dimensional joint frequency distribution of the maximum occurrence time (LT) and mean $R_{\text{max}}$ of extreme rainfall events over (a) subtropical (35°–20°S and 20°–35°N) ocean, (b) subtropical land, (c) tropical (20°–20°N) ocean, and (d) tropical land. Colors denote the relative frequencies normalized to the total number of samples in each vertical bin (%). The histogram at the right side of each figure shows the relative frequency of $R_{\text{max}}$. Colors are not shown for bins in which the total number of samples in the corresponding vertical bin is less than 10.
This might indicate that environmental conditions favorable for producing extreme rainfall rate are different from that for extreme intense convection in the same region.

Over the oceans, there are many regions with significant seasonal variation. Over subtropical oceans, the occurrence frequencies are highest in midwinter off the west coast of the continents, but they peak in autumn elsewhere. The former midwinter peak may be related to extratropical cyclone variability, which is greatest in winter. The latter autumn peak may be related to seasonal variation of sea surface temperature (SST), which is highest in autumn within these regions, and to tropical cyclones. Over tropical oceans, at latitudes between 10°...
and 20°, the occurrence frequencies tend to be highest in summertime except for the ITCZ, which exhibits the highest frequency in SON. These summertime peaks can be related partly to tropical cyclones, as will be shown later. In the deep tropics, there is a distinct peak in MAM in the eastern Pacific and eastern Atlantic, probably attributed to the SSTs, which are highest during this season.

While the seasonal occurrence of extreme rainfall events is largely coincident with seasonal variation of surface temperature in many regions, over both land and the oceans, there is a lag between the peak months. Figure 11 shows the monthly occurrence frequencies summed over the tropical/subtropical land/ocean regions. This figure presents the monthly-mean precipitation of the corresponding regions, computed using the TRMM 3A25 dataset from 2001 and 2012. The monthly occurrences of extreme events are almost in phase with the monthly variation of mean precipitation, regardless of the region or surface type, indicating that extreme events defined by near-surface rain rate are most frequent in the rainy season. It is interesting to note that this feature is different from that for the extreme events defined by convective intensity, which tend to be more frequent in the prerainy season (Zipser et al. 2006). In all four regions, there are differences in the peak months between the land and oceans. In the subtropics, the peak months are observed in midsummer, whereas the peak over oceans clearly lags by several months. These differences between the land and oceans might be attributed to the difference of response to insolation, because the oceans have larger heat capacity and thus exhibit slower response to heating. In the tropics, the peak months over the oceans also lag the peak over land by 1 or 2 months, although this is less clear than in the subtropics. The monthly variation over land also appears coincident with insolation, whereas that over the oceans might be associated with seasonal variation of SST coupled with the atmospheric circulation (Fig. 10).

Tropical cyclones are one of the major synoptic disturbances most likely connected with extreme precipitation (Konrad 2001; Lau et al. 2008). In this study, we examine the contribution of tropical cyclones to regional extreme rainfall in terms of instantaneous rainfall intensity observed from TRMM PR. Figure 12 shows fractional occurrences of extreme rainfall events that are related with tropical cyclones. Here, we define an extreme rainfall event as related to tropical cyclones, when it is located within 1000 km of a tropical cyclone center,
derived from the International Best Track Archive for Climate Stewardship (IBTrACS) dataset (Knapp et al. 2010). The occurrence frequencies of extreme rainfall events are high over the southern Indian Ocean, northwestern coastal region of Australia, west and east sides of the northern Pacific, and northern Atlantic. A notable feature is that fractional occurrences of extreme rainfall events related to tropical cyclones are at most ~0.6 and ~0.7 in the western and eastern North Pacific, respectively. This result indicates that many extreme rainfall events are related not to tropical cyclones but to some region-specific components, even for regions in which precipitation characteristics are affected significantly by tropical cyclones. The fractional occurrences are lower at latitudes above 25°N than at the lower latitudes, probably because of the lower number of cyclone tracks and relatively higher contribution from extratropical frontal systems (Catto and Pfahl 2013).

d. Interpretation of the regional characteristics of extreme rainfall

It is shown that there are significant regional, diurnal, and seasonal differences in extreme rainfall characteristics (Fig. 2). We will now examine the regional contrast of extreme rainfall type shown in Fig. 5 more closely in this subsection.

The intense and extensive extreme rainfall regions are observed mainly over the oceans near coastal areas, and some small parts land regions. In the northern Pacific and northwestern Australia, this type of extreme rainfall is likely to be associated with tropical cyclones (Fig. 12). In the Arabian Sea and the Bay of Bengal, the occurrence frequency of extreme rainfall events is maximum in JJA (Fig. 10), indicating the relationship with convective systems that contain wide convective cores and broad stratiform regions and occur frequently in association with the establishment of the monsoon (Romatschke et al. 2010). In southeastern South America, this type of extreme rainfall is observed mainly in the coastal area, neighboring the intense but less extensive and extensive but less intense regions to the west and east, respectively. This is consistent with the zonal variation of extreme convection characteristics shown by Romatschke and Houze (2010).

The intense but less extensive extreme rainfall regions are distributed widely over land and maritime continents. This type of extreme rainfall is probably related to afternoon showers and mesoscale convective systems, because the occurrence frequencies of extreme rainfall events have clear diurnal variations with the maximum in the afternoon (Fig. 9), and because the event sizes are relatively small (Fig. 2d).

The extensive but less intense extreme rainfall regions are found almost exclusively over the oceans. In the tropics, this type of extreme rainfall is likely to derive from well-organized mesoscale convective systems, because there is a small diurnal variation with a nocturnal peak occurrence (Fig. 9). In the subtropics, this type of extreme rainfall is probably associated with extratropical cyclones, except for in the northwestern Pacific east of Philippines, where the contribution of tropical cyclone is likely to be high (Fig. 12), because the seasonal occurrence of extreme rainfall events is highest in fall and winter (Fig. 11) and because the extreme rainfall event sizes are very large (Fig. 2d).

It was shown that extreme rainfalls are not necessarily linked with extreme intense convection, especially over land (Fig. 3). Therefore, our categorization of regional extreme rainfall in terms of rainfall rate and the corresponding event size can provide independent information from a conventional categorization in terms of convective intensity and event size (e.g., Liu 2011). These two points of view derive seemingly similar categorization, where, for example, the Amazon shows both relatively high convective activity (Zipser et al. 2006; Liu 2011) and high regional extreme rainfall rate (Fig. 2c). One reason for such
4. Concluding remarks

Using 12 yr of TRMM PR measurements, the characteristics of locally defined extreme rainfall are studied and their regional differences described in relation to precipitation systems that yield extreme rainfall. By considering each rainfall event as a set of contiguous rainy pixels, rather than individual rainy pixels, extreme rainfall rates can be obtained in connection with other characteristics of precipitation systems, such as the size of the rainfall event. The maximum near-surface rainfall rate, size, volumetric rainfall, and maxima of rain-top height and 40-dBZ echo-top height for each rainfall event are derived as characteristic values. Extreme rainfall events are defined with $2.5^\circ \times 2.5^\circ$ horizontal resolution, as rainfall events with maximum near-surface rainfall rates greater than the corresponding 99.9th percentile value in the grid.

The geographical distribution of regional extreme rainfall characteristics shows clear regional differences, strongly indicating that the consideration of regionality is essential for studying extreme rainfall. The intensity of the extreme surface rainfall rate ranges from a few tens to a few hundreds of millimeters per hour. Both the size and maximum rain-top height of extreme rainfall events also show clear regional differences. Our method for defining regional extreme rainfall can illuminate regional differences in precipitation systems related to extreme rainfall.

It is found that the higher convective intensity does not necessarily correspond to the higher rainfall rates, especially over land. It is also observed that larger sizes do not necessarily correspond to higher extreme surface rainfall rates over land, especially in the tropics. The relationship between regional extreme rainfall and both the corresponding size and maximum rain-top height shows interesting features. There is a modest correlation over the oceans, whereas little or no correlation is found over land.

The occurrence time of extreme rainfall events also shows clear regional differences. The maximum occurrence tends to be greater during 0000–1200 LT over the oceans, whereas it has a distinct and coherent afternoon peak for all extreme surface rainfall rate ranges over land. Over the oceans, regional extreme rainfall is generally related to large-scale precipitation systems, such as tropical cyclones, mesoscale convective systems, and subtropical frontal systems. Over land, they are associated mostly with relatively small-sized precipitation such as afternoon showers, with some notable exceptions.

There are also clear seasonal differences in regional extreme rainfall. Over land, the seasonal occurrence of extreme rainfall events is largely coincident with the seasonal variation of insolation with some notable exceptions. Over subtropical oceans, the occurrence frequencies are highest from autumn to midwinter, possibly related to the SST variation, tropical cyclones, and extratropical cyclones. A notable feature is that the fractional occurrences of extreme rainfall events related to tropical cyclones are at most $0.6$ and $0.7$ and they are relatively confined in the western and eastern North Pacific. This indicates that many extreme rainfall events are related to some region-specific components, even for those regions affected significantly by tropical cyclones.

We classify regional extreme rainfall into four types based on the extreme rainfall rate and the corresponding event size. Regions in which the regional extreme rainfalls are “intense and extensive,” “intense but less extensive,” and “extensive but less intense” are clearly separated. Regions of intense and extensive extreme rainfall are found mainly over the oceans near coastal areas. This type of extreme rainfall is likely associated with tropical cyclones, and convective systems in association with the establishment of the monsoon. Regions of intense but less extensive extreme rainfall are distributed widely over land and maritime continents, probably related to afternoon showers and mesoscale convective systems. Regions of extensive but less intense extreme rainfall are found almost exclusively over the oceans. This type of extreme rainfall is likely associated with well-organized mesoscale convective systems and extratropical cyclones.

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