Climatology and Interannual Variability of Quasi-Global Intense Precipitation Using Satellite Observations

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Journal of Climate

Submitted: September 15, 2015
Revised: February 26, 2016
Re-revised: April 30, 2016

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Abstract

Climatology and variations of recent mean and intense precipitation over a near global (50°S-50°N) domain on a monthly and annual time scale are analyzed. Data used to derive daily precipitation to examine the effects of spatial and temporal coverage of intense precipitation are the current Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) 3B42 Version 7 precipitation product, with high spatial and temporal resolution during 1998-2013. Intense precipitation is defined by several different parameters, such as a 95th percentile threshold of daily precipitation, a mean precipitation that exceeds that percentile or a fixed threshold of daily precipitation value (e.g., 25 and 50 mm day$^{-1}$). All parameters are used to identify the main characteristics of spatial and temporal variation of intense precipitation. High correlations between examined parameters are observed, especially between climatological monthly mean precipitation and intense precipitation, both over tropical land and ocean. Among the various parameters examined, the one best characterizing intense rainfall is a fraction of daily precipitation $\geq$25 mm day$^{-1}$, defined as a ratio between the intense precipitation above used threshold and mean precipitation. Regions that experience an increase in mean precipitation likely experience a similar increase in intense precipitation, especially during the El Niño-Southern Oscillation (ENSO) events. Improved knowledge of this intense precipitation regime and its strong connection to mean precipitation given by the fraction parameter can be used for monitoring of intense rainfall and its intensity on a global to regional scale.
1. Introduction

Extreme climatic events frequently occur over areas that experience anomalous precipitation regimes on several time scales. Flooding and landslides are good examples of natural hazard events that are highly connected to excessive precipitation on a daily scale (e.g., Wu et al. 2012; Kirschbaum et al. 2012). On a longer time scale, from months to seasons, anomalous lack of precipitation causes drought events producing substantial impacts on agriculture, ecosystems and society, directly affecting water resources, hydroelectric power, and changes of affected areas. Our concerns are more frequently about those natural events that cause huge economic and human losses on a daily scale. Therefore, promptness, regularity and accuracy in predicting these disastrous events (such as flooding and landslides) need constant focus and further improvement in order to minimize damage from these events.

Numerous studies have investigated the changes in intensity, frequency and trends, with causes and importance of these events. Cavalcanti (2012) showed that large-scale features and synoptic weather systems mainly cause heavy precipitation producing flooding in certain regions, over tropical and extratropical areas. A systematic increase in intensity and frequency of heavy precipitation events in tropical and subtropical regions have been clearly evidenced, and observed changes have been shown to be consistent with most climate model projections (e.g., Allan and Soden 2008; Min et al. 2011; Shiu et al. 2012). Even though precipitation extremes are expected to increase in the future over large parts of the globe as global climate warms (Easterling et al. 2000; Kharin et al. 2007; O’Gorman 2012), with higher moisture content being available to form intense precipitation events and provide additional energy to further intensify such events, we
still don’t know how strong a relationship between the mean state of precipitation and intense precipitation frequency is on the most recent climate scale.

Intensity of precipitation events is projected to increase over areas that experience increases in mean precipitation. A direct link between the mean and intense precipitation (i.e., 95th percentile) has already been confirmed in rain-gauge observations and model predictions both in space and time prior 2000 (e.g., Benestad et al. 2012). However, the increases in intense precipitation derived by different model simulations are shown to be higher than those expected in mean precipitation in most tropical and high-latitude areas (e.g., Trenberth et al. 2003; Held and Soden 2006; Kharin et al. 2007). On the opposite side, there is a tendency for drying of the mid-continental areas during warm periods, resulting in greater risk of droughts in those regions. With current climate change, and especially global warming, Lau et al. (2013) provided evidence that both intense precipitation and drought events may increase, indicating most increases in heavy precipitation over wet regions of the tropical zones around the equator, particularly in the Pacific Ocean and Asian monsoon regions. Similarly, arid land areas outside the tropics and regions with moderate precipitation could become drier (Dai 2011). A clear connection between global mean temperature and both mean and intense precipitation on a large-scale spatial domain and a long time scale (1945-1995) has been found by Benestad (2013), indicating a number of useful climate applications.

Lau and Wu (2011) have investigated the climatology and changes in precipitation over tropical oceans, however, using a shorter record of the Tropical Rainfall Measuring Mission (TRMM) data (1998-2009). They showed that intense (95th percentile) precipitation is associated with the Intertropical Convergence Zone (ITCZ), South Pacific
Convergence Zone (SPCZ) and summer monsoon regions, and experiences large increase coupled to a reduction in light to moderate rain over warmer ocean regions with increasing sea surface temperature (SST). They also found that intense precipitation events are most sensitive to changes in tropical mean SST, and that increases of 80–90% of the most extreme intense rain (the top 5%) per degree SST rise can be expected. In addition, Liu and Allan (2012) have also investigated precipitation extremes in multi-satellite data, and have confirmed a strong positive response of the tropical ocean precipitation to changes in temperature due to El Niño-Southern Oscillation (ENSO) events. It has also been shown that, even over land, extreme precipitation events are more sensitive to climate variability, such as ENSO, than monthly or seasonal total rainfall, and that the frequency of extreme events experiences a larger and spatially more extensive significant increase than these totals, with reduction of light to moderate rain (Grimm and Tedeschi 2009).

In order to develop high-resolution regional climate scenarios for climate change impact studies, including global warming, and to investigate ENSO’s natural variability, it is necessary first to analyze longer high-resolution climatic precipitation data sets focusing on intense precipitation on a regional to global scale. Unfortunately, large periods of unavailable and poor quality observational data still limit such analysis, together with low representativeness of in situ observations. Most previous studies detecting the increased frequency of intense precipitation events in tropical and subtropical regions have used either in situ data over land or long-term monthly satellite precipitation data. However, both types of data do not have sufficient spatial coverage and temporal homogeneity to analyze the intense precipitation events in detail.
Furthermore, local changes in precipitation and its extremes are highly variable, and highly dependent upon small shifts in the large-scale atmospheric circulation and regional feedbacks that current climate models still cannot simulate correctly. Consequently, current knowledge of changes in the occurrence of global intense precipitation is still quite limited.

In this study, we utilize a 16-year record of daily precipitation derived from a uniform high resolution (3-hr temporal and 0.25° grid spatial) Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) Version 7 satellite precipitation data over a near-global domain (50°N-50°S), to analyze climatological intense precipitation over land and ocean during the period 1998-2013. The emphasis here is on the climatology of “intense” precipitation, but we will also give parameters such as mean precipitation, fraction of daily precipitation, and conditional daily precipitation rate, to provide a climatological context. For this study, we consider “extreme” precipitation to be only precipitation amount above the 99th percentile threshold, but this parameter is not the focus of this study. Rather, we explore the use of various measures of intense precipitation, including high percentile thresholds (e.g., 95th percentile), mean precipitation above that percentile, number of days in a month above some daily fixed thresholds (e.g., 25 and 50 mm day⁻¹), and mean precipitation above those daily thresholds in a month. Consequently, the parameter that best describes a relationship between the mean precipitation and intense precipitation is analyzed, and can then be easily adopted globally and/or regionally to investigate regions that experience natural hazard events, such as floods and landslides, as has already been done in a preliminary fashion for landslides (Kirschbaum et al. 2012).
In addition, we investigate spatial and temporal variations of intense precipitation in relation to its natural variability (i.e., ENSO events), rather than to climate change. Several previous studies (e.g., Curtis et al. 2007; Grimm and Tedeschi 2009; Lau and Wu 2011) have already analyzed the ENSO influence on intense precipitation mostly over land and Dai et al. (1997) have found that ENSO is the single largest cause of global intense precipitation over land.

The objectives of this study are: (1) to define the best parameter that will help establish the pattern and characteristics of climatology of intense precipitation events, and (2) to understand inter-annual variations of monthly mean and intense precipitation relating them to large-scale climate variability (e.g., ENSO), using recent uniform satellite data over land and ocean over the tropical and sub-tropical domain. The remainder of this paper is organized as follows. Section 2 describes the data products used. Definitions for intense precipitation and analysis procedure are explained in section 3. Spatial patterns of intense precipitation climatology are explained in section 4. The results of the intense precipitation characteristics, both over land and ocean, and during El Niño and La Niña periods, are described and examined in section 5. Discussion and conclusions are presented in section 6.

2. Data

In this study, we utilize the Version 7 TMPA satellite precipitation product (TMPA 3B42 V7; Huffman et al. 2007, 2010), which provides near-global coverage (50°N-50°S) at 3-hourly, 0.25° resolution. The TMPA precipitation estimates are a combination of different space-borne sensors, including radar and passive microwave, infrared data, and gauge measurements. Several important changes are included in the TMPA V7 data
products: (1) additional satellite data, including the early part of the Microwave Humidity Sounder (MHS) record, the entire operational Special Sensor Microwave Imager/Sounder (SSMIS) record; (2) a new infrared (IR) brightness temperature data set from geosynchronous satellites for the period before the start of the Climate Prediction Center (CPC) 4-km Merged Global IR data set (January 1998–February 2000) with the National Climatic Data Center (NCDC) GridSat-B1 spatial resolution finer than the TMPA 0.25° resolution and full coverage of the TRMM domain; (3) uniformly reprocessed input data from several additional sources: the Advanced Microwave Sounding Unit-B (AMSU-B), MHS, TRMM Combined Instrument (TCI), TRMM Microwave Imager (TMI), the Special Sensor Microwave/Imager (SSM/I), and the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E); and (4) adjustment by the Global Precipitation Climatology Centre (GPCC) monthly surface precipitation gauge analysis (Schneider et al. 2011). An additional retrospective processing for the TMPA V7 data series had to be carried out when processing issues were discovered omitting the AMSU microwave precipitation data during 2000-2010 in the first retrospective processing (Huffman and Bolvin 2012).

Several recent studies have addressed the uncertainty of high-resolution global satellite precipitation products, showing their performance depending on the precipitation regime, being more accurate during summer times and at lower latitudes (Arkin et al. 2008; Ebert et al. 2007). For daily bias and precipitation frequency, Ebert et al. (2007) showed that the Infra-Red/Passive Microwave merged satellite precipitation estimates are almost as good as those from ground-based radar over the United States. In addition, Sapiano and Arkin (2009) performed an inter-comparison between several high-
resolution global satellite products with gauge data, and showed good performance of satellite precipitation data but with relatively high biases (except for gauge-adjusted products over land).

Su et al. (2008) evaluated an earlier Version 6 (V6) of the TMPA 3B42 precipitation data set using rain gauge data on various temporal and spatial scales. Good qualitative agreement was found between the TMPA and gauge data in the occurrence of precipitation events, but an overestimation of most high precipitation events on a daily scale over the La Plata basin in South America was observed with noticeable regional variation of the TMPA performance. On a daily scale over the contiguous United States, a study by Tian et al. (2009) showed a comparison of six different high-resolution satellite-based precipitation data sets (including the TMPA 3B42 V6 and TMPA 3B42 RT) against the gauge data. Overall, all precipitation data sets showed overestimation of strong precipitation (>40 mm day$^{-1}$) in summer and underestimation in winter, by as much as 50% in either season, and missing a significant amount of light precipitation (<10 mm day$^{-1}$) up to 40%. Consistently missed precipitation in winter was mainly observed over mountainous regions, such as the Rockies, and the northeastern U.S., confirming a common challenge to all satellite data sets. In addition, Scheel et al. (2011) confirmed that the same TMPA 3B42 V6 estimates in the Central Andes are significantly better on a monthly scale, but overestimation of heavy precipitation still exists. Therefore, we examine here the latest TMPA 3B42 V7 precipitation data set and its performance in the occurrence of heavy rainfall events (i.e., climatological intense precipitation).

3. Methodology and definitions
We compute a daily precipitation data set from 3-hourly TMPA 3B42 V7 for the period of 1998-2013, keeping the original 0.25° spatial resolution. This daily precipitation data set is used to compute monthly statistics over a 16-year climatology of various parameters related to mean and heavy precipitation on a monthly and annual time scale. To set the context of the discussion, we use the total daily precipitation value (R) at each grid point to calculate the mean monthly value of daily precipitation for each month in the year, for the 1998-2013 period (R\text{mean}, in mm day\textsuperscript{-1}). We also compute the conditional precipitation rate for the month (i.e., the mean precipitation rate for days with R >0 mm day\textsuperscript{-1}; R\text{cond}, in mm day\textsuperscript{-1}) and the fraction of daily precipitation for days in the month with R >0 mm day\textsuperscript{-1} (F_0). These three parameters are related (i.e., R\text{mean}=F_0 \cdot R\text{cond}).

For examining intense daily precipitation, we explored a number of statistical parameters to determine monthly values useful for spatial and temporal comparison. Our definitions of these parameters follow closely, but not exactly, those of the Expert Team on Climate Change Detection and Indices (ETCCDI, Karl et al. 1999; Peterson et al. 2001). We have specifically examined parameters such as percentiles near the high end of the precipitation distribution, frequency (number of days) above a threshold, and precipitation amounts over certain thresholds. This has been done to attempt to find statistics that would be useful for description of climatology and variations on a monthly scale, and for possible use and links to natural hazards, such as floods and landslides over land, and tropical cyclones and other phenomena over ocean.

Since we have a data set with a limited number of years; in terms of percentiles, we have stayed with a relatively conservative value to characterize “intense” daily rainfall (i.e., the 95\textsuperscript{th} percentile). We calculated the 95\textsuperscript{th} percentile of daily precipitation (R\text{95p}, in
mm day$^{-1}$), and the mean precipitation in a month above this daily threshold ($R_{95}$, in mm day$^{-1}$). In addition, we have calculated the number of days in a month with daily precipitation above fixed threshold values ($R \geq 25$, 50 and 75 mm day$^{-1}$; $N_{25}$, $N_{50}$, $N_{75}$), and the intense precipitation above the same daily thresholds ($R_{25}$, $R_{50}$, in mm day$^{-1}$). The fraction of intense precipitation is calculated for all examined thresholds as well ($F_{95}$, $F_{25}$, $F_{50}$), balancing their corresponding intense precipitation amounts ($R_{95}$, $R_{25}$, $R_{50}$) with the mean precipitation (e.g., $F_{95} = R_{95}/R_{\text{mean}}$). Results from examining these different statistical parameters allowed us to focus on just a few of them when we moved onto the relations between variables and their inter-annual variations. Table 1 summarizes the definitions and units for all statistical parameters we use to explain climatology of mean and intense precipitation.

4. Climatology of monthly mean precipitation

There are few high quality global or quasi-global climatologies of precipitation that span both land and ocean. The relatively recent TRMM data (1998-present) has resulted in significant new knowledge regarding rainfall system structure and other attributes across the tropics and also a rainfall climatology, the TRMM Composite Climatology (TCC) (Adler et al. 2009; Wang et al. 2014), based on information from both the TRMM Precipitation Radar (PR) and the satellite’s passive microwave sensor, the TRMM Microwave Imager (TMI). The Global Precipitation Climatology Project (GPCP) monthly product (Adler et al. 2003; Huffman et al. 2009) is a widely used analysis at 2.5° latitude-longitude resolution covering a time period over 30 years. Even though there exists a GPCP daily product (Huffman et al. 2001), for a similar time span as the TMPA, the TMPA has a higher spatial resolution (0.25°) and is considered of higher quality due
to the greater amount of microwave-based rainfall estimates in it. The absolute magnitudes of estimated mean precipitation over ocean are probably best estimated by the GPCP and TCC, which have very similar ocean totals, but with some relatively small regional differences. The TMPA may be overestimating mean values over the ocean somewhat (~8%) due to processing and calibration issues (Huffman and Bolvin 2012). However, this issue does not detract significantly from the search for information on the time and space scales of this study. The mean precipitation values over land in the TMPA are also not impacted by this issue.

The annual, January, and July means of daily rainfall (R$_{\text{mean}}$) are shown in Fig. 1. The annual climatology map shows very clear features of the Inter-Tropical Convergence Zone (ITCZ) across both the Pacific and Atlantic Oceans, with a not-as-narrow extension through the Maritime Continent into the Indian Ocean. In the Atlantic and Pacific Oceans, the axis of the annual maximum is just north of the equator, while in the Indian Ocean axis falls south of that marker. A northwest-southeast extension of the ITCZ in the South Pacific Ocean, called the South Pacific Convergence Zone (SPCZ), is another feature with the maximum values of mean rainfall. Over tropical land, most striking features with significant rainfall are located over the equatorial African and South American regions. At higher latitudes, two characteristic precipitation bands associated with extensions of ocean currents (the Gulf Stream in the North Atlantic Ocean and Kuroshio in the North Pacific Ocean) are observed along the east coasts of North American and Asian continent, both with significant annual rainfall amounts. The January and July maps show the distinct shift of the seasonal rains with migration of the sun over the tropics, with a larger shift over land than over water describing the
monsoons. Enlarged heavy rainfall areas in January are observed in the equatorial
Atlantic and the western Pacific, especially over the SPCZ, coastal Southeast Asian
region, western extension of the South Equatorial Current in the Southwestern Indian
Ocean, and east and north of Madagascar. At mid-latitudes, the rain bands associated
with the Gulf Stream and Kuroshio currents are enlarged and extended towards the
central and eastern parts of the oceans. Over the land, a shift of maximum rainfall
towards the south of the equator in Africa, South America and northern Australia is
clearly observed. A coastal region with significant rain is also found in the tropical and
subtropical South America, over the northern, southeastern and southern coast of Brazil
(including the eastern parts of the Rio de La Plata basin), and over the South Atlantic
Ocean along the Brazilian coast. In July, a strong shift of maximum rainfall towards the
north of the equator is observed in the ITCZ and SPCZ regions in the Pacific and Atlantic
Oceans. Over land, heavy rain regions are found north of the equator in Africa, Central
and South America, and near the Asian mountainous regions (i.e., the Tibetan Plateau)
where orographic effect enhances the total rainfall amount. In addition, at higher
latitudes, northeastern Asian land and coastal regions experience higher rainfall during
the Northern Hemisphere summer months. Bands of enhanced rainfall from storm tracks
over the Southern Hemisphere mid-latitudes of the Pacific and Atlantic Oceans are
observed as well. Overall, we can observe higher maximum values with smaller spatial
coverage of rainfall in July than in January.

5. Climatology of fraction of days with precipitation

Figure 2 displays maps of the fraction of days with rain >0 mm day\(^{-1}\) (F\(_0\)). This
fraction (F\(_0\)) multiplied by the conditional precipitation rate (R\(_{\text{cond}}\), Fig. 3) is equal to the
mean precipitation value ($R_{\text{mean}}$, Fig. 1), that is, $F_0 = R_{\text{mean}}/R_{\text{cond}}$, and describes how often it precipitates, irrespective of the amount. The main precipitation areas are clearly evident, as expected, with very high fractions (>0.7) in the annual map along the ITCZ over both ocean and land, with secondary maxima averaging ~0.6 over the middle latitude oceans, especially over the Northern Hemisphere. When examining the maps of monthly climatologies (shown here just January and July, Fig. 2), the fractional days of precipitation ($F_0$) over the higher latitude oceans are now roughly equivalent of those in the tropics, especially during the Northern Hemisphere winter. For example, in January the value of $F_0$ over the Pacific and Atlantic Oceans at about 30$^\circ$N is the same as the $F_0$ values over the deep tropics (between 0.7-0.9). Therefore, at these higher latitude locations, as expected, precipitation is as frequent as in the tropical belt maxima, but the intensity on average is lower.

The conditional precipitation rate ($R_{\text{cond}}$), or how hard it is precipitating when precipitation is occurring, is a first measure of intensity in this study. As seen in Fig. 3, $R_{\text{cond}}$ has a different geographic distribution than the two previous parameters. Even on the annual map, $R_{\text{cond}}$ maxima appear in locations where they were absent or muted in the $R_{\text{mean}}$ and $F_0$ maps, including eastern China, eastern North America, southeastern South America and other smaller areas over land. In the seasonal maps, during the Northern Hemisphere winter (January) higher values of $R_{\text{cond}}$ (>14 mm day$^{-1}$) are observed mostly over the tropical Southern Hemisphere (5$^\circ$N-25$^\circ$S), including most of the South American land, northern Australia, Indonesia and parts of southeast African land, and over ocean the SPCZ and the Indian Ocean area. In mid-latitudes, eastern parts of North American land and Euro-Asian land with eastern China experience higher values of $R_{\text{cond}}$. 
A northward shift of high values is observed during the Southern Hemisphere winter (July), when land (20°N-0°) experiences extremely high values of $R_{\text{cond}}$ over most of Southeast Asia, including India, Indonesia, Central America, northern South America and the La Plata basin, and northern tropical Africa; while maximum values of $R_{\text{cond}}$ over ocean are observed in most of the ITCZ and in particular over the Gulf Stream region. Over the monsoon areas of Asia and Australia, one can easily see the monsoon associated with intense rainfall events switching back and forth between the hemispheres, from January to July (Fig. 3b-c). In January, the features over eastern China and the U.S. are associated with winter cyclone events. Perhaps the most interesting features are over South America, where a large area of high values exists in January from the Amazon southward, while in July (local winter) two maxima in $R_{\text{cond}}$ exist over the northern Amazon and the southeastern coast (the La Plata basin). A maximum point value of the highest conditional mean precipitation rate in the tropical region is observed to be 44 mm day$^{-1}$ in January over the southern Philippines and 53 mm day$^{-1}$ in July over the Meghalaya mountains and west coast of India, with 30 mm day$^{-1}$ in the annual mean observed over the western coast of Colombia (Fig. 3). The month with the lowest maximum value of $R_{\text{cond}}$ is April (35 mm day$^{-1}$ over the northern Arabian Sea), while February surprisingly reaches the highest maximum point value of 122 mm day$^{-1}$ over some eastern parts of Ethiopia due to a second rainy season lasting until the end of February (figures not shown).

6. Climatology of intense rainfall

As described in the previous section, many previous studies (e.g., Gu et al. 2007; Adler et al. 2008; Huffman et al. 2009; Lau and Wu 2011) have been devoted to
characterize climatological features of mean precipitation, along with their patterns and
variability. Here focus is more on daily intense precipitation events, their means, patterns,
anomalies, and variations, using the best currently available consistent high-resolution
multi-satellite TMPA precipitation data set. A number of parameters related to intense
daily precipitation are examined, keeping in mind the relatively short duration of the data
set (16 years, 1998-2013).

6.1. 95th percentile of precipitation

The first set of intense precipitation variables we examine is related to the 95th
percentile of precipitation. That particular percentile was chosen instead of, for example,
the 99th percentile, to give a good measure of intense precipitation events, but also to
avoid producing a very noisy field at the higher percentile due to a relatively short data
record. One goal of examining these measures of intense precipitation on a daily scale is
to understand how they relate to each other, and which ones are the best parameters to
focus on, especially in relation to hazardous impacts (e.g., floods and landslides).

The distribution of the 95th percentile value (R_{95p}) is shown in Fig. 4. This parameter
is defined as a daily precipitation rate threshold (including zero values, in mm day^{-1}) in a
month at a grid point, below which 95% of the daily rainfall amounts occur, so 5% of all
the days have rainfall amounts greater than this value. For example, for months with 30
days in a month, the days with precipitation \geq 95th percentile are 1.5 days, meaning R_{95p}
contribution is from the heaviest rainfall of 1 or 2 days. The characteristic pattern of R_{95p}
follows that of R_{mean} and F_0 in the annual mean, with the typical features of the
atmospheric general circulation over the tropics: the ITCZ, SPCZ, and enhanced rainfall
over the Maritime Continent (Southeast Asia), northern tropical Africa, and Central and
northern South America; with a strong north-south precipitation gradient. Maximum values observed in $R_{\text{mean}}$ are in the range of 10-20 mm day$^{-1}$ (with an absolute maximum of 24 mm day$^{-1}$; Fig. 1a), while $R_{95\text{p}}$ gives much higher values (up to 104 mm day$^{-1}$; Fig. 4a), as expected.

Representative months of two contrasting seasons, January and July, are chosen for analysis of opposite regimes of intense monthly mean precipitation, addressing its seasonal variation (Fig. 4b-c). A north-south migration of the ITCZ is clearly observed where maximum precipitation regions reside, especially over land. A strong maximum of $R_{95\text{p}}$ (up to 47 mm day$^{-1}$) during July is also observed over the eastern parts of the Rio de la Plata basin, located in south-central South America (La Plata hereafter), with a seasonal shift northwards in January (Fig. 4b-c). A maximum value of mean precipitation over the tropics is 27 mm day$^{-1}$ in January and 43 mm day$^{-1}$ in July (Fig. 1b-c), while $R_{95\text{p}}$ has a maximum value of 142 mm day$^{-1}$ in January and 190 mm day$^{-1}$ in July (Fig. 4b-c), clearly indicating the wettest period in the tropics during boreal summer. The month with the lowest maximum value of $R_{\text{mean}}$ over the tropics is April, with a maximum of 22 mm day$^{-1}$, while $R_{95\text{p}}$ reaches maximum of 102 mm day$^{-1}$ (figures not shown).

The only areas that are wetter during the boreal winter season than the rest of the year are the westerly storm tracks regions over the Pacific and Atlantic Oceans in mid-latitudes, with the maximum $R_{\text{mean}}$ of 8-11 mm day$^{-1}$ (Fig. 1b) and the maximum $R_{95\text{p}}$ of 30-50 mm day$^{-1}$ (Fig. 4b). Despite the fact that seasonal variability of precipitation is more pronounced outside of the tropics, where rainy seasons differ much more regionally, we focus on the intense precipitation variability more in the tropical and less in the extra-tropical regions due to the data availability and quality in this region.
Even though we are looking at only 16 years of precipitation data, there are some significant differentiating spatial features between mean and intense precipitation that are worth mentioning. In comparison, regions with high intense precipitation (i.e., $R_{95p}$) are significantly larger in area than those characterized by mean precipitation ($R_{\text{mean}}$) over most of the studied quasi-global domain, except over drier land and ocean regions such as Northern Africa, South Asia and Australia during dry seasons; and west coast of South America, Central America, and parts of North America, where locally the 95th percentile amount is very close to the mean precipitation value due to its small values and insignificant seasonal variations in precipitation. The 95th percentile precipitation varies greatly between months and seasons in some locations. For example, this seasonal variability is most apparent at sites in the north of Australia, where during the wet season (December-May) some locations experience 95th percentile rainfall higher than 50 mm day$^{-1}$, while during the drier months (June-November) the same locations show tiny rainfall values. A rough factor of 5-6 between the mean precipitation ($R_{\text{mean}}$) and $R_{95p}$, and a factor of 3-4 between the mean rain rate ($R_{\text{cond}}$) and $R_{95p}$ is observed in the annual mean over the tropics that experiences most of the rainfall (figures not shown). Therefore, we investigate other similar statistical parameters that can better characterize the intense precipitation regime in recent years.

6.2. Mean and fraction of precipitation above the 95th percentile

While the $R_{95p}$ parameter gives some insight into the distribution of heavy precipitation, other additional parameters need to be examined to offer more detailed explanations and relations of parameters that accent the intense precipitation. One such parameter that emphasizes the amount of precipitation occurring during intense events is
the monthly mean precipitation with rainfall \( \geq 95^{th} \) percentile \((R_{95}, \text{in mm day}^{-1})\), defined as the total amount of precipitation \( \geq R_{95p} \) in a month divided by the number of days in that month (see Table 1). The spatial patterns of \( R_{95} \) (Fig. 5) and \( R_{\text{mean}} \) (Fig. 1) are similar over most regions, as expected, although the \( R_{95} \) patterns emphasize somewhat the areas with heavy rainfall. However, the fraction of rainfall that exceeds the \( 95^{th} \) percentile to the mean rainfall \((F_{95}=R_{95}/R_{\text{mean}}, \text{figure not shown})\) tends to vary inversely to \( R_{95} \). Over areas of higher mean rain rates, the ratio \( F_{95} \) is 0.2 to 0.3, indicating that 20-30\% of monthly rain occurs at daily rates above or equal to the \( R_{95p} \) threshold. On the other hand, in the areas with light rainfall, the ratio \( F_{95} \) is high (~0.8-1), because the \( R_{95p} \) threshold is very close to the mean rain rate with only one or two rain events in the month that account for all of the rain. Therefore, while both the \( R_{95} \) and \( F_{95} \) parameters are of interest, they are of limited value in discerning spatial and temporal variations of heavy rainfall.

6.3. Mean and fraction of precipitation above fixed thresholds

Floods and landslides are usually associated with an absolute amount of precipitation physically related to overflowing banks and/or moving soil from a slope - not from exceeding a local percentile threshold. So, another approach to investigate the intense precipitation characteristics is to examine intense precipitation parameters by evaluating the fraction of days in a month with precipitation that exceeds fixed threshold values (e.g., 25, 50 and 75 mm day\(^{-1}\); \( F_{25} \), \( F_{50} \) and \( F_{75} \)). The maximum value observed in the annual mean number of days with intense precipitation defined by the \( 95^{th} \) percentile is 1.6 days/month (5\%). Consequently, extremes based on the respective \( 95^{th} \) percentile (Fig. 4) show somewhat different spatial patterns than what is observed on maps of
fraction of days in a month with precipitation defined by any fixed thresholds over the
same locations and at the same time, due to a different selection of precipitation intensity
values.

The specific total daily precipitation threshold commonly used for determining
intense precipitation varies among regions and countries. A few examples of different
fixed thresholds, used by the national weather services or previous studies (e.g.,
Easterling et al. 2000; Gustafsson et al. 2010), give values of 20-40 mm day\(^{-1}\) for Norway
and Sweden, 20 mm day\(^{-1}\) for most of Russia and southern Canada, 50.8 mm day\(^{-1}\) for the
United States, Brazil, South Australia, northeastern China, Equatorial East Africa and
South Africa, and 100 mm day\(^{-1}\) for Japan and southeastern China.

In this study, characteristic spatial signatures of \(F_{25}\), \(F_{50}\) and \(F_{75}\) for January and July
are compared to those observed in the mean precipitation (\(R_{\text{mean}}\)). The results show fairly
similar spatial patterns between these parameters, with a lower fraction of intense
precipitation by half going from 25 to 50 mm day\(^{-1}\). The spatial distribution of monthly
mean frequency of intense rainfall (in days) suggest that local extremes in the tropics
occur mostly from June to August, with maximum values of 17, 10 and 6 days for the
three thresholds of 25, 50 and 75 mm day\(^{-1}\) (\(N_{25}\), \(N_{50}\), and \(N_{75}\), figures not shown).
August noticeably receives the highest frequency of extremes for 25 and 50 mm day\(^{-1}\)
thresholds, while June receives it for 75 mm day\(^{-1}\) threshold. The period from September
to May is relatively quieter with respect to high season extremes, with maximum point
values of 14, 8 and 4 days observed for the three fixed thresholds. A strong seasonality of
intense precipitation frequency and its temporal dependence on the mean precipitation is
observed with clustering of extremes over the regions that experience the highest values of mean precipitation.

Maps of climatological daily precipitation greater than several different thresholds (i.e., above 0, 25 and 50 mm day$^{-1}$, and 95$^{th}$ percentile; $R_{\text{mean}}$, $R_{25}$, $R_{50}$, and $R_{95}$) show their highest amounts over similar geographic areas both over land and ocean in the annual and monthly climatologies. Fraction of days parameters with intense rainfall ≥25 and 50 mm day$^{-1}$ ($F_{25}$ and $F_{50}$) follow this similar spatial pattern that is observed in $R_{\text{mean}}$ as well.

Another measure of intense rainfall is the monthly mean rainfall ≥25 and 50 mm day$^{-1}$ ($R_{25}$ and $R_{50}$, Fig. 6). The features here correspond well with spatial features previously observed for the typical mean rainfall, but are weaker in intensity than for $R_{\text{mean}}$ and stronger than for $R_{95}$. Both $R_{25}$ and $R_{50}$ exhibit similar patterns, but a higher threshold value of 50 mm day$^{-1}$ filters out some of the extended features by depicting only areas with higher amounts of rainfall. $R_{25}$ can reach a maximum point value up to 24 mm day$^{-1}$ in January and 38 mm day$^{-1}$ in July, with 20 mm day$^{-1}$ in annual mean, but high values have a range of 5-10 mm day$^{-1}$ (Fig. 6a-c). Similarly, a maximum point value of $R_{50}$ can reach up to 20 mm day$^{-1}$ in January and 34 mm day$^{-1}$ in July, with 15 mm day$^{-1}$ in annual mean map (Fig. 6d-f), having high values between 3-8 mm day$^{-1}$. In comparison, $R_{\text{mean}}$ over the tropics has a maximum point value up to 27 mm day$^{-1}$ in January and 43 mm day$^{-1}$ in July, with a maximum value of annual mean up to 24 mm day$^{-1}$ (Fig. 1). From monthly climatologies, April consistently exhibits the lowest amounts of $R_{25}$ and $R_{50}$, similarly as observed in $R_{\text{mean}}$, $R_{\text{cond}}$, and $R_{95}$. 

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Based on the preceding analysis, $R_{25}$ (Fig. 6a-c) is chosen to be a key parameter for intense precipitation (hereafter intense precipitation). Therefore, we examine the intense rainfall parameter in relation to the mean rainfall. The ratio $F_{25}$, defined as $R_{25}/R_{\text{mean}}$, gives the fraction of rain that falls above 25 mm in a day. Over a period of time (e.g., a month), it is designed to emphasize areas and times when much of the rain falls during days with intense rainfall. $F_{25}$ (Fig. 7) shows some clear differences between two parameters ($R_{25}$ and $R_{\text{mean}}$), giving some characteristic spatial features that are not observed in previously defined parameters, and some similar features that are wider in coverage with a weaker gradient than what is observed for $R_{\text{cond}}$ (a first measure of the intensity examined in this study).

High intensity parameters are distributed both over land and ocean and higher in the tropical latitudes. However, intense rainfall events with rain $\geq 25$ mm day$^{-1}$ are observed somewhat more over ocean areas (Fig. 7) in comparison to the highest values of $R_{\text{cond}}$ that are located more over land (Fig. 3). On the annual map (Fig. 7a), maxima in $F_{25}$ appear in locations similar to those observed in $R_{\text{cond}}$, but also including more intensified locations with wider spatial coverage over ocean and along the coasts, such as: east coast of Australia, most of the mid-latitudes areas of both the Atlantic and Pacific Oceans, and slightly wider equatorial Atlantic and Pacific Ocean regions (i.e., the ITCZ). A rough factor of 0.65-0.75 for $F_{25}$ is observed in the annual mean over the tropical region with the highest rainfall amounts.

Strong seasonal variations in this intense rainfall measure are very similar to those observed in $R_{\text{cond}}$. However, higher values of $F_{25}$ (>0.6) are also observed mostly over the extended tropical and mid-latitudes Southern Hemisphere ocean ($7^\circ$N-$35^\circ$S). Over land,
the highest values confirm intense events over Southeast Asian areas, related to the strong
monsoon phenomenon constantly switching between the Northern and Southern
Hemisphere. Similar features and high values over eastern China and the eastern U.S. are
associated with strong winter tropical cyclones in January (Fig. 7b). In addition, the most
significant features with high values in the Southern Hemisphere are located over a large
area of South America in January, while in July (austral winter, Fig. 7c) there are only
two maxima in intense rainfall, over the northern Amazonia and the La Plata basin. As
higher rainfall amounts tend to occur over previously mentioned moist regions, lower
rainfall tends to occur over the dryer regions with more intense convection (e.g., Sahel
and eastern Congo in Africa, and Argentina in South America).

Features in the monthly maps are consistently located over the areas where tropical
cyclones are most common (e.g., east of the Philippines, most of the Indian Ocean, and
the northern Gulf of Mexico) and over the La Plata basin, but also over the mountainous
regions with strong topographic lifting, where moderate and higher rainfall events last
longer. During Northern Hemisphere colder seasons (September-February), higher values
and wider spatial features of F25 are located over most of the northern Atlantic and
Pacific Oceans. During November-March, most observed maxima are located over the
wider SPCZ, and a persistently occurring feature across the La Plata basin and over
coastal waters in the southern Atlantic Ocean. Another set of maxima is located over the
persistent ITCZ and the east coast of Asia in the North Pacific Ocean during Northern
Hemisphere warm months (May-October). As observed, the ratio gives very strong
seasonal variations over most of the tropical regions. However, a quasi-global mean has a
typical value of only 0.34 during winter months (December, January and February) and 0.30 during summer months (July and August).

Statistical analysis of $R_{25}$, $R_{50}$, and $R_{\text{mean}}$ during a 16-year climatological period shows that intense rainfall is highly correlated with $R_{\text{mean}}$, with a correlation coefficient ($r$) of 0.96 for $R_{25}$ and 0.87 for $R_{50}$ (significant at the 95% confidence level) on a monthly time scale over the full domain examined. This highly correlated relationship between the mean and intense precipitation parameters, and their spatial distribution, both over land and ocean during the same time period, is confirmed in other data sets as well (e.g., over the global domain in daily GPCP v1.2, and over the U.S. in daily National Oceanic and Atmospheric Administration [NOAA] Climate Prediction Center [CPC] Unified Data, results not shown here).

Fig. 8 shows distributions and correlations between mean precipitation and intense precipitation (over ocean and land separately) using $R_{25}$ and $R_{50}$ as the parameters for the intense component. Slightly lower correlations between intense and mean rainfall parameters are observed when investigating land versus ocean amounts, for both fixed threshold values (Fig. 8). The intense precipitation with the 50 mm day$^{-1}$ fixed threshold gives somewhat lower correlations ($r=0.82$ for land and 0.89 for ocean) and higher root-mean-square (RMS) differences (3.08 mm day$^{-1}$ for land and 3.00 mm day$^{-1}$ for ocean) than what is observed for the 25 mm day$^{-1}$ threshold ($r=0.95$ for land and 0.97 for ocean) with lower RMS differences (2.00 mm day$^{-1}$ for land and 1.91 mm day$^{-1}$).

Figure 6 shows very characteristic spatial distributions over land and ocean, for both $R_{25}$ and $R_{50}$. The distribution of monthly climatology of $R_{\text{mean}}$ against $R_{25}$ (Fig. 8a-b), and against $R_{50}$ (Fig. 8c-d), is presented in such a way that all data values are divided into
bins in ascending order, including all grid points over the examined domain. Scatter plots of intense precipitation against mean precipitation show a wider shape at the bottom of the distribution and narrower but with a larger spread at the higher end of precipitation values. There is no significant difference between land and ocean, except for a slightly narrower distribution over ocean (Fig. 8a-b). We observe that the distribution becomes slightly wider in shape with a lower slope of the median fit for a higher threshold chosen ($R_{50}$, Fig. 8c-d).

A strong relationship between mean and intense precipitation is well defined by fitting a median line over their spatial distribution. For the 25 mm day$^{-1}$ threshold (Fig. 8a-b), a median fit is linear but with two different slopes: for smaller rainfall values between 0-13 mm day$^{-1}$ of $R_{\text{mean}}$, a slope for $R_{25}$ is $R_{25}=0.65 \cdot R_{\text{mean}}$; and between 13-35 mm day$^{-1}$ of $R_{\text{mean}}$, the slope increases to $R_{25}=1 \cdot R_{\text{mean}}$, both over land and ocean. In comparison, the 50 mm day$^{-1}$ threshold (Fig. 8c-d) gives results similar to the 25 mm day$^{-1}$ threshold for higher values (between 13-35 mm day$^{-1}$ of $R_{\text{mean}}$, a slope for $R_{50}$ equally increases as in $R_{25}$, i.e., $R_{50}=1 \cdot R_{\text{mean}}$), but a decreased slope for the lower values (between 0-13 mm day$^{-1}$ of $R_{\text{mean}}$, the slope for $R_{50}$ decreases almost double with respect to $R_{25}$, $R_{50}=0.30 \cdot R_{\text{mean}}$). Above 20 mm day$^{-1}$ of $R_{\text{mean}}$, there are a very few grid points per bin observed ($\leq 10$ grids). However, up to that precipitation value we can well define the median fit, which is consistent for the higher precipitation values as well. This result offers a great method to estimate the intense precipitation ($R_{25}$ or $R_{50}$) knowing a true value of the mean precipitation ($R_{\text{mean}}$), and vice versa, on a local and global scale.

Overall, the observed high correlation values and a strong positive linear relationship between intense precipitation and mean precipitation regimes, in terms of mean or total
accumulated amounts on a daily scale, build confidence in defining constant slopes between them. This well-defined relationship and the ratio between two analyzed parameters ($R_{\text{mean}}$ and $R_{25}$) may therefore significantly help analyze current and past intensity of rainfall amounts.

7. Interannual variability of intense rainfall

Numerous studies have shown that increase or reduction in mean precipitation are likely to be associated with different phases of natural variability. For instance, recent observations indicate that interannual climatic variability of mean precipitation is strongly related to ENSO over many regions, and that a pronounced increase in intense rainfall events is associated with warm or cold ENSO phases over many regions (e.g., IPCC 2007; Curtis et al. 2007; Grimm and Tedeschi 2009; Lau and Wu 2011). Interdecadal modes of climate variability also produce changes in mean precipitation, as well as in the frequency of extreme events (e.g., Grimm and Saboia 2015; Grimm et al. 2016). In order to focus on interannual variability of intense rainfall, we investigate both El Niño and La Niña’s influence on mean and intense precipitation.

There are just a few strong recent ENSO events observed during the 16-year period of this study (e.g., El Niños in 1998, 2002-03, 2009-10, and La Niñas in 1998-99, 1999-2000, 2007-08, 2010-11, 2011-12). The strength of ENSO is typically defined by using the Niño3.4 monthly anomaly index of sea surface temperature. The Niño3.4 index over the Niño3.4 region (5°N-5°S, 160°E-150°W) used here is obtained from NOAA CPC. El Niño and La Niña periods are defined by choosing El Niño/La Niña months classified as either the top third or bottom third of ranked monthly values of Niño3.4 index anomalies during the available TMPA precipitation data record (1998-2013). Monthly Niño3.4
index values considered are then $>0.14^\circ$C and $<-0.62^\circ$C. Corresponding monthly values of the TMPA 3B42 V7 precipitation anomalies of mean precipitation (e.g., $R_{\text{mean}}$) and intense precipitation (e.g., $R_{25}$ and $R_{50}$) are derived and analyzed for El Niño, La Niña and neutral periods.

The strongest ENSO signal is observed over the Pacific and Indian Oceans; however, ENSO also influences many other regions over the globe. Maps of seasonal mean precipitation anomalies ($R_{\text{mean}}$) during El Niño period show: a strong precipitation increase over the equatorial Pacific and Indian Oceans, the ITCZ and SPCZ tropical regions, and a slight increase over the Southeast U.S. and the La Plata basin in South America; and a decrease over the Maritime Continent, Amazonia, and the equatorial Atlantic Ocean (Fig. 9a-d). During La Niña, a dipole regime observed in seasonal mean precipitation anomalies is nearly opposite, as expected (Fig. 9e-h). The same persistent regime is also observed in anomalies of mean and intense precipitation ($R_{\text{mean}}$, $R_{25}$, and $R_{50}$) during both El Niño and La Niña periods (figures not shown). Figure 9 confirms the strongest ENSO signal and the largest spatial coverage of rainfall amounts during December-January-February (DJF) season, and the weakest signal with the smallest spatial coverage during June-July-August (JJA) season, both for El Niño and La Niña periods, respectively.

In a similar way to the monthly analysis of intense rainfall, we investigate a relationship between anomalies of mean precipitation ($R_{\text{mean}}$) and intense precipitation (e.g., $R_{25}$) for El Niño, La Niña, and neutral months. Figure 10 shows a set of scatter plots between $R_{\text{mean}}$ and $R_{25}$ anomalies during El Niño, La Niña, and neutral periods, over tropical land and ocean. The most pronounced variations in mean precipitation anomalies
and the highest maximums in intense precipitation anomalies are observed in the tropics.

Therefore, we investigate this strong positive relationship between two parameters for the narrower tropical region (23.5°N-23.5°S). Mean and intense precipitation anomalies in the scatter plots show slightly different characteristics during El Niño versus La Niña periods, with a shift towards more positive versus negative anomalies (red/yellow colors in Fig. 10). With a higher number of grid points (such as over ocean), a tail of the observed linear distribution is longer, both in positive and negative anomalies. Similarly, as expected, a shorter extension of the distribution is observed over land, confirming the highest intense rainfall amounts mostly over the tropical oceans.

The results also give consistently higher amounts of positive heavy rainfall anomalies during La Niña period over tropical land and especially during El Niño period over tropical ocean (up to 4 mm day⁻¹), observed as an extension of the slightly wider distribution with a larger number of grid points (Fig. 10b,d). In contrast, higher amounts of negative heavy rainfall anomalies are observed during El Niño over land (up to -3.5 mm day⁻¹) and during La Niña over ocean (up to -4.3 mm day⁻¹; Fig. 10a,e). This is all due to placement of land (e.g., South America) in relation to the precipitation variations. The distribution of intense and mean precipitation anomalies for neutral period gives significantly lower rainfall amounts (in a range of ±2 mm day⁻¹), with more uniform and symmetrical shape, both over land and ocean. Higher correlations between \( R_{\text{mean}} \) and \( R_{25} \) anomalies are observed during El Niño and La Niña periods (\( r=0.92 \) for land and \( r=0.97-0.98 \) for ocean) versus neutral periods (0.88 for land and 0.94 for ocean). Slightly higher correlations observed over ocean in individual El Niño/La Niña period are probably due to more uniform rainfall data over ocean than over land. A slope of the positive linear
median fit in the distributions of $R_{\text{mean}}$-$R_{25}$ anomalies is very similar and consistent for El Niño and La Niña periods, and slightly higher over land than over ocean ($R_{25}=0.75 \cdot R_{\text{mean}}$ for land and $R_{25}=0.65 \cdot R_{\text{mean}}$ for ocean, Fig. 10a-b,d-e). As noted above, neutral periods experience much lower change in mean and intense rainfall amounts, but a higher slope of the linear median fit ($R_{25}=0.90 \cdot R_{\text{mean}}$ for land and $R_{25}=0.85 \cdot R_{\text{mean}}$ for ocean, Fig. 10c,f).

Results similar to those for $R_{25}$ are observed for the $R_{50}$ distribution over the tropics as well (figure not shown). However, with the higher daily threshold of 50 mm day$^{-1}$, overall change in $R_{50}$ is even lower than the observed change in $R_{\text{mean}}$, with a decreased slope of the linear median fit in the distribution of rainfall anomalies (a change factor of 0.40-0.50 during El Niño/La Niña period and 0.65-0.70 during neutral period). The $R_{\text{mean}}$-$R_{50}$ distribution gives a wider shape of observed anomalies and slightly lowers correlations both over land and ocean (0.88-0.98 for $R_{25}$ vs. 0.70-0.88 for $R_{50}$).

8. Regions with intense rainfall strongly related to ENSO

A few interesting regions located in areas with the observed peaks in mean and intense precipitation are chosen for a more detailed analysis of interannual variability of intense rainfall. The first region is defined over the West Pacific Ocean, as a 5°x5° grid box (6°S-1°S, 177°E-182°E), over which an average of $R_{\text{mean}}$, $R_{25}$ and $R_{50}$ is computed (Fig. 11). Corresponding time series are analyzed then over the highest amounts of rainfall, showing the overall variability of intense precipitation ($R_{25}$ and $R_{50}$), following closely the mean rainfall variation of $R_{\text{mean}}$. As expected, high correlations between mean and intense precipitation anomalies ($r=0.99$ for $R_{25}$ and 0.95 for $R_{50}$) are observed over the West Pacific Ocean region (Fig. 11a).
The same parameters are also analyzed in relation to the Niño3.4 index. A scatter plot of mean and intense precipitation anomalies with respect to the Niño3.4 index anomalies shows a strong positive linear relationship (Fig. 11b). High correlations of 0.66 for R_{25} and 0.61 for R_{50} (both significant at the 95% confidence level) between the Niño3.4 index and intense precipitation anomalies are observed over the West Pacific Ocean region. R_{mean} gives slightly higher correlation of 0.70 with the Niño3.4 index.

The West Pacific region is then compared with a 5°x5° region over the Philippines (10°N-15°N, 122°E-127°E) that includes both land and ocean areas, to address main differences between these two regions experiencing the opposite extreme sign in R_{mean}, R_{25} and R_{50} anomalies (Fig. 12). The scatter plots of mean and intense precipitation anomalies show strong positive values during El Niño period (red color values in Fig. 12a) and strong negative values during La Niña period (blue color values in Fig. 12a) over the West Pacific Ocean region, and the opposite dipole regime with strong positive values during La Niña and strong negative values during El Niño period over the Philippines region (Fig. 12b). During neutral period, anomalies are distributed around a center of the scatter plots. Two contrasting regions give high correlations between mean and intense precipitation anomalies (0.99 for R_{25} and 0.95 for R_{50} over the Pacific region, and 0.98 for R_{25} and 0.94 for R_{50} over the Philippines) and significantly small RMS differences (1.15 mm day^{-1} for R_{25} and 2.23 mm day^{-1} for R_{50} over the Pacific region, and 0.72 mm day^{-1} for R_{25} and 1.43 mm day^{-1} for R_{50} over the Philippines).

Another pair of smaller secondary peaks in R_{mean}, R_{25} and R_{50} anomalies is observed over the continental South America in the La Plata basin (33°S-28°S, 299°E-304°E) and in central Amazonia (5°S-0°, 301°E-306°E). Both regions over the South American land
experience strong ENSO signal, but with somewhat weaker precipitation anomalies and a lower $R_{25}/R_{\text{mean}}$ ratio than observed in the Pacific/Philippines regions during El Niño/La Niña period. All regions show consistently high significant correlations ranging between 0.95-0.99 for $R_{25}$ and 0.81-0.96 for $R_{50}$, with a strong positive linear fit. However, the Pacific/Philippines distributions show higher RMS differences of 0.72-1.15 mm day$^{-1}$ for $R_{25}$ and 1.43-2.23 mm day$^{-1}$ for $R_{50}$ versus South American 0.36-0.71 mm day$^{-1}$ for $R_{25}$ and 0.84-1.33 mm day$^{-1}$ for $R_{50}$ (Fig. 12), and this is due to higher rainfall variability over ocean. In addition, El Niño/La Niña identified values over the South American land are not separated in the way they are over the West Pacific/Philippines regions and somewhat in the La Plata basin (distributed only as positive or negative anomalies during El Niño or La Niña, seen in Fig. 12c-d vs. 12a-b), indicating that other factors, besides ENSO, must play a role there. In the La Plata basin, besides mid-latitude effects, there are also other influences from the Pacific and Atlantic Oceans, which play an even more significant role in the Amazon region. They can be similar or opposite to the ENSO influence, enhancing or weakening the resulting effect on both inter-annual and inter-decadal time scales (Grimm 2011; Grimm and Saboia 2015).

9. Discussion and conclusions

Satellite-based estimation of precipitation, specifically the TRMM-based TMPA 3B42 V7 analysis has allowed us to examine climatology and variations of recent intense daily precipitation during 1998-2013. This study analyzes different parameters representing mean and intense precipitation, their relationships and variability, contributing to our understanding of the precipitation behavior at climate scale. The relatively short 16-year data record used here limits our examination of extreme daily
precipitation, but allows for a careful study of intense daily precipitation, including its climatology and variations that should be related to events such as floods and landslides. This capability is due to the TMPA’s relatively high quality, i.e., mostly microwave-based, high resolution (3-hr, 0.25° lat./lon.), continual calibration, continuity, and uniformity over a near-global domain (50°N-50°S).

Climatologies of mean rainfall, conditional mean rainfall and fraction of rainfall days are examined and compared, and begin to reveal areas and times where and when heavier rainfall is more frequent. We tested several commonly used parameters to define intense precipitation, such as: mean monthly 95th percentile of daily precipitation, mean and fraction of precipitation that exceeds the 95th percentile, fraction of intense precipitation above fixed daily thresholds of 25 and 50 mm day⁻¹, and mean rainfall above same fixed thresholds, to infer which parameter best characterizes the heavy rainfall regime. Spatial patterns and features of various mean and intense precipitation parameters compare well to each other, with some differences over land and ocean. The overall results show a very strong relationship between mean and intense precipitation. Specifically, consistently high significant correlations with a strong positive linear relationship are observed between two interesting parameters: the monthly mean precipitation (mean precipitation $\geq$0 mm day⁻¹, $R_{\text{mean}}$) and intense precipitation (mean precipitation $\geq$25 mm day⁻¹, $R_{25}$).

Among the various examined parameters, the one best characterizing the intense rainfall is observed to be a ratio between intense precipitation and mean precipitation ($R_{25}/R_{\text{mean}}$). This ratio is considered to be a good measure of rainfall intensity. The results show high significant correlations and a strong positive linear relationship between these two parameters ($R_{25}$ and $R_{\text{mean}}$), explaining the contribution of intense rainfall to total
rainfall. We consider this analysis to be a first attempt of this kind to determine the best measure for intense rainfall.

From analysis of interannual variability of intense precipitation, we confirm a strong positive linear relationship and consistently high correlations between mean and intense precipitation anomalies, especially during El Niño and La Niña periods. The results also confirm that El Niño and La Niña events with their effects equally contribute to the observed connection between mean and intense precipitation, with no significant difference between land and ocean. In general, most of the intense rainfall events are observed over tropical ocean. However, the results show that intense rainfall events are stronger and more frequent during La Niña periods over tropical land and during El Niño periods over tropical ocean. Overall, the observed change in intense rainfall anomalies is lower than the one observed in mean rainfall anomalies during El Niño/La Niña period, and it decreases with a higher fixed threshold (a factor of 0.65-0.75 for R_{25} and 0.40-0.50 for R_{50}).

Intense rainfall is the major factor of causing floods and landslides worldwide, especially in recent years. Therefore, improved knowledge of the intense precipitation regime and its strong connection to the mean precipitation on a global to regional scale can offer more consistent current and near-future estimates of heavy rainfall, providing help in preventing damages caused by extreme events (i.e., floods, flash floods, and landslides). Future research should focus on the analysis of intense precipitation and flood events, together with economic and social systems, including additional factors such as population, critical infrastructures, and financial indices of cost that help estimate the potential risks and impacts of extreme and heavy rainfall events. Providing accurate
estimates of future intense precipitation events due to climate change, global warming, and/or natural climate variability (i.e., ENSO) is crucial. For the future, the Global Precipitation Measurement (GPM) mission will significantly contribute to an improved record of intense precipitation, extending to a more global domain, and allowing for a longer, enhanced climate record to be used. This should allow a better specification of the intense precipitation relationships in the coming years.

Acknowledgments

This research was supported by the NASA NEWS Program and the NASA PMM Program. TRMM 3B42 V7 product data were provided by the NASA Precipitation Processing System (PPS) at ftp://trmmopen.pps.eosdis.nasa.gov/trmmdata/.

Niño3.4 Index data were provided by the CPC NCEP NOAA at http://www.esrl.noaa.gov/psd/data/climateindices/list/.

The authors thank anonymous reviewers for their helpful comments and suggestions.
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Figure Captions

**Figure 1** (a) Annual, (b) January, and (c) July mean precipitation climatology ($R_{\text{mean, mm day}^{-1}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 2** (a) Annual, (b) January, and (c) July mean climatological fraction of days with precipitation $>0$ mm day$^{-1}$ ($F_0=R_{\text{mean}}/R_{\text{cond}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 3** (a) Annual, (b) January, and (c) July mean climatological conditional precipitation rate ($R_{\text{cond, mm day}^{-1}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 4** (a) Annual, (b) January, and (c) July mean 95$^{\text{th}}$ percentile daily precipitation value ($R_{95\text{p, mm day}^{-1}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 5** (a) Annual, (b) January, and (c) July mean precipitation $\geq 95^{\text{th}}$ percentile daily precipitation ($R_{95, \text{mm day}^{-1}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 6** Annual, January, and July mean precipitation (a)-(c) $\geq 25$ mm day$^{-1}$ threshold ($R_{25, \text{mm day}^{-1}}$) and (d)-(f) $\geq 50$ mm day$^{-1}$ threshold ($R_{50, \text{mm day}^{-1}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 7** (a) Annual, (b) January, and (c) July mean climatological fraction of daily precipitation $\geq 25$ mm day$^{-1}$ ($F_{25}=R_{25}/R_{\text{mean}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 8** Scatter plots of monthly climatology of mean precipitation ($R_{\text{mean, mm day}^{-1}}$) and intense precipitation (a)-(b) $\geq 25$ mm day$^{-1}$ ($R_{25, \text{mm day}^{-1}}$) and (c)-(d) $\geq 50$ mm day$^{-1}$ ($R_{50, \text{mm day}^{-1}}$) over the TRMM domain ($50^\circ\text{N}-50^\circ\text{S}$), separately over land and ocean.
derived from the TMPA 3B42 Version 7 data during 1998-2013. The color bar indicates the number of grid points with the attributed values in a logarithmic scale. Median (black dashed line) is calculated for a distribution of all 12 months. Correlation coefficient and RMS difference between intense rainfall ($R_{25}$ and $R_{50}$) and $R_{\text{mean}}$ are displayed. Correlation values are significant at the 95% confidence level.

**Figure 9** Mean precipitation anomalies (mm day$^{-1}$) for 4 seasons (DJF, MAM, JJA, SON) for (a)-(d) El Niño and (e)-(h) La Niña period, derived from the TMPA 3B42 Version 7 data during 1998-2013.

**Figure 10** Scatter plots of mean precipitation ($R_{\text{mean}}$, mm day$^{-1}$) and intense precipitation $\geq 25$ mm day$^{-1}$ ($R_{25}$, mm day$^{-1}$) anomalies for El Niño, La Niña and neutral period, over the tropical domain (23.5°N-23.5°S), over (a)-(c) land and (d)-(f) ocean, derived from the TMPA 3B42 Version 7 data during 1998-2013. The color bar indicates the number of grid points with the attributed values in a logarithmic scale. Correlation coefficient between $R_{25}$ and $R_{\text{mean}}$ is displayed. Correlation values are significant at the 95% confidence level.

**Figure 11** (a) Time series of mean precipitation ($R_{\text{mean}}$, mm day$^{-1}$; blue line) and intense precipitation $\geq 25$ mm day$^{-1}$ ($R_{25}$, mm day$^{-1}$; black line) and $\geq 50$ mm day$^{-1}$ ($R_{50}$, mm day$^{-1}$; red line) anomalies, and (b) scatter plot of $R_{\text{mean}}$, $R_{25}$, and $R_{50}$, and Niño3.4 index anomalies, averaged over a 5°x5° box over the West Pacific Ocean (6°S-1°S, 177°E-182°E), derived from the TMPA 3B42 Version 7 precipitation data during 1998-2013. Correlation coefficient and RMS difference between intense rainfall ($R_{25}$ and $R_{50}$) and $R_{\text{mean}}$ are displayed in (a), and correlation coefficient between $R_{\text{mean}}$, $R_{25}$, and $R_{50}$ with
respect to the Niño3.4 index in (b). Correlation values are significant at the 95% confidence level.

Figure 12 Scatter plots of mean precipitation ($R_{\text{mean}}$; mm day$^{-1}$) and intense precipitation $\geq 25$ mm day$^{-1}$ ($R_{25}$, mm day$^{-1}$; filled circles and black line) and $\geq 50$ mm day$^{-1}$ ($R_{50}$, mm day$^{-1}$; empty circles and red line) anomalies, with corresponding linear fit for El Niño (red), La Niña (blue) and neutral period (black), averaged over a 5°x5° box over: (a) the West Pacific Ocean, (b) Philippines, (c) La Plata basin, and (d) Amazonia, derived from the TMPA 3B42 Version 7 data during 1998-2013. 5°x5° boxes are chosen denoting two largest maximums and minimums observed in global anomalies. Correlation coefficient and RMS difference between intense rainfall ($R_{25}$ and $R_{50}$) and $R_{\text{mean}}$ are displayed. Correlation values are significant at the 95% confidence level.
Table Captions

Table 1 Definitions and units for monthly parameters of mean and intense precipitation.
**Table 1** Definitions and units for monthly parameters of mean and intense precipitation.

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</tr>
<tr>
<td>Mean conditional precipitation rate (mean precipitation rate</td>
<td>$R_{\text{cond}}$</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>for days with $R &gt; 0$ mm day$^{-1}$)</td>
<td></td>
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</tr>
<tr>
<td>Fraction of days in a month with $R &gt; 0$ mm day$^{-1}$</td>
<td>$F_0$</td>
<td></td>
</tr>
<tr>
<td>($R_{\text{mean}}/R_{\text{cond}}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>INTENSE PRECIPITATION:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95$^{th}$ percentile of daily precipitation in a month</td>
<td>$R_{95p}$</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>Monthly mean precipitation with $R \geq 95^{th}$ percentile (Total $R$</td>
<td>$R_95$</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$\geq R_{95p}$ in a month/total days in a month)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fraction of daily precipitation with $R \geq 95^{th}$ percentile</td>
<td>$F_95$</td>
<td></td>
</tr>
<tr>
<td>($R_{95}/R_{\text{mean}}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly mean precipitation with $R \geq 25$ and 50 mm day$^{-1}$</td>
<td>$R_{25}$, $R_{50}$</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>(Total $R \geq 25$ and 50 mm day$^{-1}$ in a month/total days in a month)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of days within a month with $R \geq 25$, 50 and 75 mm</td>
<td>$N_{25}$, $N_{50}$, $N_{75}$</td>
<td>day</td>
</tr>
<tr>
<td>day$^{-1}$ threshold</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fraction of daily precipitation with $R \geq 25$ and 50 mm day$^{-1}$</td>
<td>$F_{25}$, $F_{50}$</td>
<td></td>
</tr>
<tr>
<td>($R_{25}/R_{\text{mean}}$ and $R_{50}/R_{\text{mean}}$)</td>
<td></td>
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</tr>
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</table>
FIG. 1. (a) Annual, (b) January, and (c) July mean precipitation climatology ($R_{mean}$, mm day$^{-1}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.
FIG. 2. (a) Annual, (b) January, and (c) July mean climatological fraction of days with precipitation $>0$ mm day$^{-1}$ ($F_0 = R_{\text{mean}}/R_{\text{cond}}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.
FIG. 3. (a) Annual, (b) January, and (c) July mean climatological conditional precipitation rate ($R_{\text{cond}}$, mm day$^{-1}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.
FIG. 4. (a) Annual, (b) January, and (c) July mean 95th percentile daily precipitation value ($R_{95p}$, mm day$^{-1}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.
FIG. 5. (a) Annual, (b) January, and (c) July mean precipitation ≥95\textsuperscript{th} percentile daily precipitation (R\textsubscript{95}, mm day\textsuperscript{-1}), derived from the TMPA 3B42 Version 7 data during 1998-2013.
FIG. 6. Annual, January, and July mean precipitation (a)-(c) ≥25 mm day\(^{-1}\) threshold (R\(_{25}\); mm day\(^{-1}\)) and (d)-(f) ≥50 mm day\(^{-1}\) threshold (R\(_{50}\); mm day\(^{-1}\)), derived from the TMPA 3B42 Version 7 data during 1998-2013.
FIG. 7. (a) Annual, (b) January, and (c) July mean climatological fraction of daily precipitation $\geq 25$ mm day$^{-1}$ ($F_{25}=R_{25}/R_{mean}$), derived from the TMPA 3B42 Version 7 data during 1998-2013.
FIG. 8. Scatter plots of monthly climatology of mean precipitation ($R_{\text{mean}}$, mm day$^{-1}$) and intense precipitation (a)-(b) $\geq 25$ mm day$^{-1}$ ($R_{25}$, mm day$^{-1}$) and (c)-(d) $\geq 50$ mm day$^{-1}$ ($R_{50}$, mm day$^{-1}$) over the TRMM domain (50°N-50°S), separately over land and ocean, derived from the TMPA 3B42 Version 7 data during 1998-2013. The color bar indicates the number of grid points with the attributed values in a logarithmic scale. Median (black dashed line) is calculated for a distribution of all 12 months. Correlation coefficient and RMS difference between intense rainfall ($R_{25}$ and $R_{50}$) and $R_{\text{mean}}$ are displayed. Correlation values are significant at the 95% confidence level.
FIG. 9. Mean precipitation anomalies (mm day$^{-1}$) for 4 seasons (DJF, MAM, JJA, SON) for (a)-(d) El Niño and (e)-(h) La Niña period, derived from the TMPA 3B42 Version 7 data during 1998-2013.
**FIG. 10.** Scatter plots of mean precipitation ($R_{\text{mean}}$, mm day$^{-1}$) and intense precipitation $\geq 25$ mm day$^{-1}$ ($R_{25}$, mm day$^{-1}$) anomalies for El Niño, La Niña and neutral period, over the tropical domain (23.5°N-23.5°S), over (a)-(c) land and (d)-(f) ocean, derived from the TMPA 3B42 Version 7 data during 1998-2013. The color bar indicates the number of grid points with the attributed values in a logarithmic scale. Correlation coefficient between $R_{25}$ and $R_{\text{mean}}$ is displayed. Correlation values are significant at the 95% confidence level.
FIG. 11. (a) Time series of mean precipitation ($R_{\text{mean}}$, mm day$^{-1}$; blue line) and intense precipitation $\geq$25 mm day$^{-1}$ ($R_{25}$, mm day$^{-1}$; black line) and $\geq$50 mm day$^{-1}$ ($R_{50}$, mm day$^{-1}$; red line) anomalies, and (b) scatter plot of $R_{\text{mean}}$, $R_{25}$, and $R_{50}$, and Niño3.4 index anomalies, averaged over a 5°x5° box over the West Pacific Ocean (6°S-1°S, 177°E-182°E), derived from the TMPA 3B42 Version 7 precipitation data during 1998-2013. Correlation coefficient and RMS difference between intense rainfall ($R_{25}$ and $R_{50}$) and $R_{\text{mean}}$ are displayed in (a), and correlation coefficient between $R_{\text{mean}}$, $R_{25}$, and $R_{50}$ with respect to the Niño3.4 index in (b). Correlation values are significant at the 95% confidence level.
FIG. 12. Scatter plots of mean precipitation ($R_{\text{mean}}$; mm day$^{-1}$) and intense precipitation $\geq 25$ mm day$^{-1}$ ($R_{25}$, mm day$^{-1}$; filled circles and black line) and $\geq 50$ mm day$^{-1}$ ($R_{50}$, mm day$^{-1}$; empty circles and red line) anomalies, with corresponding linear fit for El Niño (red), La Niña (blue) and neutral period (black), averaged over a $5^\circ \times 5^\circ$ box over: (a) the West Pacific Ocean, (b) Philippines, (c) La Plata basin, and (d) Amazonia, derived from the TMPA 3B42 Version 7 data during 1998-2013. $5^\circ \times 5^\circ$ boxes are chosen denoting two largest maximums and minimums observed in global anomalies. Correlation coefficient and RMS difference between intense rainfall ($R_{25}$ and $R_{50}$) and $R_{\text{mean}}$ are displayed. Correlation values are significant at the 95% confidence level.