LETTER

Global precipitation system size

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Abstract
The size of precipitation systems is an important parameter of precipitation process and dynamics. This study uses the latest Integrated Multi-satellitE Retrievals for Global Precipitation Measurement data during 2015–2019 to investigate the global distribution of precipitation system size, its spatial and temporal pattern, as well as its relationships with precipitation amount, frequency, intensity, and duration. Our results show that large precipitation systems (>10^6 km^2) occur more frequently over ocean. Most land areas are dominated by medium-size precipitation systems (10^4–10^6 km^2), except that some relatively smaller precipitation systems (<10^4 km^2) are dominant over the eastern Pacific, some parts of southern Atlantic the northern Africa, and central Asia. The most apparent seasonal contrast in precipitation system size occur over midlatitude oceans, the southeast United States, and the Amazon Basin. The diurnal contrast of precipitation system size is weaker over the oceans where the latitude is greater than 30°, and stronger over land and tropical oceans. The precipitation system size is highly positively spatial-correlated with precipitation amount, frequency, intensity, and duration. The strongest temporal associations of precipitation system size with precipitation amount, frequency, intensity, and duration on monthly scale occur over the tropics, with correlation coefficients greater than 0.8. This study indicates evident regional differences, which can provide new information to deepen the understanding of local synoptic systems in regional studies.

1. Introduction
Precipitation plays a key role in global water and energy cycle (Trenberth et al 2003, Kidd and Huffman 2011, Hou et al 2014, Chen 2020, Zhang 2020). Precipitation systems, formed by diverse dynamic processes, vary from ~100 m to over 1000 km in the horizontal (Lovejoy 1982, Holder et al 2008, Skok et al 2009, Barnolas et al 2010, Otsuka et al 2017, Teo et al 2017). Precipitation systems with small horizontal extents, such as thunderstorms, are formed by local convection arising from instabilities in the atmosphere, while precipitation systems that are large in size are often associated with frontal lifting or wide-spread horizontal convergence (Mölders and Kramm 2014). Precipitation systems of various sizes also behave differently in terms of rainfall contributions (Liu 2011, Houze Jr et al 2015), latent heat release (Wilcox and Ramanathan 2001, Liu et al 2015), and radiative effects through clouds (Machado and Rossaow 1993, Yuan and Houze 2010, Wood and Field 2011, Chen et al 2017). Therefore, accurate knowledge of precipitation system size is essential for understanding the dynamic processes and environmental implications of precipitation. Moreover, the size distribution of precipitation systems has a crucial influence on the parameterization of clouds and rain in global circulation models (GCMs) (Wilcox and Ramanathan 2001, Mesnard and Sauvageot 2003, Chen et al 2017), which can further improve the accuracy of precipitation prediction.

Before the satellite era, ground-based observations were the main data source for precipitation studies, including rain gauges and ground radar (Sun et al 2018). However, the drawbacks of ground-based measurements, such as spatial heterogeneity and sparse coverage in remote regions (Kidd et al 2017), made ground-based estimates more appropriate for
investigating local rainfall and limited for working on the spatial characteristics of large-size precipitation systems.

In recent decades, great developments have been made with satellite-based precipitation observations (Kidd and Levizzani 2011, Kucera et al. 2013, Yang et al. 2013). By providing more spatially homogeneous and temporally complete estimates over most areas of the globe, satellite precipitation data can compensate for deficiencies in gauge observations (Sun et al. 2018). With the transition from indirect infrared (IR) sensors to the more direct passive microwave (PMW) and radar sensors, the inversion accuracy of precipitation satellite data is also gradually improving. Under this background, scientists began to pay attention to the scaling behaviors of precipitation systems (Lovejoy 1982, Peters et al. 2012, Traxl et al. 2016, Teo et al. 2017), especially after the beginning of the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 1998). For instance, Liu et al. (2008) and Nesbitt et al. (2006) used TRMM products to study the size of each precipitation feature (PF), and showed the global spatial pattern of feature size by assigning each PF to the grid based on their centroid location.

On February 28 2014, the Global Precipitation Measurement (GPM) Core Observatory was launched, which marked the next generation of precipitation measurement program (Hou et al. 2014). With more advanced sensors (the dual-frequency precipitation radar (DPR) and the GPM Microwave Imager), a more unified satellite constellation, improved spatial-temporal resolution, and global coverage (Hou et al. 2014, Skofronick-Jackson et al. 2017), GPM products are expected to become more accurate precipitation estimates. Therefore, its primary level-3 gridded product, the Integrated Multi-satellite Retrievals for GPM (IMERG), which is regarded as the successor of the TRMM Multisatellite Precipitation Analysis (Huffman et al. 2007), also provides a great opportunity to study global precipitation systems.

Compared with the previous TRMM products, the IMERG dataset could bring new insight into research regarding global precipitation systems with its advanced technology. For example, the IMERG dataset has a temporal resolution at 0.5 h and a spatial resolution at 0.1° × 0.1° globally (Huffman et al. 2019), which has been greatly enhanced compared with the TMPA product at three hourly, 0.25° × 0.25° resolution and 50° S−50° N coverage (Huffman et al. 2007). Furthermore, because of the improved DPR sensitivity, the detection ability of light rain can be enhanced (Hamada and Takayabu 2016), which is important when detecting some weaker rain in the edge of precipitation systems. Also, the IMERG algorithm integrates the advantages of many previous merging algorithms. For example, the CMORPH Kalman filter Lagrangian time interpolation algorithm (Joyce and Xie 2011) could help to better represent precipitation system motion and provide spatially complete propagation fields.

There are several existing relative studies on the distribution of precipitation system size in GPM era (Liu and Zipser 2015, Zhou et al. 2019). Liu and Zipser (2015) used the GPM Ku band radar to investigate where the largest precipitation systems exist worldwide by exhibiting their geographic centers. Zhou et al. (2019) used the IMERG product to examine the spatial-temporal characteristics of extreme precipitation events over the contiguous United States, which did not include general precipitation systems and just over specific regions rather than the global domain. Therefore, although there are some related studies using previous precipitation estimates (Nesbitt et al. 2006, Liu et al. 2008, Liu and Zipser 2015), additional studies are needed regarding the global geographical distribution of precipitation system size by using the latest satellite precipitation estimates, which is the main motivation of our study.

For the first time, this study uses the latest merged satellite precipitation data from GPM (IMERG) to calculate and obtain the global geographical distribution of precipitation system size worldwide. Furthermore, the seasonal and diurnal cycles are investigated. Finally, the relationships of precipitation system size with precipitation amount, frequency, intensity, and duration are estimated.

2. Data and methods

The IMERG product is the primary level-3 gridded product with a temporal resolution of half hour and 0.1° × 0.1° in the global horizontal domain (Huffman et al. 2019). In this study the version used is Final Run Version 06B, which is computed from various precipitation estimates based on multi-satellite PMW sensors that are intercalibrated with the GPM Combined Ku Radar–Radiometer Algorithm product and merged with IR estimates, as well as adjusted with the Global Precipitation Climatology Project Satellite–Gauge product. With the advanced primary data source (the GPM Core Observatory), sampling constellation, and merging algorithms, the IMERG product is promising to provide useful information for global precipitation research (Guo et al. 2016, Asong et al. 2017, Dezfuli et al. 2017, Chiaravalloti et al. 2018, Prakash et al. 2018).

In this study, the selected study period is five full years from 2015 to 2019, considering the start time of the GPM-era IMERG product is June 2014. Since there are still some missing data at higher latitudes because of snow and ice (Huffman et al. 2019), the selected study area is 60° N–60° S, which is also the native spatial range of GPM. Here, we choose 0.1 mm h$^{-1}$ as the threshold for precipitating grid boxes. The horizontal size of precipitation systems in this study is defined as the contiguous precipitating
areas. First, we group the connected precipitating grids to precipitation systems. Then, we record the size of the precipitation systems where each grid box is located.

To denote the average state of precipitation system size in each grid box, we use the median size of precipitation systems where each grid box is located for further analysis. Then we calculate the median precipitation system size of each grid box for each season during 2015–2019, namely, December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). And we also calculate the median precipitation system size of each grid box during each local time (LT) period to analyze the diurnal variation by converting the Universal Time Coordinated (UTC) time that IMERG estimates are provided in to LT based on time zones. Here, we divide the day into six groups, namely, midnight (2200–0200 LT), early morning (0200–0600 LT), morning (0600–1000 LT), noon (1000–1400 LT), afternoon (1400–1800 LT), and evening (1800–2200 LT).

We also examine whether a relationship exists between precipitation system size and other precipitation properties. We calculate the precipitation amount, frequency, intensity, and duration of each grid box from hourly data during the period of 2015–2019. Here, the frequency is defined as the proportion of rainy hours to all hours. The duration is calculated as follows: the consecutive hourly precipitation data are together regarded as a precipitation event, and we record the duration of each event for further calculation. Since other precipitation properties are all one-dimensional variables, we use the square root of the precipitation system size for further calculation of the correlation coefficient.

3. Results

3.1. Geographical distribution

To obtain the quasi-global geographical distribution of precipitation system size, first, the size of precipitation systems is categorized into <10⁴ km², 10⁴–10⁶ km², and >10⁶ km². Then, the frequency contribution to the total precipitation time for each category in each grid box is calculated (figures 1(a)–(c)). Generally, most regions of the world are dominated by precipitation systems with size 10⁴–10⁶ km², with frequency over half of the precipitation hours (figure 1(b)). Large precipitation systems (>10⁶ km²) appear more frequently over ocean, especially the midlatitude and high latitude oceans as well as the intertropical convergence zone (ITCZ) (figure 1(c)). The large precipitation systems that occur over mid and high latitude oceans may be related to the extratropical cyclones and warm ocean currents in the subtropics, while those over

Figure 1. Geographic patterns of the frequency contributions of precipitation systems with different sizes: (a) <10⁴ km²; (b) 10⁴–10⁶ km²; and (c) >10⁶ km², to the total precipitating hours in each grid box. (d) Geographic pattern of the median precipitation system size for all hours during 2015–2019.
ITCZ may correspond to the frequent occurrence of mesoscale convective systems (MCSs) with large sizes over the warm pool regions of the western Pacific and Indian Oceans (Yuan and Houze 2010, Chen et al 2019).

Figure 1(a) shows that the frequency of small precipitation systems (<10^4 km^2) are quite low over most regions of the world, which are more likely to occur over some dry zones such as the southeastern Pacific, some parts of the southern Atlantic, the Sahara Desert, and central Asia. Some existing studies (Peters et al 2012, Teo et al 2017) have shown the high frequency of small precipitation systems around the world from a general perspective, but it is not the same with each grid box and the results may vary with geographical location. Here we go further to show a grid-based analysis that calculates the size of precipitation systems where each grid box is located, which could get more information from each grid box. If we calculate the proportion of small precipitation systems to total precipitation systems from the general perspective, our results will be consistent with the existing studies (Peters et al 2012, Teo et al 2017).

To simplify and display the information on the sizes of precipitation systems in one figure for further analysis, we use the median size of precipitation systems where each grid box is located as a variable to represent the mean state of precipitation system size of each grid box. Figure 1(d) shows the global pattern of the median precipitation system size. The red and yellow parts of figure 1(d) are consistent with the green and yellow parts of figure 1(c), which suggest regions where large-size precipitation systems often occur. Similarly, the green and blue parts in figure 1(d) are in accordance with the red parts in figures 1(b) and (a), which represent the medium and small sizes, respectively. Therefore, the median precipitation system size is appropriate for presenting the size distribution of precipitation systems, and we can use it for further analysis.

3.2. Seasonal variation
To examine the variation in precipitation system scale in different seasons, figure 2 shows the seasonal composite quasi-global distribution of median precipitation system size from the 2015–2019 period. Overall, the annual cycle is more obvious over ocean except for the southern Indian Ocean. Over tropical oceans, large precipitation systems are concentrated over the Indian–Pacific warm pool during JJA compared with those more concentrated over the central Pacific in DJF. Over higher latitudes from 30° to 60°, both the Pacific and Atlantic in the two hemispheres are characterized by larger precipitation systems more often in winter than in summer, which may be corresponded to midlatitude cyclones that occur more in winter.

In terms of continental areas, the most obvious annual cycle occurs over the southeast United States and the Amazon Basin. The precipitation systems over the southeast United States are smaller during JJA when the extreme precipitation events are most frequent in this region, which may be
related to the tropical systems and daily thunderstorms (Schumacher 2006, Zhou et al 2019). Similarly, there are smaller precipitation systems in JJA than in DJF over the Amazon Basin, which may be attributed to the areas of MCSs that are related to the increased land surface-atmospheric feedbacks in terms of more soil moisture and actual evapotranspiration caused by more direct solar radiation (Jaramillo et al 2017).

3.3. Diurnal variation

Apart from seasonal variations, precipitation systems also have various properties during different local hours. Figure 3 shows the diurnal variation of precipitation system size. Considering that the diurnal variation of absolute values of precipitation system size is not very obvious in the geographic maps, we calculate the relative difference between the median precipitation system size for each period and all years in each grid box during 2015–2019. Figure 3 shows that the diurnal cycle of precipitation system size is rather weak over the oceans where the latitude is greater than 30°, such as the high latitude Pacific, Atlantic, and Indian Ocean, which is consistent with the knowledge of relatively muted diurnal variability over these regions. Over the tropical and subtropical oceans, the size of precipitation systems reaches a minimum around midnight (2200–0200 LT) and slightly increases in the early morning (0200–0600 LT). Many previous studies have revealed the diurnal cycle of total rainfall over this region—often peaking in the early morning or before dawn (Vincent and Lane 2017, Kim et al 2019). The reason for the difference between the diurnal cycles of precipitation system size and total rainfall can be explained by the diurnal cycle of MCSs that contribute a lot to the total rainfall. The maximum rainfall contribution from MCSs in the early morning is because of an increased number of MCSs at that time rather than the increasing MCS areas (Nesbitt and Zipser 2003), which also indicates that the diurnal cycles of precipitation system size and rainfall are controlled.
Figure 4. Density scatterplots of the square root of median precipitation system size with (a) annual mean amount (mm yr$^{-1}$), (b) frequency (%), (c) mean intensity (mm h$^{-1}$), and (d) mean duration (h). Each point represents an average value during 2015–2019 for each grid box. $R$ and $p$ represent the spatial correlation coefficient and $p$-value for testing the hypothesis, respectively.

3.4. Relationships with other precipitation properties

We also examine whether a relationship exists between precipitation system size and precipitation amount, frequency, intensity, and duration. First, we use the average values during 2015–2019 of all the grid boxes to analyze the spatial correlation between precipitation system size and other precipitation properties. Figure 4 shows the density scatterplots of the square root of median precipitation system size with annual mean amount, frequency, mean intensity, and mean duration. Figure 5 shows the global distribution of the mean state of other precipitation properties. The results indicate that generally precipitation system size is highly positively correlated with other precipitation properties with correlation coefficients ranging from 0.61 to 0.7, indicating that the larger precipitation systems are often accompanied by a higher total amount, higher frequency, stronger intensity, and longer duration, which is more obvious over ocean (figures 1 and 5). The mechanism behind the phenomenon could be deep convective systems or large-scale moisture convergence due to large-scale vertical velocities that help to maintain the strong precipitation systems with large size (Lochbihler et al. 2017).

Then, to investigate the temporal correlation and regional difference, we calculate the monthly median precipitation system size, monthly average precipitation amount, frequency, intensity, and duration of each grid box during the period of 2015–2019, and then use this monthly series to calculate the correlation coefficient between precipitation system size and other precipitation variables (figure 6). The results

by different factors and therefore manifest different features.

The diurnal variation over land is different from that over ocean areas, and varies significantly among different regions. Figure 3 shows that the precipitation system size over most land regions increases from a minimum at noon, when the most prominent land–ocean contrast appears, to a maximum in the late afternoon, then steadily decreases during nighttime, and slightly increases in the morning, especially over the Amazon and tropical Africa. Over some land areas, the precipitation system size seems not to show the afternoon peak, such as the Tibetan Plateau, the Arabian Peninsula, the Sahara, and Australia. The reason behind the diurnal cycle of precipitation system size over land areas can involve many complicated formation mechanisms and can be affected by various factors, such as land–sea thermal contrast, the local orography, low-level wind anomalies, and so on. These mechanisms need more detailed studies focused on specific regions (Kim et al. 2019).
show that precipitation amount, frequency, intensity, and duration share a similar pattern in terms of their relationships with precipitation system size, except that the relationship between intensity and system size seems relatively weaker than the others. Also, the correlation coefficient is higher over tropical areas, including tropical Africa, the south coast of Asia, the Maritime Continent, the north coast of Brazil, and

Figure 5. Global patterns of average values of precipitation properties during 2015–2019: (a) annual mean amount (mm yr$^{-1}$), (b) frequency (%), (c) mean intensity (mm h$^{-1}$), and (d) mean duration (h).

Figure 6. Global patterns of temporal correlation coefficients for the relationships of the square root of median precipitation system size with (a) amount, (b) frequency, (c) intensity, and (d) duration. The correlation coefficients are calculated by monthly time series of each grid box. All the points pass the $t$-test at a significance level of 0.05.
the tropical oceans, which indicates that the monthly variations in precipitation system size are more consistent with those in amount, frequency, intensity, and duration over these regions. Meanwhile, the size of precipitation systems over some midlatitude land regions is also highly related to other properties, such as the Central Siberian Plateau and the northern parts of North America. To some extent, the relationships between precipitation system size and other precipitation properties could provide some information on the precipitation mechanism over different regions. For example, those areas with strong relationships between size and other properties may be controlled by relatively monotonous precipitation type, while those with weak ones may be affected by various precipitation process.

4. Conclusions and discussion

The size of precipitation systems is very important for understanding the dynamic processes and environmental implications of precipitation, and the promotion of precipitation parameterization in GCMs. However, research investigating the global geographic distribution of precipitation system size is still needed. This study uses the latest GPM level-3 product IMERG V06B during 2015–2019 to obtain the spatial patterns of precipitation system size in a quasi-global domain, then analyzes their seasonal and diurnal cycles, and finally investigates the relationships between system size and other precipitation properties. The major conclusions are summarized as follows:

(a) Large precipitation systems (>10⁶ km²) occur more frequently over ocean than over land, but some coastal lands, especially the midlatitude and high latitude oceans as well as the ITCZ. Most land is dominated by medium-size precipitation systems (10⁴–10⁶ km²), while relatively smaller precipitation systems (<10⁴ km²) are dominant over the eastern Pacific, some parts of southern Atlantic the northern Africa, and central Asia.

(b) The seasonal cycle is more obvious over oceans except for the southern Indian Ocean. The most apparent annual variation occurs over midlatitude oceans, the southeast United States, and the Amazon Basin.

(c) The diurnal cycle is weaker over the oceans where the latitude is greater than 30°, while those over most tropical oceans have an obvious afternoon peak. The diurnal variations over land areas vary significantly among different regions, and most of them experience the maximum in the late afternoon, except for the Tibetan Plateau, the Arabian Peninsula, the Sahara Desert, and Australia.

(d) The precipitation system size is positively spatially correlated with precipitation amount, frequency, intensity, and duration. The highest monthly scale temporal correlation coefficients of system size with amount, frequency, intensity, and duration occur over tropical areas, including tropical Africa, the south coast of Asia, the Maritime Continent, the north coast of Brazil, and the tropical oceans, with correlation coefficients greater than 0.8.

With the latest GPM IMERG precipitation estimates, the geographical distribution of precipitation system size is analyzed on a gridded scale. The results indicate evident regional differences, which can provide new information to deepen the understanding of local synoptic systems in regional studies. Many previous system-based studies either pay attention to the scaling behavior of precipitation systems from the perspective of distribution law (Lovejoy 1982, Peters et al 2012, Traxl et al 2016, Teo et al 2017), or displayed the geographical centers of precipitation systems (Nesbitt et al 2006, Liu et al 2008, Liu and Zipser 2015), which could merely show the general frequency of precipitation systems with different size rather than reveal the real and complete geographical pattern of precipitation system size of each grid box. Therefore, our gridded results can show more information on the geographical distribution of precipitation system size, as well as its seasonal and diurnal cycle, compared to the previous studies.

Moreover, the new grid-based perspective of investigating precipitation system size could be more widely used and may bring new ideas into precipitation studies. For example, the variable we use to present information on the size of precipitation systems, namely, the median size of precipitation systems where each grid box is located, has been suggested to be rather appropriate and may provide a new evaluation metric in grid-scale model verification. Also, by using the gridded results of precipitation system size, we could combine precipitation system size with other gridded atmospheric factors, such as temperature, to make further comprehensive analysis and get the geographical distribution to investigate the regional differences in the future.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://pmm.nasa.gov/data-access/downloads/gpm.

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