The Asymmetric Distribution of Rainfall Frequency and Amounts in India

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ABSTRACT

Studies of rainfall usually focus on the total amount precipitating throughout a certain period. Compared to rain rates associated with extreme events, the rain rates associated with the most frequent events is understudied. In this study, the characteristics of daily precipitation in India are explored using two metrics - rain frequency peak (the most frequent non-zero rain rate) and rain amount peak (the rain rate at which the most amount of rain falls). These metrics are computed over India using local and global datasets to investigate the characteristics of typical daily precipitation accumulations. These values are sensitive to the dataset used for this analysis since the temporal and spatial resolution of the rainfall data will influence the rain frequency peak and rain amount peak. Our study reveals the rain frequency peak is highest during the summer monsoon, while the winter season exhibits lower values, particularly at higher latitudes. Similarly, the rain amount distribution indicates dominance of heavy rain rates during the monsoon and post-monsoon seasons, leading to high total precipitation. The maximum rain frequency peak for any region in India reaches up to a value of 35 mm/day while the maximum rain amount peak reaches up to a value as high as 90 mm/day. These metrics would be useful in systematically evaluating typical daily precipitation in regional climate models and assessing downstream impacts of uneven precipitation such as lower crop yields, flood-drought alterations, and fluctuating water availability.

Keywords: Precipitation characteristics, rain frequency peak, rain amount peak

1. Introduction

Extreme precipitation is a widely studied topic as they frequently lead to widespread flooding and damage to life and property, while events that occur most frequently and contribute to the most amount of precipitation are under studied. The typical precipitation over a particular area is generally quantified at a climatological scale, usually averaged over a month, season, or longer. While this approach is useful to distinguish wet and dry seasons, it fails to inform us of the nature and quantity of typical daily precipitation over a location, which arguably influences majority of our decisions with regards to rain, compared to extreme events that are infrequent and atypical. This is also relevant to understand downstream impacts of uneven precipitation. For example, Fishman (2016) found that decreases in the number of rainy days can overturn the benefits of increased total precipitation for the yields of most major crops. While total daily precipitation is a frequently communicated metric, it is insufficient to define a typical rainy day's precipitation since rainfall varies with each month, season, and year. The response of rainfall patterns and the changes in the distribution of precipitation to global warming also need to be studied using precipitation metrics such as rain frequency and rain amount. In precipitation frequency studies, the total frequency and intensity of precipitation are two commonly used metrics to represent how often it rains and how heavy a rain event is. Englehart and Douglas (1985) found that precipitation frequency, given by the number of days per month or season receiving greater than a specified amount of rainfall, is more normally distributed and more spatially coherent than total precipitation. A few other studies have investigated total frequency and intensity in rainfall observations (A et al., 2020a; Adarsh et al., 2020; Biasutti and Yuter, 2013; Chen et al., 1996; Dai, 2001a; Hosseinzadehtalaei et al., 2020; Marzuki et al., 2021; Singh et al., 2021; Sun et al., 2006; Trenberth et al., 2017; Zhang et al., 2023). Gehne (2016) and Herold (2016) both revealed considerable uncertainty in observational products.

Most of the literature is focused on extreme rainfall events that lead to natural disasters such as floods (e.g., Ricko et al., 2016). These include statistics related to the heaviest day of precipitation in a season or a year and the percentile of the distribution related to a particular precipitation rate. Finding appropriate ways to distinguish light and heavy rain events by looking at their statistical distributions is a topic of active research. Some of the earliest works focused on the rain frequency distribution, first qualitatively (Dai, 2001; Petty, 1995) and then utilizing categorical bins (e.g., Dai, 2006). Later, Watterson and Dix (2003) computed the amount of rain falling in each categorical bin, referred to as the rain amount distribution or the rain volume distribution in certain studies (We use the term rain amount distribution throughout this study). Note that the sum of the rain amount distribution for all the bins gives us the total precipitation. Sun (2007) utilised bins that were linearly spaced in rain rate to quantify the rain distribution. Though it provides a mathematical basis for the analysing the distribution of rain, it has imperfect sampling properties since the daily accumulation of rain (rain rate) spans orders of magnitude. Similarly, Pendergrass and Hartmann (2014) used logarithmically spaced rain rate bins to compute the rain amount and the rain frequency distributions. All rain distributions such as rain frequency distribution, rain amount distribution, etc. depend significantly on the selection of bin structure for rain rates.

Similar investigations into the statistical properties of precipitation have also been done over India. In one of the earliest studies, Ananthakrishnan (1970) studied the space-time variations of Indian rainfall by examining the pentad (5-day totals) normal rainfall curves of the representative stations of different regions of the country. Further, Ananthakrishnan and Soman (1989) performed a statistical analysis of the daily rainfall series of 15 Indian stations to develop normalized rainfall curves (NRC) that associated cumulated percentage rain amount and the cumulated percentage number of rain days. Goswami et al. (2006) demonstrated that despite considerable year-to-year variability, there are significant increases in the frequency and the intensity of extreme monsoon rain events over central India during the period of 1951 to 2000.

Thus, there is a lack of literature with a focus on typical precipitation events that occur the most often and contribute the most precipitation and latent heating (Pendergrass and Deser, 2017). This is particularly true for India, where precipitation studies have been focused on the Indian Summer Monsoon Rainfall (ISMR), rather than the typical daily precipitation. By studying typical precipitation events, this research has implications for a more nuanced understanding of global precipitation patterns. Metrics such as rain amount peak and rain frequency peak that are utilized in this study provide insights into the most common and impactful events. In one such study, Pendergrass and Deser (2017) has proposed a few precipitation metrics to quantify the characteristics of daily rainfall by analysing the distributions of rain computed using the observational precipitation datasets. In this study, we adopt metrics two metrics from this paper, rain frequency peak and rain amount peak, which focuses on the global climatological characteristics of typical daily precipitation. Logarithmic bins are used in this study to ensure an even representation of data across a wide range of precipitation values, capturing extreme events and providing a mathematically sound approach for analysing daily rainfall distributions. Similar method of categorical bin is used by various studies such as Akinsanola A A *et al* (2020) ; Pendergrass & Deser (2017); and Pendergrass & Hartmann, (2014a). Here, we not only present quantitative values to answer the question asked at the very beginning "How much rain falls on a typical rainy day?" but also analyse the seasonal and spatial variation of these precipitation metrics for India. This study contributes to a comprehensive understanding of India's precipitation patterns, crucial for water resource management and climate studies. The identified rain frequency and amount peaks, along with seasonal variations, provide valuable insights into the dynamics of India's rainfall. Moreover, this study extends to make a comparison between these metrics and the rain distributions computed for multiple datasets.

The rest of this paper is arranged as follows. Section 2 discusses the methodology adopted and provides information on the observational datasets used for analysis. There is a detailed case study on the four metropolitan cities of India in Section 3 that illustrates the significance of the defined precipitation metrics in studying the typical daily precipitation characteristics. Section 3 presents the quantification of daily precipitation characteristics of India. In Section 4, the rain frequency distribution and the rain amount distribution computed for two different datasets, i.e. IMD and CHIRPS are compared and subjected to detailed analysis. Section 5 shows the climatological seasonal variation of rain distributions and the precipitation metrics along latitude and longitude studied in detail. Section 6 contains the precipitation metrics map for India that provides crucial insights into how the defined precipitation metrics vary in different regions of India. Section 7 concludes the report by summarising and providing other necessary information relevant to this study.

2. Datasets & Methodology

2.1 Observational Datasets:

Two gridded precipitation datasets, one national and another global, are utilized in this study. The first is the high-resolution (0.25° x 0.25°) daily gridded rainfall dataset prepared by the Indian Meteorological Department (IMD) covering mainland India (Pai et al., 2014). This long dataset covering the period of 1901-2018 has been generated using rainfall measurements from more than 7000 gauging stations and captures the spatial variability of rainfall across the country better than other gridded datasets due to the rapidly increasing spatial density of gauging stations. The station data has been converted to gridded data by spatially interpolating using the Inverse Distance Weighted scheme (IDW, Shepard, 1968). The IDW method, while a widely used interpolation method, exhibits limitations including sensitivity to sample density and the tendency to produce artifacts near domain edges, introducing potential inaccuracies in interpolated values which are further carried over to the IMD datasets.

The Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) dataset is a relatively new quasi-global rainfall product developed by the U.S. Geological Survey (USGS)/Climate Hazards Group science team. The latest CHIRPS Version 2.0 dataset (http://chg.geog.ucsb.edu/data/chirps/) with a spatial resolution of 0.05° × 0.05° was used in our study which incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series (1981-2020). A common period of 1981-2018 between the two datasets has been selected to study and compare the typical characteristics of daily precipitation.

2.2 Precipitation Metrics:

In order to relate the characteristics of daily precipitation to their contribution the mean and variability of rainfall throughout the country, we take recourse to metrics such as rain frequency peak and rain amount peak.

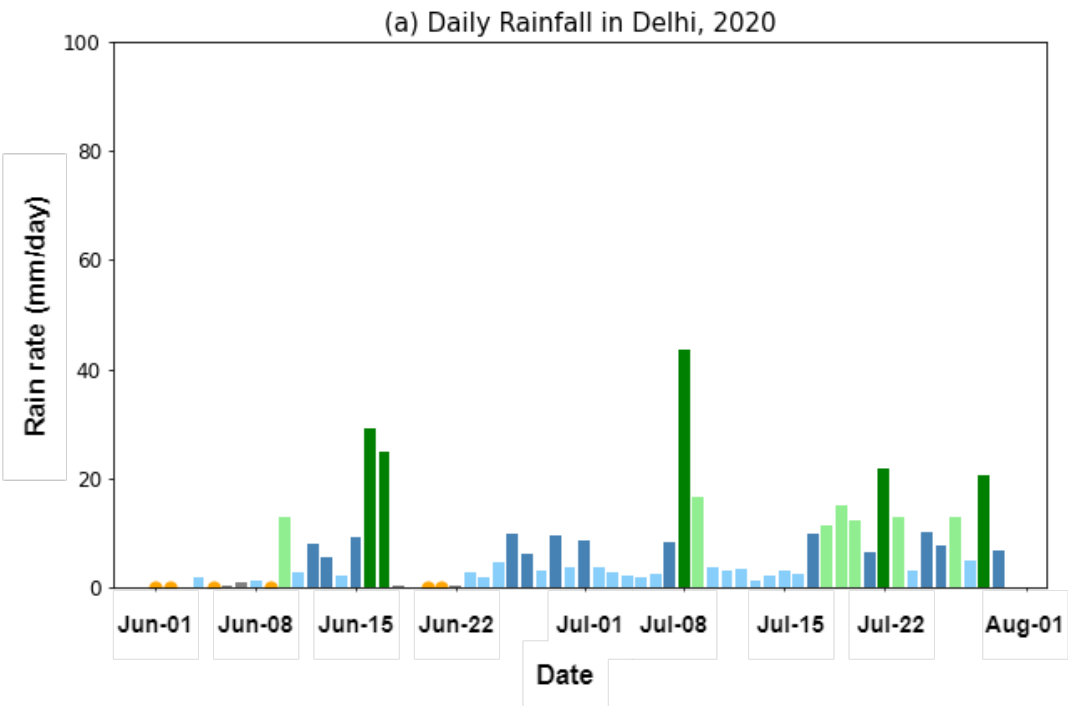
a) **Rain Frequency Peak:** This metric gives us the non-zero rain rate with the maximum frequency. We have identified the rain rate corresponding to the rain frequency peak by computing the frequency distribution of daily rainfall wherein frequency is presented in terms of the percentage of the total number of days. First, we create bins from 0.1 mm/day to 100 mm/day distributed logarithmically. Note that a day receiving rain rate less than 0.1 mm/day is counted as a dry day while rain rate greater than 100 mm/day is counted as an extremely wet day. Though we have calculated the percentage of dry days in this metric, we haven't calculated the frequency of extremely wet days regarding them to be extreme events and not crucial for our daily precipitation analysis. We will, however, present the calculations related to the extremely wet days in the next metric.

b) **Rain Amount Peak:** This metric gives us the rain rate at which the most rain falls. We have identified the rain rate corresponding to the rain amount peak by computing the distribution of the amount of precipitation contributed by any individual rain rate towards total precipitation. The amount is presented in terms of the percentage. Similar to the rain frequency peak metric, we created bins from 0.1 mm/day to 100 mm/day distributed logarithmically. Note that the rain rate less than 0.1mm/day is counted as dry days while the rain rate greater than 100mm/day is counted as extremely wet days. While we have calculated the percentage of precipitation contributed by extremely wet days in this metric, we haven't computed amount of precipitation for dry days since their contribution towards total precipitation is minimal compared to the contribution of other rain rates.

3. Illustration of Precipitation Characteristics over Metropolitan Cities

To illustrate how rainfall frequency and amount distribution describe precipitation characteristics, let's examine the rain frequency and rain amount distribution for the four metropolitan cities of India, i.e. Delhi, Mumbai, Kolkata, and Chennai (Fig. 1-4).

Let's consider the time series of daily precipitation in Delhi for the months of June and July of 2020 obtained from the IMD daily rainfall dataset. Note that throughout this report, daily precipitation accumulation is referred to by either "rain rate" following (Pendergrass and Hartmann, 2014a) or "intensity" following Stone et al. (2000). The time series of daily rainfall in Delhi is shown in Fig. 1(a). Days with no precipitation are indicated with orange circles on the abscissa, and this convention is followed in all other plots to display zero values. Days with non-zero precipitation are marked with vertical bars wherein bar length indicates rain rate, and all the bars are colour coded according to discrete rain-rate bins. This will help to visualise the rain frequency distribution (Fig. 1b) and rain amount distribution (Fig. 1c), both of which are also colour coded according to the rain rate bins. For Delhi, monsoon starts in late June and thus, over these two months, the total precipitation is 405 mm, which is equivalent to an average rain rate of 6.75 mm/day.



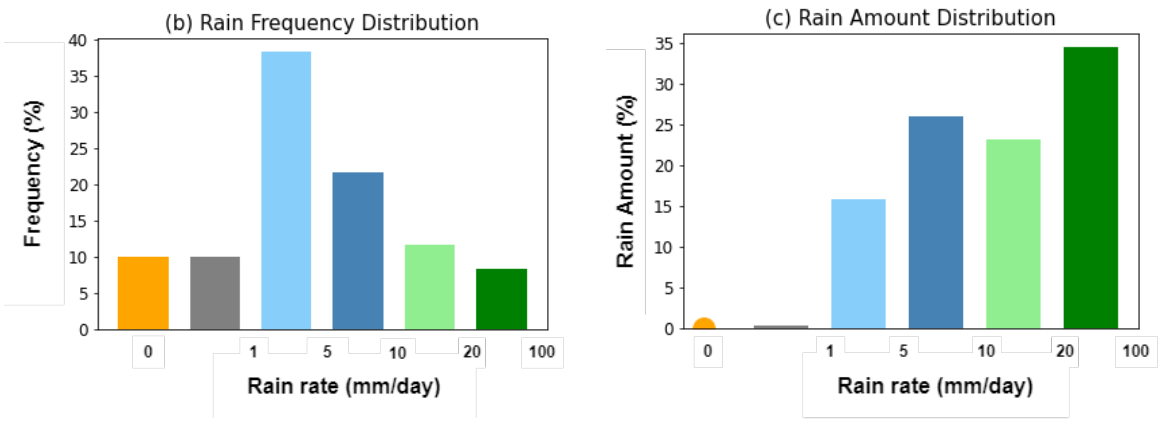


Fig. 1. Illustrative example of computing the rain frequency distribution and rain amount distribution. (a) Time series of daily rainfall during 1st June – 30th July, 2020 in Delhi, India. Daily precipitation accumulation in mm/day indicated by bars which are colour coded by rain rate (*Orange* for zero-valued rain rate, grey for non-zero valued rain rates < 1 mm/day, *sky blue* for values between 1 to 5 mm/day, *dark blue* for values between 5 to 10 mm/day, *light green* for values between 10 to 20 mm/day, and *dark green* for values > 20 mm/day). Circles on the x axis indicate zero value. (b) Rain frequency distribution and (c) Rain amount distribution (histograms are calculated from the example time series).

For quantifying how often rain falls at different rain rates the distribution of rain frequency (Fig. 1b) is constructed. The frequency of any logarithmically spaced rain rate bin is calculated as the percentage of the number of days in that bin to the total number of days in the time period. The sum of the rain frequency distribution is 100%. We find that the percentage of dry days is 13.3%, out of which 10% of days experience zero rain rate (orange) and 3.3% of days experience non-zero rain rate below 0.1 mm/day coming from the rain rate bin of 0 to 1 mm/day (grey) having a total frequency of 10%. Precipitation between rain rate 1 to 5 mm/day (sky blue) has the highest frequency of 38.3%, precipitation between rain rate 5 to 10 mm/day (dark blue) occurs on 21.7% of the total days, 11.7% of the rain happens between rain rate 10 to 20 mm/day (light green), and the rain falls between rain rate 20 to 100 mm/day (dark green) for the remaining 8.3% of the days.

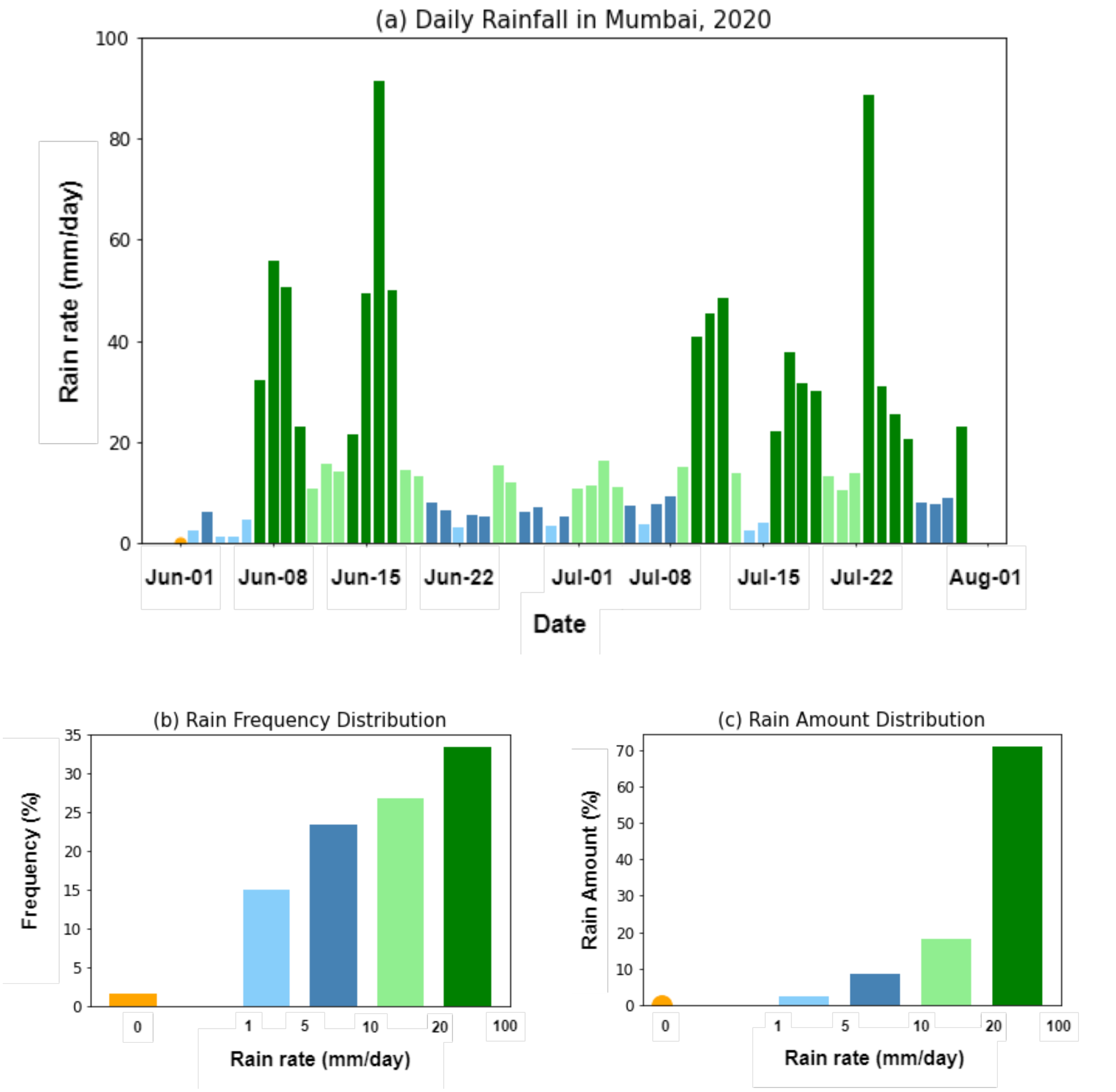


Fig. 2. (a) Time series of daily rainfall during 1st June – 30th July, 2020 in Mumbai, India. (b) Rain frequency distribution and (c) Rain amount distribution computed for Mumbai's rainfall time series.

For quantifying, how much rain falls at different rain rates the distribution of rain frequency as shown in Fig. 1(c). The rain amount for any logarithmically spaced rain rate bin is calculated as the sum of all the rain falling within that particular bin, represented by a bar in terms of percentage of the total precipitation for the complete time series. The sum of the rain amount distribution is also 100%. The bin with low rain rates, i.e. 0 to 1 mm/day (grey coloured bar) contributes only 0.4% of the total precipitation while, 1 to 5 mm/day (sky blue coloured bar) having the highest frequency, contribute only 15.8% of the total precipitation which is minimal. However, the moderate and heavy bins with rain rates between 5 to 10 mm/day (dark blue), 10 to 20 mm/day (light green) and 20 to 100 mm/day (dark green) containing only 21.7%, 11.7% and 8.3% of the total days respectively contribute around 26%, 23.2% and 34.5% of the total precipitation respectively. Note that it is the heaviest bin corresponding to the rain rates between 20 to 100 mm/day (dark green) with the highest contribution, i.e. 34.5% of the total rainfall even though it only has 8.3% of the days. This example demonstrates how rain amount distribution highlights the days with heavy rainfall, and these heavy precipitation days contribute disproportionately towards the total precipitation.

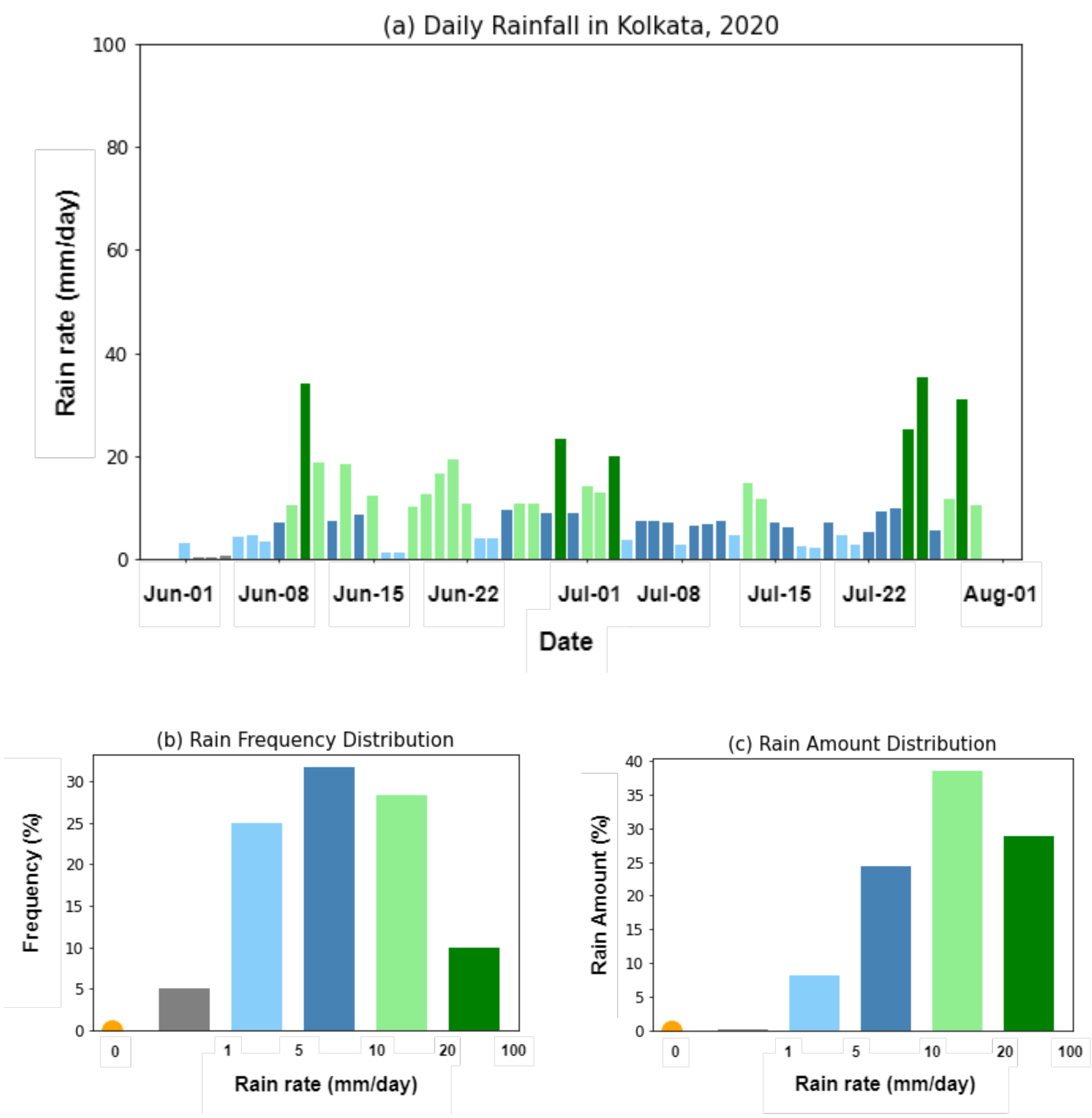


Fig. 3. (a) Time series of daily rainfall during 1st June – 30th July, 2020 in Kolkata, India. (b) Rain frequency distribution and (c) Rain amount distribution computed for Kolkata's rainfall time series.

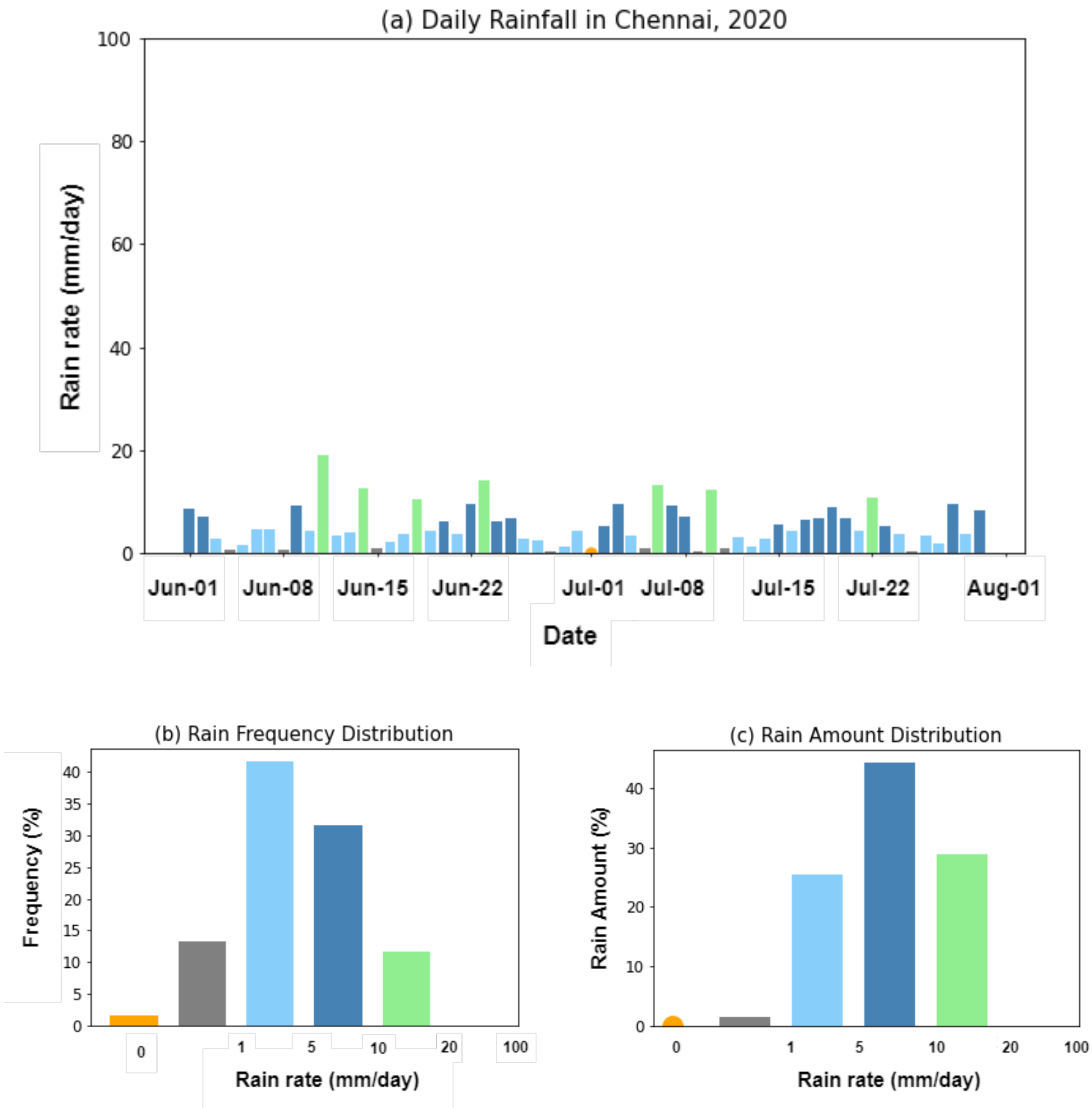


Fig. 4. (a) Time series of daily rainfall during 1st June – 30th July, 2020 in Chennai, India. (b) Rain frequency distribution and (c) Rain amount distribution computed for Chennai's rainfall time series.

For the given two-month period under consideration, the total precipitation of all four cities is 405 mm for Delhi, 1154 mm (highest amongst all four) for Mumbai, 586 mm for Kolkata, and 320 mm for Chennai. While the comparison of rain frequency distribution and rain amount distribution of these cities can notably help gain insight into their daily precipitation characteristics, let's keep our focus on just the rain frequency peak and rain amount peak (the two defined precipitation metrics) for this case study. The rain frequency peak for Delhi and Chennai lies in the rain rate bin of 1 to 5 mm/day, for Kolkata lies in the rain rate bin of 5 to

10 mm/day, while for Mumbai lies in the heaviest bin, i.e. 20 to 100 mm/day. The heavier the rain rate bin is, the more amount it contributes towards total precipitation. Since the rain frequency peak of Mumbai lies towards heavy rain rate it has the maximum total rainfall amount out of all four metro cities.

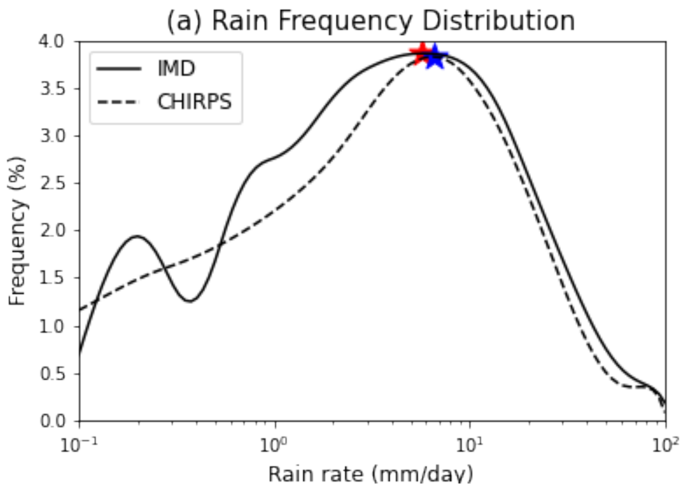
The rain amount peak for Delhi and Mumbai lies in the heaviest rain rate bin of 20 to 100 mm/day which is evident since these heavy precipitation days contribute disproportionately towards the total precipitation except for Kolkata and Chennai for which it lies in the rain rate bin of 10 to 20 mm/day and 5 to 10 mm/day respectively. The rainfall in Chennai's case is highly concentrated in the 5 to 10 mm/day rain rate bin, and the rain frequency of the heavier bins is also relatively low due to which the rain amount peak for Chennai lies in the moderate bin. Note that even though the percentage of dry days is just 1.67% for Chennai compared to 13.33% for Delhi's case, Delhi's total precipitation is more than that of Chennai. It is due to the fact that the frequency of days with heavy rain rate is higher for Delhi which is contributing much more towards Delhi's total precipitation as also corroborated by the higher rain amount percentage of the heaviest bin in case of Delhi.

While these distributions with the rain rates have significant importance, the rain rate at which we obtain the peaks for these distributions, i.e. the two defined metrics: rain frequency peak and rain amount peak are also highly substantial in studying the characteristics of daily precipitation in India.

4. Quantifying India's typical daily precipitation characteristics

In order to develop a more robust understanding of national trends, we present the distributions of rain frequency and rain amount for India using the IMD daily dataset, as shown in Fig. 5 illustrate how often rain falls and how heavy it is when it falls at different rain rates. To analyse the differences that can exist in the defined precipitation metrics when computed using different datasets, Fig. 5 shows a comparison plot for spatially averaged annual mean rain frequency distributions (Fig. 5a) and rain amount distributions (Fig. 5b) for IMD daily dataset and CHIRPS daily global dataset. Note that the CHIRPS dataset is sliced to only consider the Indian region, i.e. latitude from 6.5°N to 38.5°N & longitude from 66.5°E to 100°E, similar to the range that exists in the IMD dataset. Moreover, the resolution of CHIRPS dataset (grid size 0.05° × 0.05°) was scaled down to match with the resolution of IMD dataset (grid size 0.25° × 0.25°) for accurate comparison of the precipitation metrics between the two datasets. The two-precipitation metrics, i.e. the rain frequency peak and the rain amount peak are marked by a red star for IMD dataset and a blue star for CHIRPS dataset in Fig. 5.

The first metric shown in Fig. 5a is the rain frequency peak for India. It is defined as the non-zero rain rate having the maximum frequency as denoted by the percentage of the total number of days. In simple words, it is the most frequent rain rate greater than zero. The rain frequency distribution (Fig. 5a) for India attains peak rain rate of 5.7 mm/day in the IMD dataset (Fig. 5a) and 6.6 mm/day in the CHIRPS dataset (Fig. 5a), which will be referred to as the rain frequency peak. Overall, the rain frequency distribution (with rain rate bins on logarithmic scale) is negatively skewed as it falls off rapidly toward heavier rain rates than low rain rates. The percentage of dry days, i.e. days with rain rate less than 0.1 mm/day is 73.9% in case of CHIRPS, slightly greater than 71.5% for IMD dataset. Though the frequency for any rain rate for CHIRPS rainfall dataset is mostly lower than the frequency for IMD dataset which is also evident by somewhat larger percentage of dry days for CHIRPS, the rain frequency peak for CHIRPS occurs at a higher rain rate than IMD.



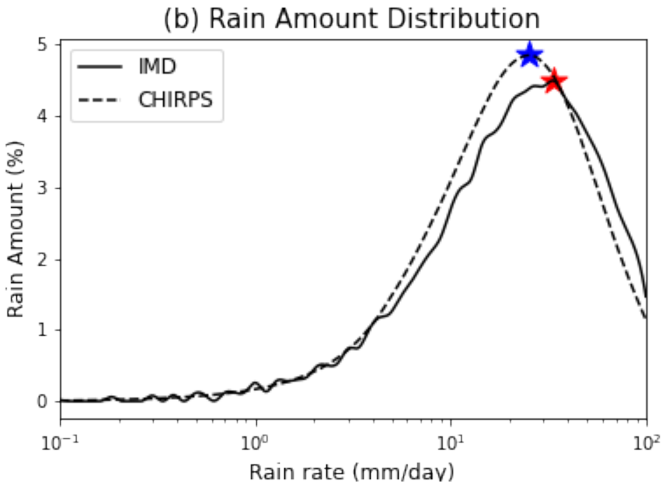


Fig. 5. Comparison between the climatological distribution of annual mean (a) rain frequency and (b) rain amount for India from IMD daily dataset (solid line) for the years 1979 – 2016 & from CHIRPS daily global dataset (dashed line) for the years 1981 – 2020. The red star denotes the rain frequency peak in (a) and the rain amount peak in (b) for IMD data. The blue star denotes the rain frequency peak in (a) and the rain amount peak in (b) for CHIRPS data.

The second metric is the rain amount peak which is defined as the rain rate that contributes to the maximum amount of rain towards total precipitation. The rain amount distribution (Fig. 5b) for India with rain rate bins on logarithmic scale is also negatively skewed with a longer tail at low rain rates than high rates and has relatively only one peak or maxima. The rain amount distribution curve for CHIRPS tracks the rain amount distribution curve for IMD for light rain rates, but then exceeds the IMD curve for moderate rain rates to finally dip below the IMD curve at heavy rain rates. It is because the total precipitation for the CHIRPS dataset is lower (CHIRPS also has a higher percentage of dry days than IMD) than the IMD dataset due to which the rain amount percentage is higher even if the frequency percentage is lower.

Though the rain amount percentage at moderate rain rates for CHIRPS rainfall dataset is higher than the percentage for IMD dataset, the rain amount peak for CHIRPS occurs at a lower rain rate than IMD, displaying the importance of heavy rain rates towards total precipitation. The rain amount peak for the CHIRPS global dataset is 25.4 mm/day (blue star in Fig. 5b) compared to the rain amount peak of 33.3 mm/day (red star in Fig. 5b) for IMD. It is necessary to remind that the values of these precipitation metrics, i.e. the rain frequency peak and the rain amount peak along with their distributions precipitation dataset used for analysis are influenced by the inherent uncertainties in these precipitation datasets. These precipitation metrics can significantly help in defining the typical daily precipitation characteristics in probably the most straightforward way possible, i.e. just by means of two numerical values. Although the accuracy of the precipitation metrics is determined by the bin width used for computations (smaller bins provide higher accuracy but require more sampling and thus more computational power), they don't depend on the bin width in a systematic manner.

5. Climatological distribution of rain in India

5.1 Seasonal variation of rain frequency distribution:

	Seasons	DJF	MAM	JJAS	OND	Annual
Latitude	**Maximum**	5.547	6.829	9.587	6.760	5.697
	Minimum	0.000	0.001	0.029	0.000	0.024
	Mean	0.959	1.721	4.053	1.410	2.310
Longitude	**Maximum**	4.169	11.400	15.121	3.270	8.816
	Minimum	0.000	0.000	0.194	0.000	0.080
	Mean	0.742	1.987	4.576	1.022	2.431

Table 1: Rain frequency across different seasons (denoted as DJF, MAM, JJAS, and OND), particularly when analysed along both latitudinal and longitudinal transects.

In order to highlight the spatial and temporal variability of rain frequency and amount, we decompose them along the latitudinal and longitudinal transects. To further highlight their seasonal variability, we look at the plots of summer monsoon (denoted as JJAS for June, July, August and September), pre-monsoon (denoted as MAM for March, April, and May), post-monsoon (denoted as OND for October, November and December), and winter (denoted by DJF for December, January, and February). Note that the majority of the rainfall in this country (80%) come from summer monsoon.

The rain frequency distribution of India is decomposed into contributions from different latitudes in Fig. 6a and longitudes in Fig. 6b to observe the variation of distribution with latitude and longitude. This variation of the rain frequency distribution is plotted for each season side by side to study the seasonal variation of typical rainfall characteristics of India as well. The rain rate is plotted on the x-axis on the log scale. Latitude or longitude is plotted on the y-axis, where latitude varies from 6.5°N to 38.5°N and longitude varies from 66.5°E to 100.0°E. The rain frequency distribution corresponding to any latitude or longitude is plotted using a colour bar (shown with the plot) with the frequency percentage at any rain rate defined by the colour's intensity.

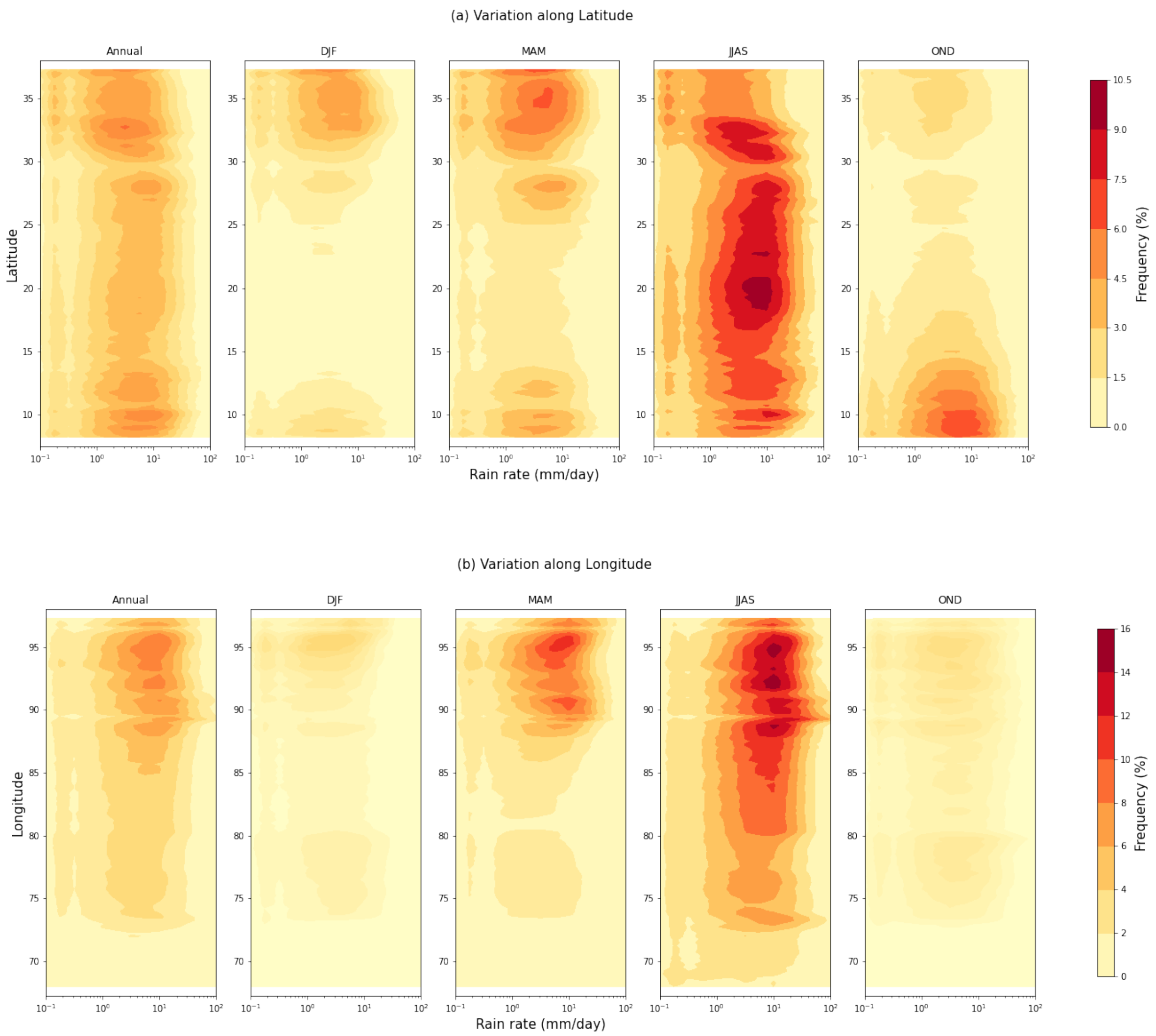


Fig. 6. Climatological zonal, annual-mean rain frequency distribution for India from IMD daily dataset for the years 1979 – 2016 and also stratified by seasons. (a) Seasonal variation with latitude and (b) Seasonal variation with longitude. (DJF is December, January and February, MAM is March,

April and May, JJAS is June, July, August and September, and OND is October, November and December)

The preliminary observation that can be made from the plots in Fig. 6a is that the frequency percentage is highest (evident by the high intensity of the colour) in case of JJAS, which is quite apparent as these months belong to the rainy season in India. For the DJF plot corresponding to the winter season in India, the frequency is relatively low except for higher latitudes. This can be accounted to the snow that falls in the northern Himalayan region during the winter season, and this snowfall even continues till pre-monsoon (or summer) season of MAM. The frequency starts decreasing during the post-monsoon (or autumn) season of OND in most parts of India except for lower latitudes. This can be due to the retreating monsoon winds that create extreme weather conditions characterised by high humidity resulting in rainfall and cyclones in the coastal regions. Since India's maximum part at very low latitude (around 10°N) is a coastal area, this leads to high rain frequency percentage for these latitudes.

There is a break observed between the contours at around 30°N latitude for each rain frequency distribution plot in Fig. 6a which can be an indicator of the change of the contributing area from plains dominant region to mountains (Himalayas) dominant region. It should be noted that while the frequency percentage varies significantly throughout India with latitude, the rain frequency peak is relatively similar during the winter and summer monsoon seasons. However, there is a sudden increase in the rain frequency peak during the monsoon and autumn seasons for latitudes between 30°N to 40°N that mainly comprises the Indian plains. It is quite evident that these plain regions receive high rainfall during the monsoon and post-monsoon season while relatively low rain during the summer season due to the prevailing high temperatures. Though the plains receive heavy rainfall during JJAS and OND, the relatively low precipitation during the DJF and MAM counter that high rainfall, reducing the yearly mean frequency and rain frequency peak. Hence, India's annual mean rain frequency distribution plot is relatively uniform both in terms of rain frequency peak and the corresponding frequency percentage.

Similar to the variation of rain frequency distribution with latitude in Fig. 6a, the frequency percentage is highest in case of JJAS for the variation of rain frequency distribution with longitude as shown in Fig. 6b, which is evident as these months belong to the rainy season in India. When dividing India in longitudinal stripes, most of these stripes in the eastern part of India cover significantly less area. Thus, they are highly personalised to specific locations even if the rain frequency distribution is averaged over the region. Due to this, the frequency percentage is very high at eastern longitudes of India (90°E - 95°E) since the rain frequency distribution is mainly determined by the regions like Meghalaya that receive heavy rainfall, home to the area receiving the highest world's highest average annual precipitation of more than 11,000 mm. It is also because of this reason that the maximum frequency percentage is higher when averaged along longitude than in the case of averaged along latitude.

5.2 Seasonal variation of rain amount distribution:

	Seasons	**DJF**	**MAM**	**JJAS**	**OND**	**Annual**
Latitude	**Maximum**	6.240	6.209	5.835	6.078	5.278
	Minimum	0.000	0.000	0.000	0.000	0.000
	Mean	1.582	1.578	1.510	1.549	1.525
Longitude	**Maximum**	24.453	19.278	6.248	16.1722	5.965
	Minimum	0.000	0.000	0.000	0.000	0.000
	Mean	1.607	1.514	1.466	1.519	1.480

Table 2: Rain amount across different seasons (denoted as DJF, MAM, JJAS, and OND), particularly when analysed along both latitudinal and longitudinal transects.

Similarly, the rain amount distribution is only plotted for the rain rates from 1 to 100 mm/day and while the rain amount distribution for the rain rates from 0.1 to 1 mm/day is cut off from these plots. It is done based on the observation made in Fig. 5b where it is evident that the rain amount percentage is significantly low for the rain rates of 0.1 to 1 mm/day and not crucial for our study.

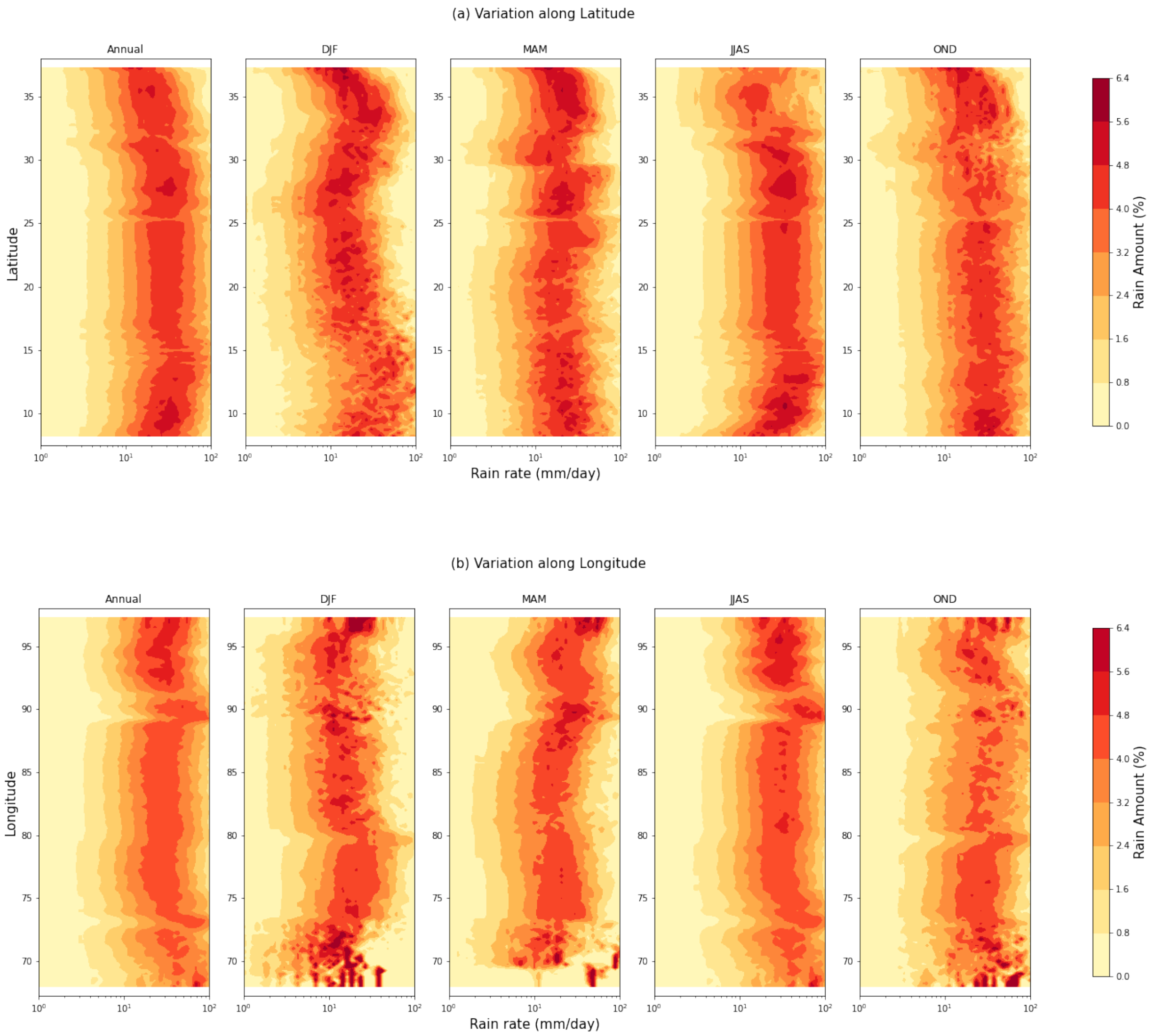


Fig. 7. Climatological zonal, annual-mean rain amount distribution for India from IMD daily dataset for the years 1979 – 2016 and also stratified by seasons. (a) Seasonal variation with latitude and (b) Seasonal variation with longitude. (DJF is December, January and February, MAM is March, April and May, JJAS is June, July, August and September, and OND is October, November and December)

It can be observed that the rain amount distribution is dominated by the heavy rain rates in the plots for JJAS and OND, indicating a high amount of total precipitation which is apparent as these months belong to the monsoon and post-monsoon seasons in India. The plots for MAM and OND show a similar rain amount distribution and rain amount peak for all latitudes throughout India during the summer and autumn seasons with a slight variation at around 30°N. The annual rain amount peak at around 8°N is relatively low during the monsoon season, i.e. in JJAS plot but still has high rain amount percentage. This indicates that the total amount of precipitation for this region is lower than other latitudes which is also evident by the comparatively lower frequency of rainfall observed in the rain frequency distribution plot of JJAS in Fig. 6a. The annual mean plot for the rain amount distribution, however, is quite uniform but has relatively lower rain amount peak at very low and very high latitudes. The high latitudes belong to the Himalayan region while the low latitudes observed in the JJAS plot receive relatively lower total precipitation, and thus, the rain amount peak is lower.

Similar to the variation of rain amount distribution with latitude in Fig. 7a, the rain amount peak is higher in case of JJAS and OND for the variation of rain amount distribution with longitude as shown in Fig. 7b, which is evident as these months belong to the monsoon and post-monsoon season in India. As explained earlier, when looking at India longitudinally, most of these stripes in the eastern part of India cover significantly less area. Thus, they are highly personalised to specific locations even if the rain amount distribution is averaged over the region. It is also because of this reason that the rain amount peak is relatively higher in the annual mean plot of rain amount distribution along the longitude as well.

Similarly, the rain amount peak is also high for very low longitude. These longitudinal stripes belong to the western regions of Gujrat, which has a lower frequency of rainfall as observed in the rain frequency distribution plots (Fig. 6b). As most of the rain in this region falls at lighter rain rates, the heavy rain rate even having low frequency can still result in high rain amount peak since heavy rain rates contribute disproportionately towards total precipitation. Overall, the annual mean rain amount distribution plot for India is relatively similar along the longitudes, except for some minor spikes at around 90°E, 72°E and very low longitudes. The reason for this significant spike at very low longitudes and 90°E has already been described. The increase in rain amount peak at around 72°E is because a larger area of these longitudinal stripes belongs to India's west coastal region, which receives high amounts of heavy rainfall.

6. Maps of climatological annual mean precipitation metrics

6.1 Rain frequency peak:

To illustrate how the rain frequency peak metric varies throughout India, the rain frequency peak corresponding to each pair of latitude and longitude for India is plotted in Fig. 8. This plot is prepared using the IMD daily dataset with the latitude and longitude varying from 6.5°N to 38.5°N and 66.5°E to 100°E respectively. Note that the rain rate in terms of mm/day corresponding to the rain frequency peak metric is represented using a colour bar shown on the right side of Fig. 8.

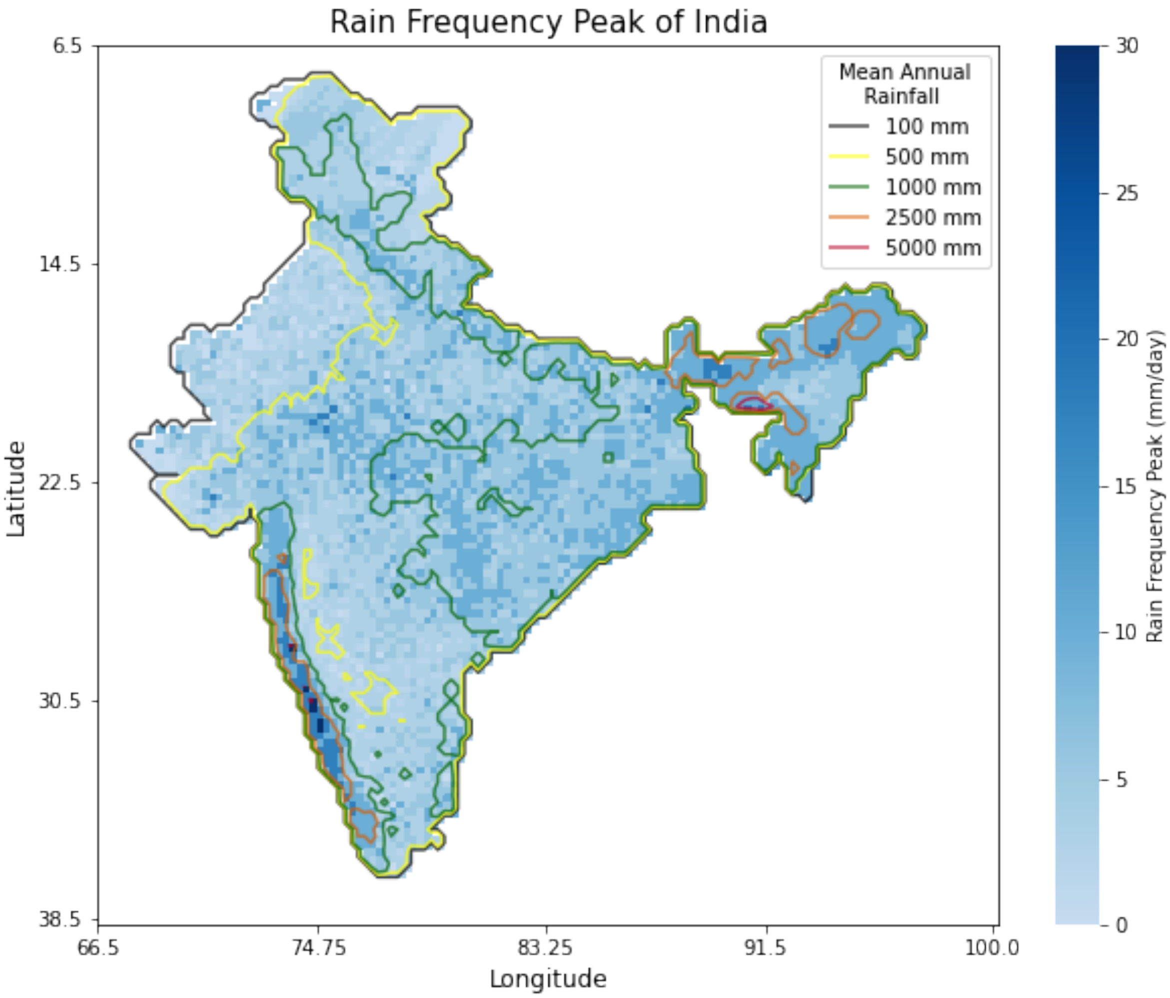


Fig. 8. Map of climatological annual mean rain frequency peak for India from IMD daily dataset for the years 1979 – 2016. (Rain frequency peak is represented in terms of mm/day, defined by the colour map on the right)

The western coast and the eastern parts of India, however, have higher values of rain frequency peak, especially the western coast. The rainfall in India's western coast is frequent due to the presence of the Western Ghats that result in higher rainfall because of the prevailing rain-bearing winds. The eastern parts of India also receive rain frequently, which was also observed in the plots for rain frequency distribution variation with the longitude (Fig. 6b). It must be remembered that this plot shows the most frequent non-zero rain rate throughout India. The maximum rain frequency peak for any region in India reaches up to a value of 35 mm/day compared to 5.7 mm/day rain rate for annual mean rain frequency peak averaged spatially throughout India.

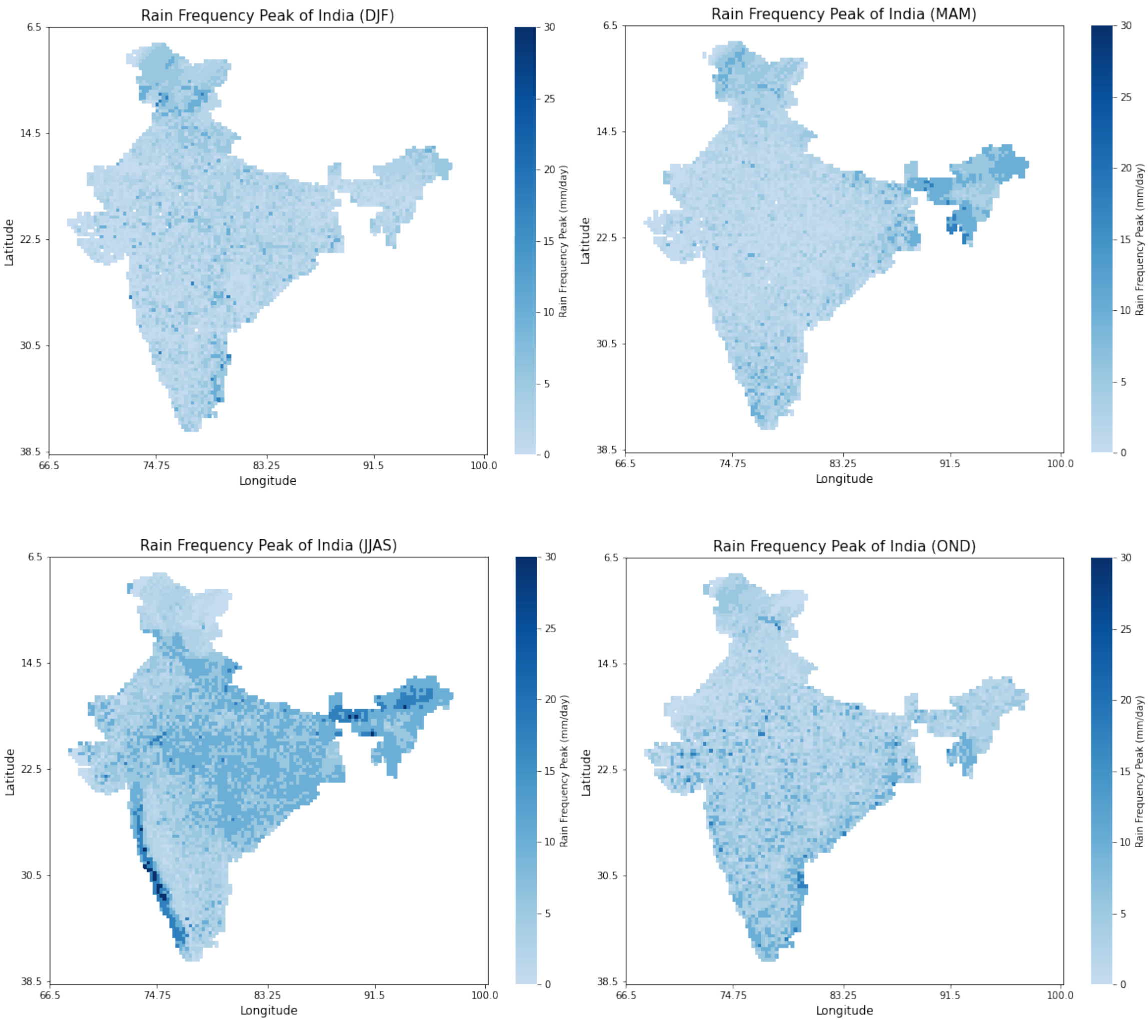


Fig. 9. Climatological zonal rain frequency peak for India from IMD daily dataset for the years 1979 – 2016 stratified by seasons. (DJF is December, January and February, MAM is March, April and May, JJAS is June, July, August and September, and OND is October, November and December)

6.2 Rain amount peak:

To illustrate how the rain amount peak metric varies throughout India, the rain amount peak corresponding to each pair of latitude and longitude for India is plotted in Fig. 10. This plot is prepared using the IMD daily dataset with the latitude and longitude varying from 6.5°N to 38.5°N and 66.5°E to 100°E respectively. The points lying outside India's boundary are not crucial for our study and hence not present in the figure. Note that the rain rate in terms of mm/day corresponding to the rain amount peak metric is represented using a colour bar shown on the right side of Fig. 10.

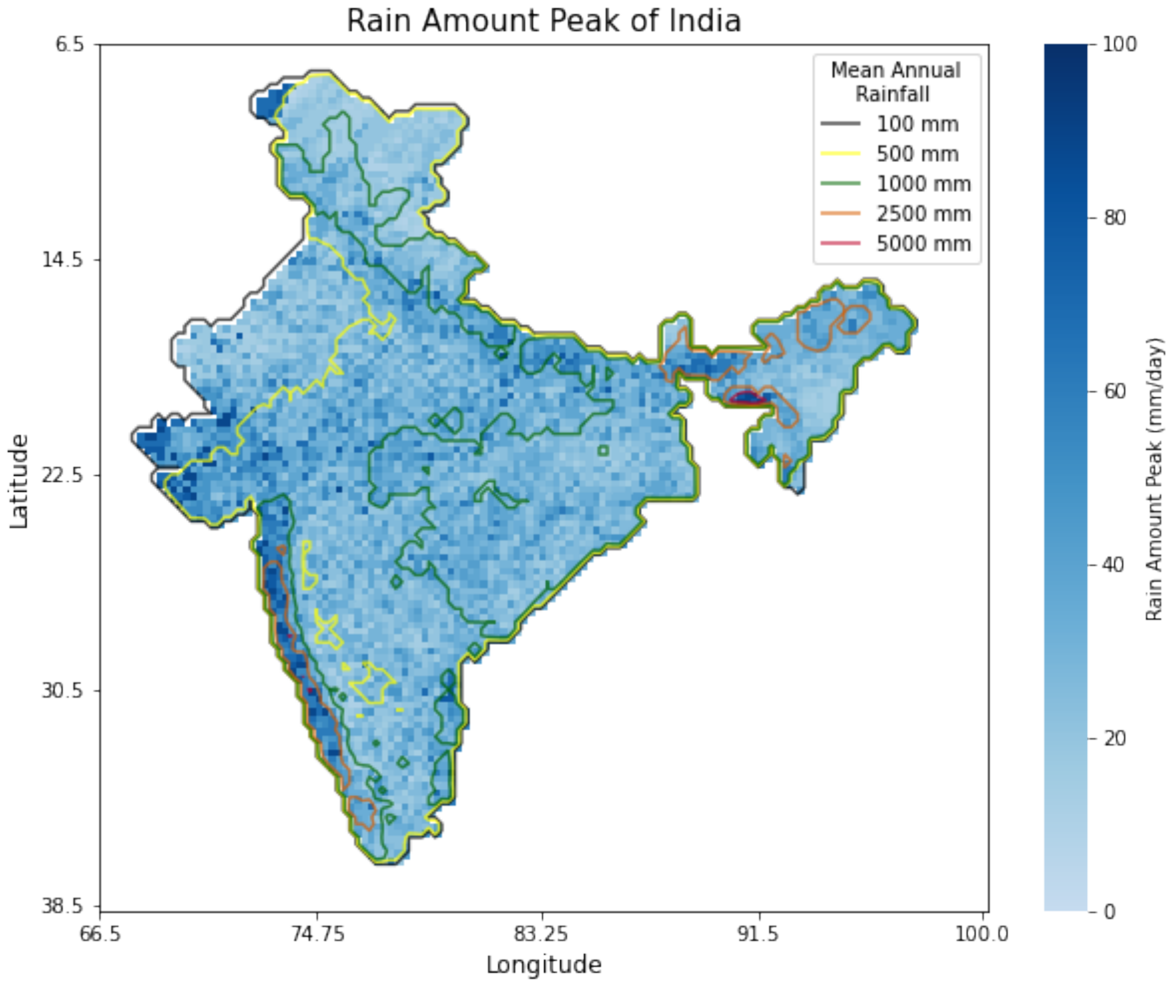


Fig. 10. Map of climatological annual mean rain amount peak for India from IMD daily dataset for the years 1979 – 2016. (Rain amount peak is represented in terms of mm/day, defined by the colour map on the right)

The western coast of India, as expected, has high rain amount peak compared to other regions of India. Meghalaya has the maximum rain amount peak, which is evident due to the fact that it experiences a high amount of rainfall at heavy rain rates from the south-west monsoon winds. It is quite intriguing to notice that while the rain frequency peak in the north-eastern part of Jammu & Kashmir is quite low, it has a significantly high rain amount peak. Similarly, the western parts of Gujrat also have high rain amount peak but a very low value of rain frequency peak. This is because of the high contribution of heavy rain rates towards total precipitation compared to very light rain rates resulting in an increased value of rain amount peak for specific regions. The state of Rajasthan, which receives very low rainfall throughout the year has both low rain frequency peak and low rain amount peak, which is apparent because of the existence of Thar desert. The maximum rain amount peak for any region in India reaches up to a value as high as 90 mm/day compared to 33.6 mm/day rain rate for annual mean rain amount peak averaged spatially throughout India.

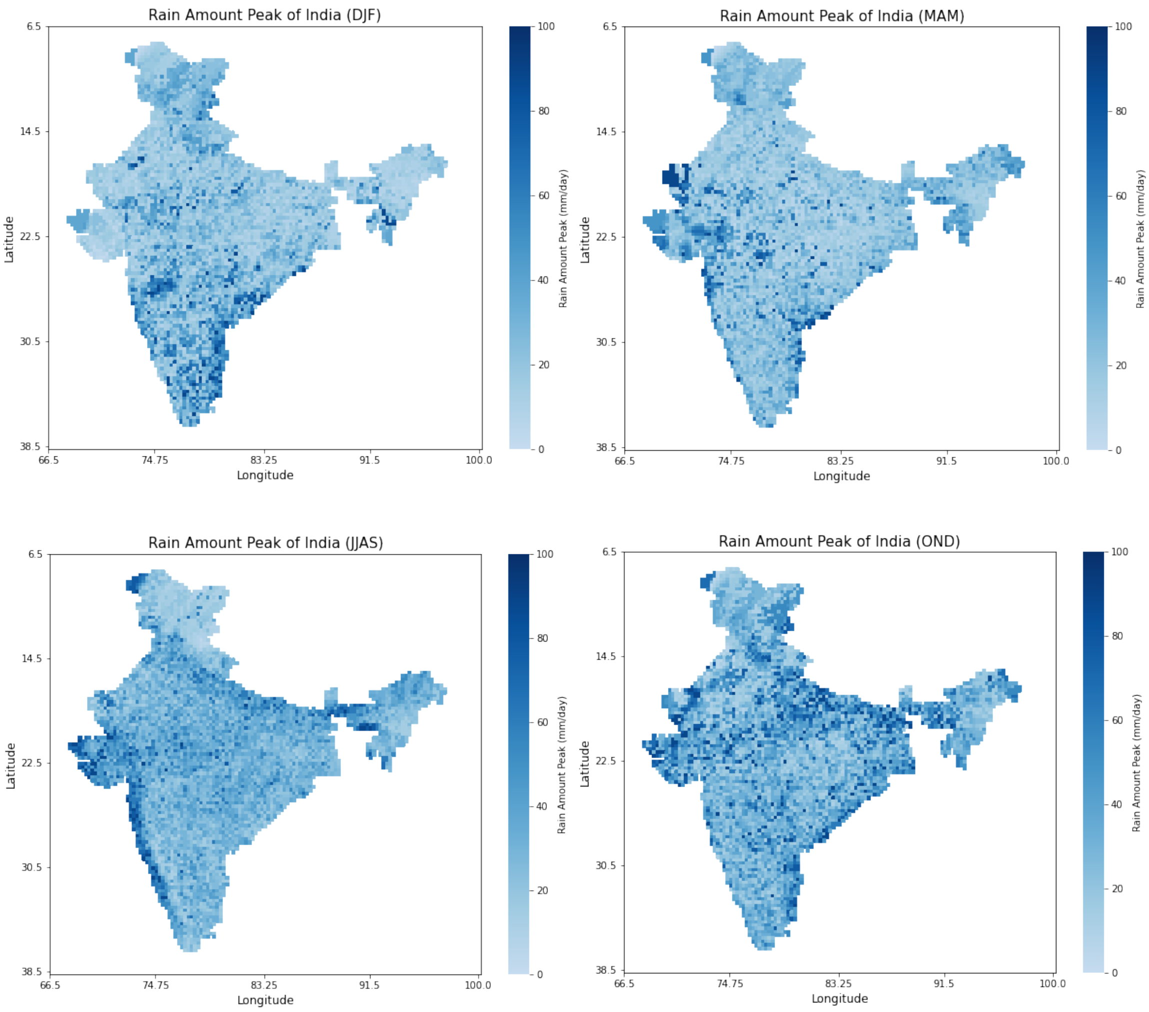


Fig. 11. Climatological zonal rain amount peak for India from IMD daily dataset for the years 1979 – 2016 stratified by seasons. (DJF is December, January and February, MAM is March, April and May, JJAS is June, July, August and September, and OND is October, November and December)

7. Conclusions

Our study underscores the usefulness of two precipitation metrics, namely the rain frequency peak (indicating the most frequent nonzero rain rate) and the rain amount peak (representing the rain rate where the most rain falls), in characterizing the typical daily precipitation of a region. The analysis of two distinct datasets, IMD and CHIRPS, has provided valuable insights into the quantitative variations of these metrics, highlighting the complex nature of precipitation patterns.

A key observation from our comparative analysis is that while there are quantitative variations in the rain frequency and amount metrics between the IMD and CHIRPS datasets, the qualitative trends remain consistent. This implies a degree of robustness in these precipitation metrics, emphasizing their utility across different observational datasets. Regionally, India exhibits distinct patterns in rain frequency and amount distributions. The western coast and eastern regions, influenced by geographical features such as the Western Ghats and prevailing rain-bearing winds, stand out with higher rain frequency peaks. Conversely, the western coast and Meghalaya dominate in terms of rain amount peaks, showcasing the influence of monsoons. Notably, Jammu & Kashmir's northeast demonstrates regional differences, with a low rain frequency peak but a significantly high rain amount peak, highlighting the complex composition of precipitation.

The rain amount distribution concentrates on the larger part of the total rainfall, thus making it a simple and conservative target since it is relatively easy to record them for models and somewhat hard to miss them from observations. Hence, more emphasis should be given to rain amount distribution than rain frequency distribution when analysing the typical precipitation characteristics. Studying the typical rainfall characteristics rather than just extreme rain events that quite often lead to floods is significantly essential for many reasons. Such a case is of the farmers for whom it does not matter how heavy rain can fall on a single random day but knowing how often it rains is crucial for them. It would be a worthy endeavour to enhance the state of our knowledge of the absolute magnitude of the total precipitation and the frequency distribution of rain.

In summary, our study contributes to advancing the discourse on precipitation metrics, regional variations, and the need for a nuanced understanding of typical rainfall patterns, addressing critical gaps in our current knowledge and paving the way for informed decision-making in agriculture, water resource management, and climate studies.

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Data Availability Standards

- CHIRPS precipitation data (https://www.chc.ucsb.edu/data/chirps)
- IMD precipitation data (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html) are freely available online.

Compliance with Ethical Standards:

The authors declare that they have no conflict of interest.

Author Contributions:

- MS conceived and designed the analysis.
- YG performed the analysis.
- YG, MS, and BG wrote the paper.

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