The relationship between central Indian terrestrial vegetation and monsoon rainfall distributions in different hydroclimatic extreme years using time-series satellite data

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Abstract

The study explored the dependence of the Spatio-temporal pattern of rainfall and its variability on the spatial distribution of forests in Central Indian Landscape, which covers ~1Million Km^2, includes five states, and supports a population of 329 million people. The monsoon rainfall is, thus, a crucial source of freshwater for these population. We analyzed the relationship between rainfall and satellite-derived vegetation vigour, vegetation fraction, and elevation across 22 experimental zones across central India (i.e., forested, non-forested, and agricultural regions; buffer zones within and outside forests). Around 87% of annual rainfall is received during monsoon, with maximum rainfall (~1600 mm) in Odisha and minimum (~900 mm) in Maharashtra. The average rainfall was greater (~1500 mm) inside forests than in non-forested regions (~1000 mm). Moreover, 245 mm km^{-2} yr^{-1} of rainfall observed over forests during monsoon, but only 215 mm km^{-2} yr^{-1} in non-forested areas. Overall, rainfall increases from forest edge towards forest core logarithmically at a rate of ~10 mm km^{-1} yr^{-1}, and it decreases exponentially when moving away from forest edge at an average rate of -20 mm km^{-1} yr^{-1} over 0-to-50 km range, and at a rate of -7.5 mm km^{-1} yr^{-1} over 50-to-100 km range. This rate of decrease was maximum in Madhya Pradesh and Jharkhand and minimum in Chhattisgarh. The results confirmed a crucial role of forests in the distribution of monsoon rainfall, but in the elevated and Western-Ghats regions orographic effect is dominant. These findings are of great concern to forest policymakers to conserve and protect the central Indian forests.

Keywords: Tropical forest, Central India, Rainfall variability, Western-Ghats, MODIS, CHIRPS.

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1. Introduction

Global warming may increase the average annual temperature in India from 1.33 °C to 4.44 °C by the end of the 21st century (Sanjay and Revadekar, 2020). This is likely to be associated with decreasing water availability and recurring droughts. During the nineteenth and twentieth centuries, India experienced seven major droughts (1876–1882, 1895–1900, 1908–1924, 1937–1945, 1982–1990, 1997–2004, and 2011–2015), and several were linked with famines that caused millions of deaths (Mishra et al. 2019). Although the Vegetation of the central Indian landscape plays a significant role in regulating the climate of the Indian sub-continent, global warming-induced changes in the local climate may affect the central Indian forests and, thereby, disrupt this regulation (Sukumar et al. 2016; Roxy et al. 2017). Additionally, central India is under high anthropogenic pressure as millions of people depend on forests for their livelihoods, fuel, biomass, medicines, forest products and other ecological services (Saxena 2003; SFR 2017; Singh et al. 2020). Thus, an increasing human population is already threatening India's tropical Vegetation through deforestation and livelihood impacts, putting this crucial climate regulatory mechanism at further risk (Chaturvedi et al. 2010; Zhu et al. 2016; Mishra et al. 2016).

Rai and Dimri (2019) studied the long-term trends in, and the seasonality of, rainfall in India and revealed an increasing trend in central India during 1971-2015. However, Sanikhani et al. (2018) observed a decreasing monsoon rainfall trend over Madhya Pradesh and Chhattisgarh based on ground observations from 1901 to 2010, with an increasing trend observed only in the post-monsoon months (i.e. November and December). In view of global warming and the increasing likelihood of extreme rainfall events (Roxy et al. 2017) and forest fires, as well as population growth, preserving the status and health of India's tropical Vegetation is vital for its own services and, indirectly, for its regulatory services in sustaining rainfall at a regional scale in the central Indian sub-continent. The projected changes in climate including high drought frequency, coupled with deforestation and forest degradation, are expected to affect greatly the livelihoods of central India's large population (Chaturvedi et al. 2010; Mohanty 2020). Hence, exploring the links between forests and rainfall at the regional level is essential. Since the central Indian forest is fragmented, with large and small patches of intact forests, the precise role of this forest in regulating rainfall patterns and water availability are poorly understood. Therefore, greater understanding of the influence of the central Indian forests on rainfall distribution at this regional scale is needed.

The hydrological system is regulated by air, land temperature, and precipitation variation across different areas, and these together affect the ecological processes of natural Vegetation (Andreae et al. 2004; Griffin and Prager 2017) which, in turn, alter atmospheric feedback mechanisms and affect the occurrence of climatic events (Sheil 2018). It is still unclear whether forests are net users or producers in the water cycle (Ellison et al. 2017;

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Bennett and Barton 2018). Marsh (1864) believed forests to be great water producing "biotic pumps", but not a factor influencing climatic patterns and atmospheric circulation at a larger scale. Makarieva and Gorshkov (2007) reinforced the biotic pump theory and explained the physics behind the underlying processes in detail. In simple terms, massive areas of forest, like the Amazon and Congo, attract rain by sucking moist air from the oceans to interior parts of continents located hundreds of kilometres away. However, the biotic pump hypothesis remains controversial (Meestres et al. 2009). Also, meteorologists believe that rainfall regimes, their distribution and shifts across the globe can be better understood by meteorological parameters and rainfall variation than through changes in the forest-induced atmospheric water cycle. Although research has provided various explanations, none can satisfactorily model the relationship between Vegetation and climate at the global scale (Sheil 2018).

Rainfall is a natural phenomenon, and its occurrence and spatial distribution depends on multiple atmospheric and biospheric factors (Morales 1977). Although climatologists tried to address this issue with general circulation models (GCMs), no climatic models explain the influence of forests on cloud formations and moisture convection (Stevens and Bony 2013). Most climatic models have a coarse spatial resolution leading to large uncertainties (Svoboda et al. 2014) in predicting regional rainfall and microclimatic variation (Stevens and Bony 2013; Sheil 2018; Maclean 2020). Hence, it is vital to understand rainfall regimes at watershed-to-basin levels in the forested regions of the world (Kurtzman et al. 2009). Regional topography, land use and land cover (LULC), and local climatic variability are potentially important for the characterization of spatial rainfall patterns and hydrological processes at multiple spatial scales (Meestres et al. 2009; Sanchez-Moreno et al. 2013; Putnam and Broecker 2017; Spracklen et al. 2018).

Historically the world's tropical forests have reduced from 12% to 5% of the Earth's surface area due to deforestation. Four hundred twenty million hectares of forest area was lost since 1990, with an average net loss of 4.7 M ha yr^{-1} during 2010 to 2020, to make way for agricultural land and in response to the demand for food and wood (FAO 2020; Hansen et al. 2013; Brandon 2014; Spracklen et al. 2018). However, Tian et al. (2014) reported a significant loss of forests from 89 million ha to 63 million ha from 1880 to 2010, and these forest loss must have affected India's climate feedback loop (Devaraju et al., 2015; Paul et al., 2016, 2018; Masroor et al., 2020; Haughan et al. 2022). Similarly, in Amazon, the impact of deforestation can be seen clearly through a reduction in rainfall and recurring patterns of drought (Li et al. 2008; Anderson et al. 2010; Atkinson et al. 2011; Spracklen and Garcia-Carreras 2015; Staal et al. 2020b).

Ground-based rainfall networks are important for evaluating the link between forests and rainfall, but such networks are distributed unevenly across the globe. Advances in remote sensing such as the provision of satellite-

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based continuous rainfall data have filled this gap and provided the opportunity to study the interdependence between forests and rainfall distributions regionally and globally (Sykes 2009; Meng et al. 2014; Gebremicael et al. 2019). For example, remote sensing satellite-based rainfall and vegetation indices have been used to characterize and model vegetation vigour and its variability, forest degradation, and climatic changes (Paruelo et al. 2001; Bonan 2008; Krishnaswamy et al. 2013; Zhang et al. 2015; Gao et al. 2018; Singh et al. 2021).

Here, we investigate the dependence of the spatio-temporal distribution of rainfall on the spatial distribution of forests in the central Indian forested landscape. Specifically, in a natural experiment we explored and compared quantitatively the spatio-temporal variability in rainfall within (i) forested, (ii) adjacent non-forested and (iii) agricultural regions. Further, the aim was to measure the rate of change in rainfall in the presence and absence of forests across different buffer zones, and the variability in rainfall in different elevation and density classes inside and outside forests. We used CHIRPS monthly rainfall data, MODIS normalised difference vegetation index (NDVI), vegetation continuous field (VCF) and ASTER elevation data to examine the inter-annual and monthly variability in rainfall in the different strata. We selected the central Indian tropical forested landscape spreading over five states of India as the study site.

2. Materials and Methods

2.1 Study area

Central India is a complex tropical forested landscape spread over five Indian states (Maharashtra (MH), Madhya Pradesh (MP), Chhattisgarh (CH), Odisha (OD) and Jharkhand (JH)) covering a total area of 9,86,580 km^2, extending between 15°- 26° N and 72° - 88° E (**Fig. 1a**). It contributes 2,93,273 km^2 of the total Indian forested area (i.e. 8,09,537 km^2), including human-dominant agricultural systems (SFR 2021). It has a series of protected forest patches conserved as wildlife sanctuaries (108 nos.), national parks (22 nos.), tiger reserves (17 nos.), elephant reserves (8 nos.) and undisturbed core forest areas that regulate the ecological balance by preserving biodiversity and the regional climate (Sharma et al. 2013; Singh et al. 2020). During the monsoon (June to September), the region receives more than 80% of its annual rainfall (Roxy et al. 2017). The Western Ghats and the Eastern Ghats are two mountain ranges located along the west and east coast of India. Central India refers to the Deccan plateau region which lies between these two mountain ranges. (Please see **figure S15** for elevation variation over the study area) The average maximum temperature rises to 42 °C during the summer, and the minimum temperature reaches 10 °C in winter (Duhan et al. 2013). Vast stretches of this tropical deciduous forest form the catchments of several central highland rivers, which provide irrigation and drinking water in the region

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(Krishnaswamy et al. 2013) and shelter for numerous flora and fauna, including the protected, but endangered tigers (Sharma et al. 2013).

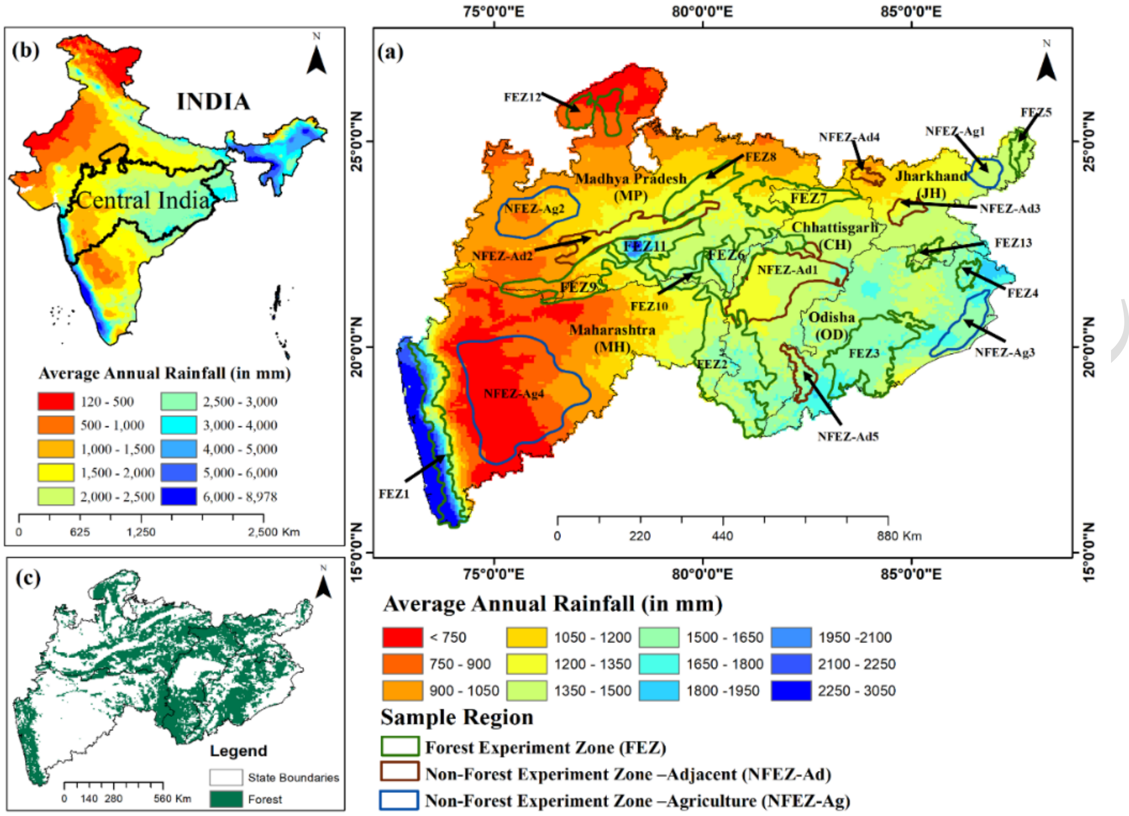

Figure 1. (a) Study area showing different experimental zones overlaid on a map of average annual rainfall (based on 2001-2018 data), (b) study area extent within India, overlaid on a map of average annual rainfall (based on 2001-2018 data) and (c) forest mask.

The region is also marked by the presence of Tendu (*Diospyros melanoxylon*) leaf collected for Bidi (cigarette) making and non-timber forest products (*Madhuca indica*), which provide income to millions of local people (Hunter 1981; Saxena 2003; Mahadule and Vimmy 2011; Singh et al. 2020). The climate change-induced erratic and recurring rainfall deficit is likely to affect the agricultural and forest productivity of the region, and people's livelihoods. Bundelkhand in Madhya Pradesh, Palamu in Jharkhand, Marathwada, and Vidarbha in Maharashtra are drought-prone regions in the central Indian landscape (Singh and Jeganathan 2016; Singh et al. 2019). Five major types of forest exist in India, with the largest land surface area (~68.5% of total forest cover) occupied by tropical forests (Champion and Seth 1968). Within the tropical forest, tropical dry deciduous (~38%) and tropical moist deciduous (~30%) forests cover the largest part, especially spreading across central India (Jeganathan and Nishant 2014), and they play a significant role in regulating the climate of the Indian subcontinent. India's contribution to carbon sequestration is enormous: natural forests sequester about 145.6

million tonnes-equivalent of CO_2 annually (SFR 2021), acting as a carbon sink and, hence, providing a potential carbon credit under the Kyoto Protocol in the international market (SFR 1995).

2.2 Data

2.2.1. Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data

The most comprehensive archive of gridded rainfall data at a spatial resolution of 0.05° (~5 km) and at a quasi-global level since 1981 is provided by the Climate Hazards Group Infra-Red Precipitation with Station (CHIRPS) data (Funk et al. 2015). The monthly precipitation dataset (CHIRPS version 2.0) from 2001 to 2018 was used in this research (downloaded from ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRP/month-ly/). The CHIRPS data utilizes satellite-derived precipitation estimates and *in situ* gauge station data to create gridded rainfall time-series (Funk et al. 2015). CHIRPS data were used by many researchers across the globe (Duan et al. 2016; Aadhar and Mishra 2017; Dinku et al. 2018; Gao et al. 2018; Saeidizand et al. 2018; Singh et al. 2020). Aadhar and Mishra (2017) observed varying levels of bias in the CHIRPS rainfall data including under-estimation in the Western Ghats and over-estimation in North East India relative to low bias over semi-arid regions in the western part of India. In the present research, since we were interested mainly in the relative variability in rainfall within forested and non-forested landscapes, this bias is effectively cancelled out. Also, the study region falls under semi-arid and dry sub-humid climates (Tewari et al., 2013) and, hence, the bias is minimal in these regions. Moreover, various previous studies have cross-validated CHIRPS datasets with other datasets and found that CHIRPS performed better with station data (Jonah et al., 2021; Saicharan et al., 2023).

2.2.2. MODIS data and its pre-processing

The NDVI is one of the most widely used vegetation indices and correlates well with vegetation cover, density, health, photosynthetically active radiation and primary productivity (Herrmann et al. 2005). Hence, in this research, we used Moderate Resolution Imaging Spectro-radiometer (MODIS) - MOD13Q1 V6 Terra time-series NDVI data (16-day interval; 250 m spatial resolution) over 18 years (2001 to 2018) from the LPDAAC (Land Processing Distributed Active Archive Center (https://lpdaac.usgs.gov). Central India is covered by six MODIS tiles (i.e. h24v06, h24v07, h25v06, h25v07, h26v06, h26v07). NDVI composites were extracted individually, and noisy pixels were eliminated based on quality flags. Each annual NDVI time-series was corrected for dropouts and outliers using valid temporal neighbours, and finally smoothed using the discrete Fourier transform (Dash et al. 2010; Jeganathan et al. 2010; Singh et al. 2021).

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A forest mask was prepared, using the most recent comprehensive vegetation type map (CVT) produced at 1:50,000 scale using the LISS III sensor (23.5 m) for the Indian subcontinent (Roy et al. 2015), based on a two-tier approach (i.e. 23.5 m to 250 m, and 250 m to 5 km) (Singh et al. 2020). At first we created a new binary map having two classes i.e., forest (1) and no-forest (0) from CVT. Then we estimated percentage of forest pixels within each of the 250m pixel grids of MODIS data. Next, the grids having >75% of forest were considered as forest mask at 250m (Tier-1). Similarly, from the 250m forest mask we estimated the forest percentage within each of the 5km pixel grids of CHIRPS data. Then the grids having >20% of forest were considered as forest mask at 5km (Tier-2). The smoothed NDVI data were upscaled from 250 m to 5 km using mean aggregation (Singh et al., 2021). Then, aggregated NDVI values falling within the 5 km forested mask were extracted for further area analysis with rainfall to investigate inter-annual rainfall variability inside and outside forests. In addition, MODIS VCF data (MOD44B v006; 250 m spatial resolution) were used to stratify forest density, and ASTER global digital elevation model (ASTGTM v003; 30 m spatial resolution) data were used to stratify elevation. The VCF and elevation data were upscaled to 5km based on mean aggregation, and used to derive area statistics with rainfall. A schematic illustration of the methodology followed in this research is shown in **Fig. 2**.

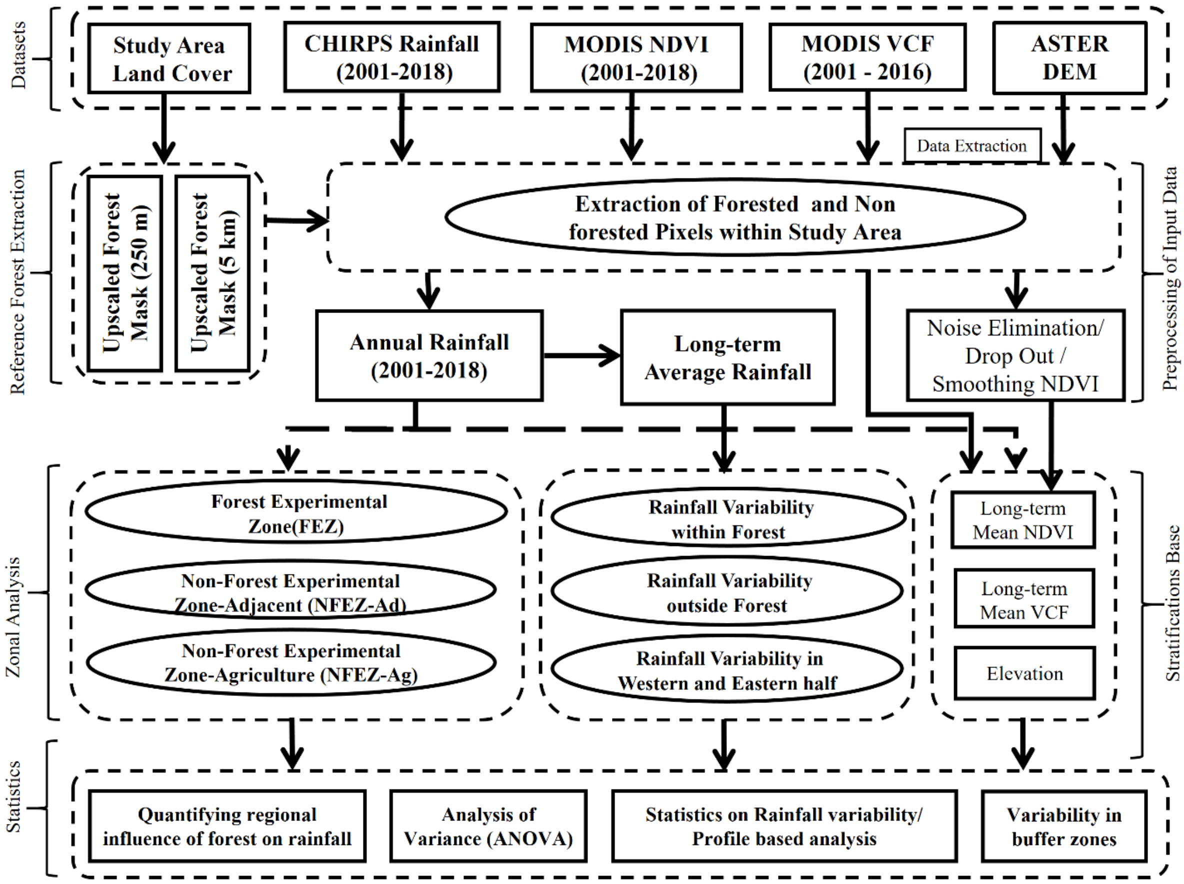

Figure 2. Overall methodology.

2.3 Methods

2.3.1. Level-1: regional level stratified analysis

First, the annual rainfall time-series for 18 years was analysed and compared to understand the general pattern and spatio-temporal variability in normal, dry and wet years. Next, long-term average rainfall (LTA_RF) for the whole region was estimated and scrutinised to understand its variability inside and outside forested regions based on different stratification levels: (a) within different NDVI classes, (b) within different forest density classes, and (c) within different elevation ranges. For this purpose, a long-term average NDVI map (LTA_NDVI) was prepared and classified into nine classes based on vegetation vigour, ranging from sparse vegetation to highly dense vegetation (Gu and Wylie, 2015; Singh et al., 2020, 2021). The LTA_VCF data were classified into eight classes revealing different percentages of tree cover (Adzhar et a., 2021). These classes were used to understand the relation of rainfall with vegetation vigour and density. The elevation data (ranging from 1 to 1643 m) were classified into 10 classes to study the effect on altitude on rainfall. Rajeevan et al. (2008) observed an increase in the number of extreme events over central India during the last five decades. Many studies have shown that central India observed a decreasing trend in annual rainfall (Paul et al. 2016; Sahany et al. 2018; Kumar et al. 2019; Singh et al. 2021). With warming expected to continue over central India due to global climate change, it is necessary to examine the monthly rainfall pattern. Thus, long-term monthly average rainfall was calculated from the 18 years (2001-2018) time-series of rainfall data. Also, the state-level variability in the rainfall pattern was analysed.

2.3.2 Level-2: analysis based on experimental zones

To evaluate the spatio-temporal association between rainfall and forests, we quantified the rainfall variability in different places, inside and outside of forests and in forest and non-forest classes, and compared them. For this experiment, we demarcated 22 zones (**Fig. 1a**). We categorized these zones as (i) Forest experimental zone (FEZ) (i.e. inside the forested areas), (ii) Non-forest experimental zone-adjacent (FEZ-Ad) (i.e. adjacent to forested regions, but outside forest edges) and (iii) Non-forest experimental zone-agriculture (FEZ-Ag). A total of 13 FEZ, 5 FEZ-Ad and 4 FEZ-Ag zones were demarcated manually across the study region (**Fig.1a**). At first, LTA-RF was analysed in each of these zones to characterize the rainfall variability. Also, buffer zones were created inside and outside FEZ to characterize the rate of increase or decrease in the LTA_RF in these two contrasting environments. Core zones represent intact forested areas, and outside buffer zones represent heterogeneous areas where all human interaction occurs, which usually have greater disturbances and temperatures than core areas. In

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addition, rainfall variability in the western and eastern coastal zones was analysed over the four buffer zones, each of 50 km (up to 200 km), to understand the role of forests in coastal areas.

2.3.3. Analysis of Variance (ANOVA)

In this research, ANOVA was used to test the rainfall magnitude and variability in different years and different rainfall conditions: (i) Level-1: in different experimental zones (FEZ, NFEZ-Ad & NFEZ-Ag); (ii) Level-2: in forested and non-forested areas; and (iii) Level-3: in different spatial profiles across the study area.

2.3.4. Profile-based analysis

To explore the rainfall distribution across the study area we created four different linear profiles: AB – Easter Coast to Western edge; CD – Easter Coast to North-western edge; EF – Western Coast to North-eastern edge; GH – Western coast to Northern edge of the study region (see **Fig. 12** for details). We created a forest density map based on the percentage of forested pixels occurring within 5 km grid cells. Each profile line was used to extract long-term average rainfall, forest density and annual rainfall from dry (2002), normal (2011) and wet (2013) years. Finally, all the extracted values for each profile were plotted against the cumulative distance of each pixel from the starting point along each profile.

3. Results

3.1. Spatio-temporal variability of rainfall

The long-term average rainfall derived from the 18 year time-series dataset is shown in **Fig. 1a.** The average rainfall was higher in the states of Odisha (OD) and Chhattisgarh (CH), and while the lowest rainfall was seen mostly in MH, MP and the Northwestern part of Jharkhand (JH), where vegetation density is the lowest. Table 1 shows the area statistics describing the long-term average annual rainfall during 2001 to 2018 over the study area. The highest rainfall was observed along the Western Ghats located near the coastal region of MH. The forests near the coastal region of the study area received a high magnitude of average rainfall (around 1650 – 1800 mm). The accumulated rainfall over 18 years is shown in **Fig. S1**. Around 20.29 % of the total study area received above > 1500 mm of long-term average rainfall. It is highly likely that the spatial distribution of rainfall over the Western Ghats is due mainly to the orographic effect of topography (Tawde and Singh, 2014; Thakur et al. 2019; Phadtare et al., 2022).

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Table 1. Area statistics of long-term annual average rainfall (2001 to 2018) over Central India

Rainfall (mm)	Area in Km^2	Area in %
< 750	79800	9.22
750 - 900	99450	11.49
900 - 1050	129450	14.96
1050 - 1200	95100	10.99
1200 - 1350	113550	13.12
1350 - 1500	194200	22.44
1500 - 1650	115475	13.34
1650 - 1800	27625	3.19
1800 - 1950	6225	0.72
1950 - 2100	4500	0.52
2100 -2250	4375	0.51
2250 - 3050	17350	2.00

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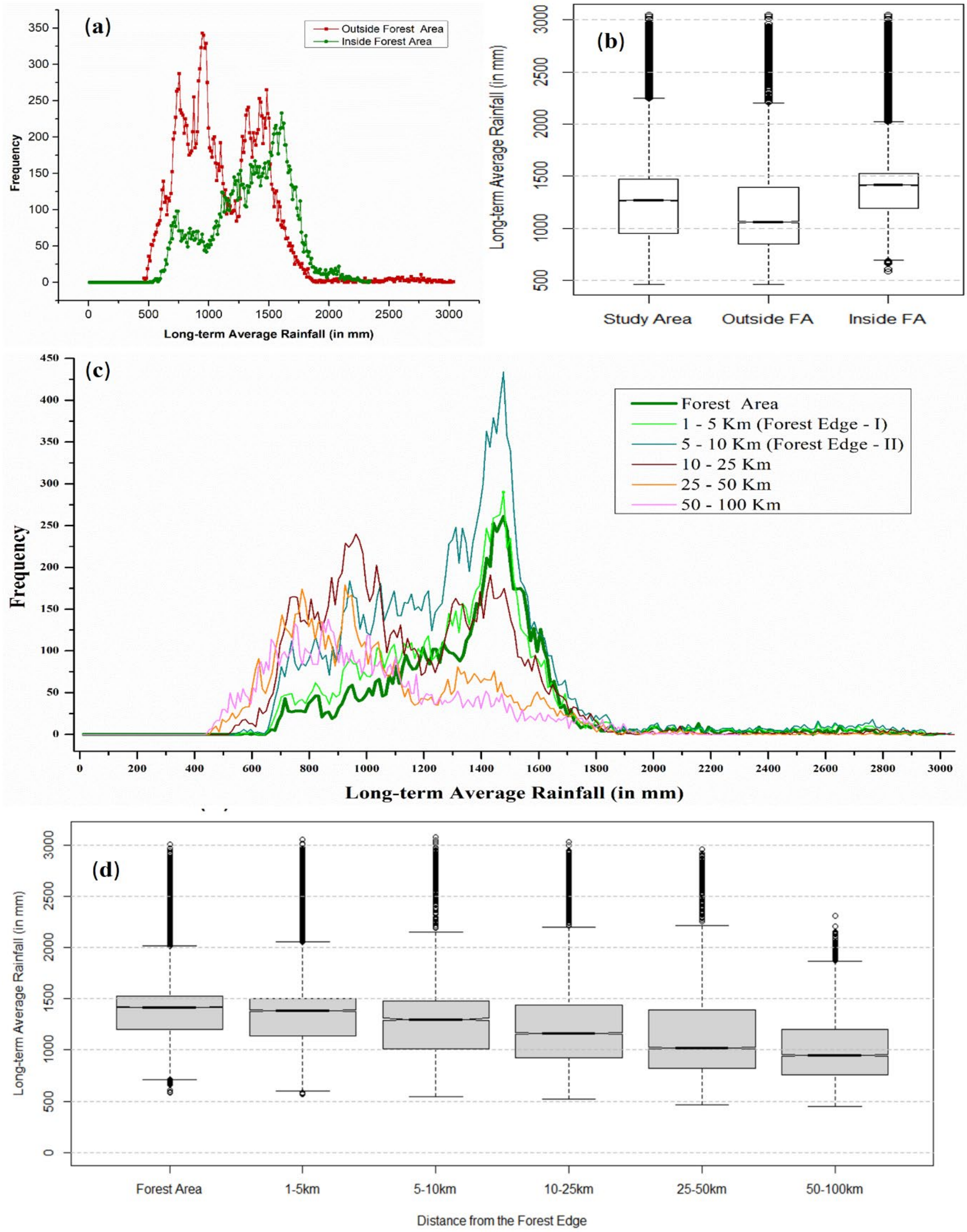

Figure 3. Rainfall variability in the study region. (a) Difference in the frequency of rainfall inside and outside forest areas, (b) Box-plot of rainfall range, (c) Frequency of rainfall in different buffer zones away from forest areas, (d) Box-plot of rainfall range at different distances from forest areas.

3.2. Spatial-temporal variability of rainfall inside and outside forested regions

To characterize the distribution of rainfall on an inter-annual basis over the study area the rainfall variability was quantified annually for inside and outside forested areas (**Fig. S2**). The frequency distribution of rainfall (**Fig. 3a**) in the non-forested area appears to be bimodal (peaks at 900 mm and 1400 mm) representing two contrasting environments in the western (high) and easternmost states (low), respectively. In Odisha, the forested regions are well distributed (where rainfall is high), but in Maharashtra there is a large patch of non-forest area (where rainfall is low) (**Fig. 4**). Interestingly, the rainfall is high in the smaller patches of non-forest area which are surrounded by dense forested zones, as in Odisha and in the south of Chhattisgarh. Rainfall variability outside the forested region can be linked mainly to three factors: (a) distance from the coast, (b) surrounding dense forest patches and (c) topographic juxtaposition (Kattel et al., 2012; Muluneh et al., 2017; Liu et al., 2020). The higher frequencies of lower rainfall magnitude (500 to 1000 mm) were observed mainly over the non-forested region, while inside the forested region higher rainfall magnitudes are observed (1000 to 1800 mm). Similarly, mean rainfall is greater than 1400 mm inside the forested region (**Fig. 3b.**).

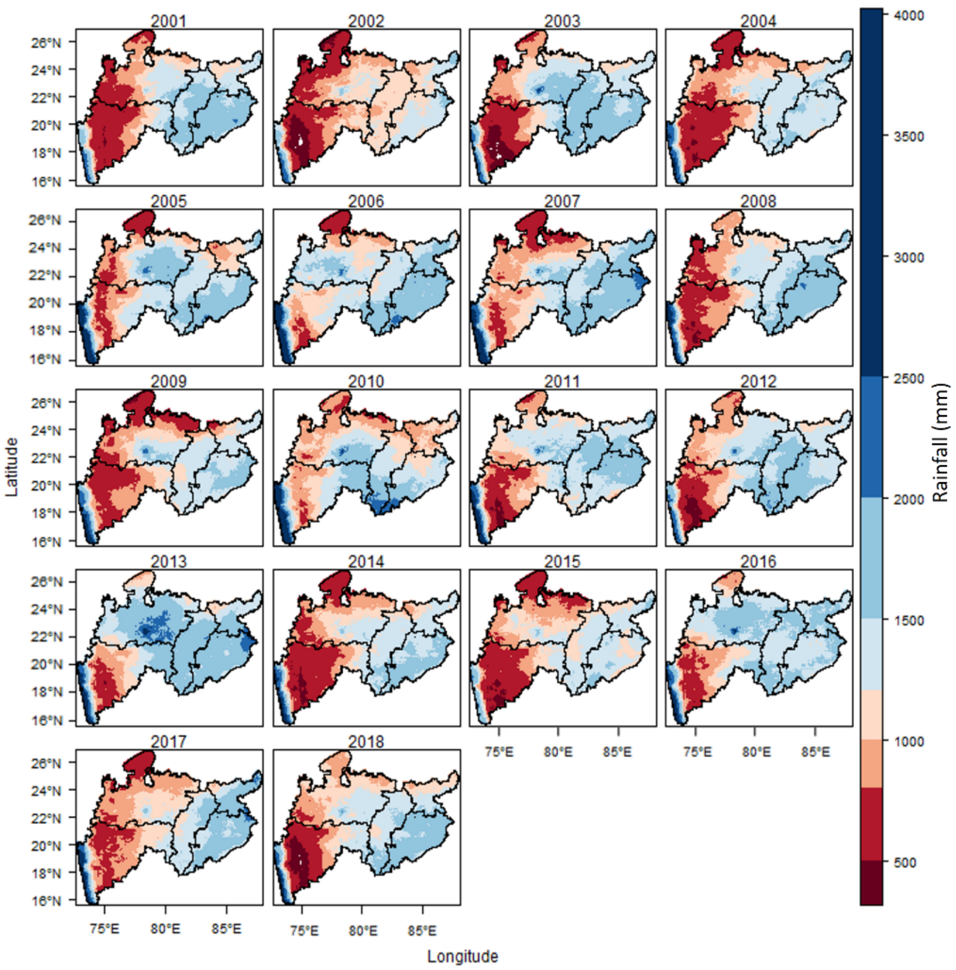

Figure 4. Inter-annual rainfall variability during 2001 to 2018.

The annual variability in rainfall over 18 years was assessed for inside and outside forested regions (**Fig. S2a and Fig. S2b**), and the average rainfall was found to be low for outside forested areas compared to inside forested regions ($p<0.05$), irrespective of whether it was a wet or dry year. The spatial-temporal pattern of the annual average rainfall over 18 years and the long-term accumulated rainfall in the study area are shown in **figures 1a & S1**. It is seen that the eastern region received more rain (see blue shades) than the western region, except in the Western Ghats. **Table 2** shows the area percentage in different rainfall classes observed over 18 years in central India. Comparatively, the Western Ghats received the highest magnitude of orographic rainfall. In **Fig. 4,** one can see a consistent rainfall pattern of above 1000 mm in forested regions such as for Chhattisgarh, Odisha, south-eastern Madhya Pradesh and Jharkhand. This result suggests an association of rainfall with forested areas.

Table 2. Area statistics in different rainfall categories during 2001 to 2018.

Year	Rainfall Classes (in mm)									
	1 - 300	300-500	500 - 800	800 - 1000	1000 - 1500	1500 - 2000	2000 - 2500	2500 - 3000	3000 - 3500	3500 – 4100
2001	0.00	0.24	23.22	13.88	34.76	26.85	1.05	0.00	0.00	0.00
2002	0.17	6.66	21.77	17.34	49.70	3.22	1.05	0.01	0.00	0.00
2003	0.05	4.79	13.48	12.38	34.55	32.87	1.73	0.05	0.00	0.00
2004	0.00	0.71	25.43	17.53	47.94	5.70	1.91	0.78	0.00	0.00
2005	0.00	0.01	10.69	16.55	42.48	26.14	1.35	1.14	1.52	0.11
2006	0.00	0.01	6.22	8.08	51.02	30.06	1.54	1.16	1.87	0.04
2007	0.00	0.00	12.33	18.84	32.97	30.65	2.58	1.37	1.06	0.21
2008	0.00	0.72	17.74	16.17	37.35	25.14	1.39	1.23	0.24	0.02
2009	0.00	0.62	24.92	17.37	45.41	9.04	1.58	0.88	0.18	0.00
2010	0.00	0.00	3.76	24.18	46.47	18.72	3.75	1.25	1.71	0.15
2011	0.00	1.32	10.02	12.23	51.32	21.82	1.37	0.88	0.82	0.21
2012	0.00	2.42	9.33	16.62	44.06	25.68	1.78	0.11	0.00	0.00
2013	0.00	0.06	5.56	7.02	31.11	48.17	6.11	1.58	0.40	0.00
2014	0.00	1.46	24.85	16.00	42.24	13.01	1.33	1.08	0.04	0.00
2015	0.00	1.61	23.81	15.44	53.93	4.85	0.35	0.00	0.00	0.00
2016	0.00	0.01	7.53	10.20	49.57	29.82	1.49	0.91	0.43	0.04
2017	0.00	0.00	15.78	23.48	37.11	20.01	2.02	1.20	0.40	0.00
2018	0.01	4.60	10.71	15.57	47.29	19.81	1.03	0.92	0.04	0.00

3.3. Rainfall variability with NDVI, forest density and elevation

Various studies revealed that NDVI and rainfall are correlated in areas limited in water. We analysed the variability in the long-term average rainfall in different classes of long-term average NDVI (**Fig. 5a**). In Fig. 5a, one can observe a high rainfall in low NDVI classes, contrary to the association revealed above. However, one has to consider the observed regional variability from the point of view of different factors. Interestingly, the

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highest rainfall amounts found in the lower NDVI classes 0.0-0.05 are mainly from the Western Ghats region. An increasing rainfall pattern was observed when the NDVI values increased from 0.2 to 0.85 (For details see **S3**). In **Figure 5b** one can also see increases in rainfall with NDVI similar to **Figure 5a** and, hence, this again is contradictory.

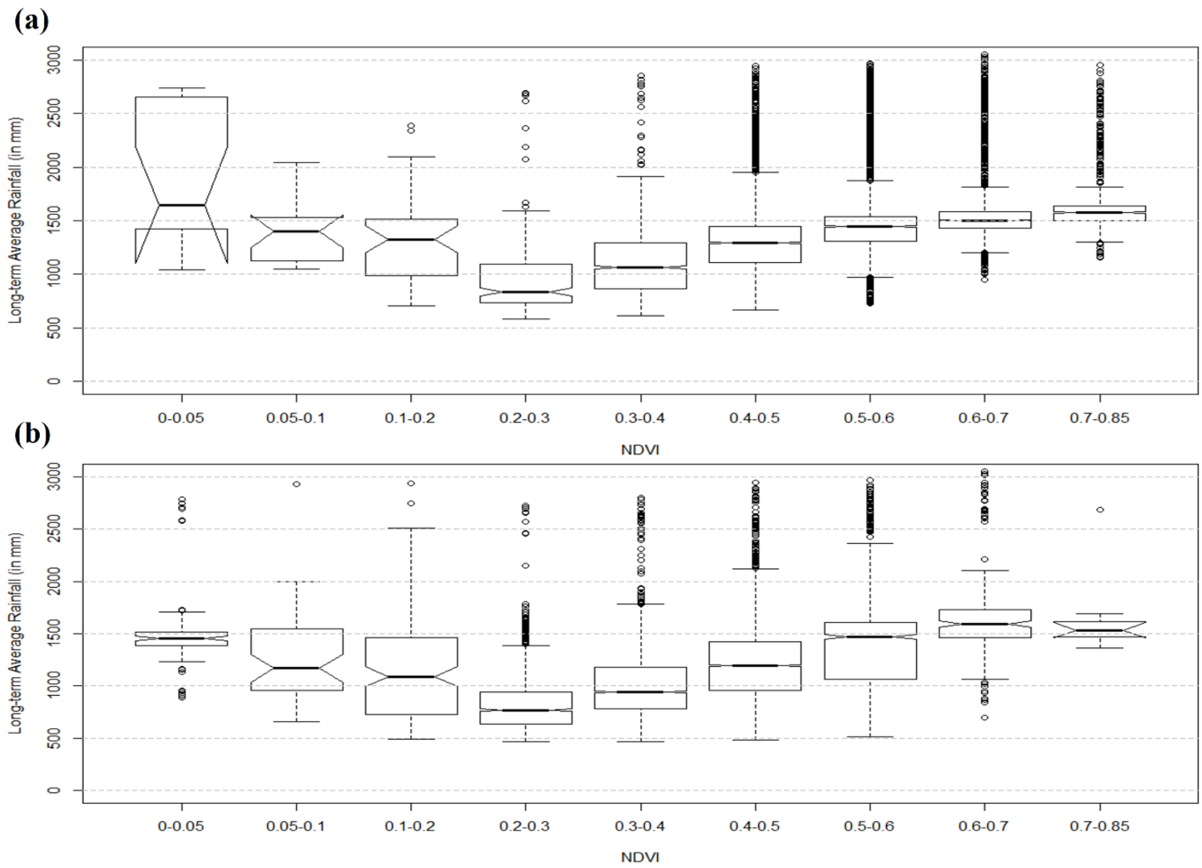

Figure 5. Rainfall variability within different NDVI classes: (a) inside forested region and (b) outside forested region.

Here again, the juxtaposition of pixels surrounded by forest patches needs to be considered. As there were so many smaller patches of non-forest pixels surrounded by dense forest patches in the eastern part of the study area, these patches alter the rainfall statistics when grouped together with other larger patches of non-forest area of the western region. To avoid confusion, we divided the study region into two halves: east and west, and also ignored non-forest patches from the Western Ghats region which has a strong influence from orographic phenomena (**Fig S4 & S5**). While Comparing the variability in the long-term average rainfall in different forest density classes inside and outside forested regions, a clear increasing trend in rainfall pattern in the higher density classes is observed (**Fig. 6a**). The role of altitude (along with forest/non-forest zones) was examined for its association with rainfall. The average rainfall was higher in the lower elevation classes than in the higher elevation classes, with lower elevation mainly in the western and eastern coastal regions. It is observed that the variance in rainfall was low inside forested regions even at different elevations (See Fig. **S5** for spatial distribution). However, the variance was large in the non-forested areas. An increasing rainfall pattern is observed as the elevation increases beyond 400 m (**Fig. 7a & b**). **Table 3** provides area statistics about rainfall variability in different classes of NDVI, elevation and vegetation density (i.e. VCF).

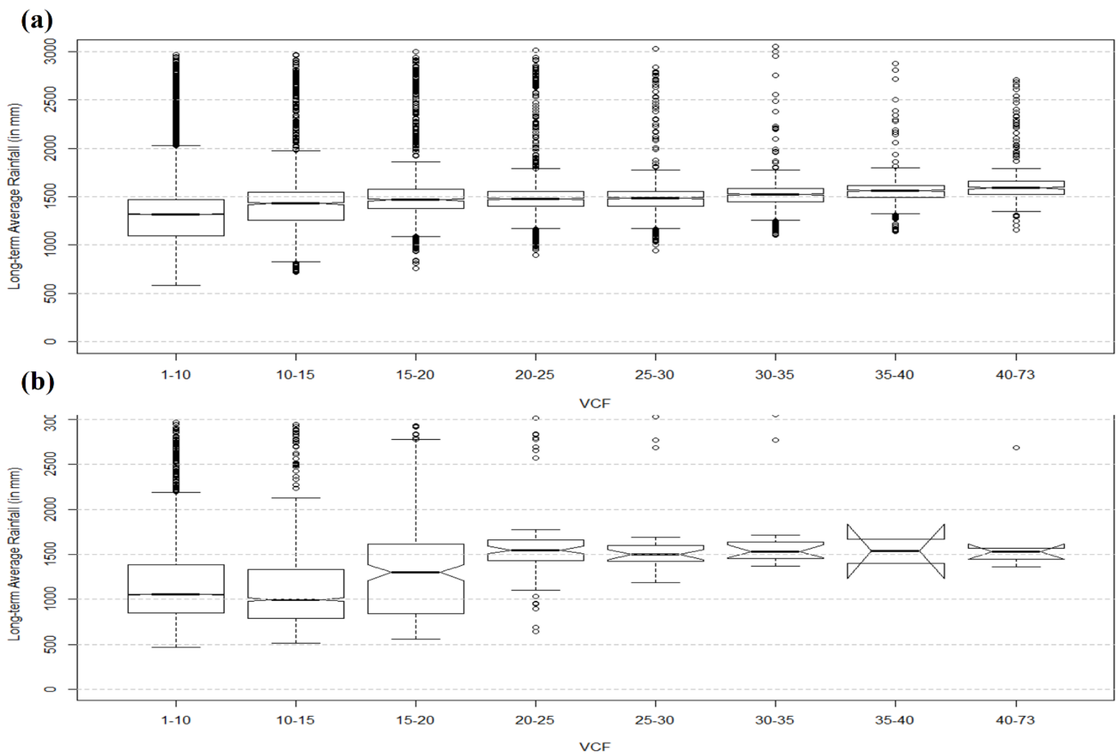

Figure 6. Rainfall variability within different VCF classes: (a) inside forested region and (b) outside forested region.

Table 3. Area statistics in % for different categories of NDVI, Elevation and VCF.

NDVI			**ELEVATION**			**VCF**		
Classes	**IN**	**OUT**	**Classes (in m)**	**IN**	**OUT**	**Classes (in %)**	**IN**	**OUT**
0 - 0.05	0.56	1.60	0 - 50	1.80	5.58	0	0.50	1.53
0.05 - 0.1	0.09	0.21	50 - 100	2.44	2.09	1-10	54.64	89.48
0.1 - 0.2	0.28	0.93	100 - 200	9.30	9.43	10- 15	10.48	7.40
0.2 - 0.3	1.59	6.66	200 - 300	14.46	20.85	15 - 20	8.54	1.04
0.3 - 0.4	12.91	36.10	300 -400	19.94	17.63	20 - 25	9.16	0.29
0.4 - 0.5	31.37	46.51	400 - 500	20.16	17.11	25 - 30	7.84	0.16
0.5 - 0.6	26.53	7.07	500 - 600	13.62	14.86	30 - 35	4.07	0.07
0.6 - 0.7	20.78	0.86	600 - 700	8.39	8.08	35 - 40	2.34	0.02
0.7 0.85	5.89	0.06	700 - 800	4.79	2.92	40 - 73	2.44	0.02
-	-	-	800 - 1643	5.10	1.46	-	-	-

Note: IN = Inside forest, OUT = Outside Forest

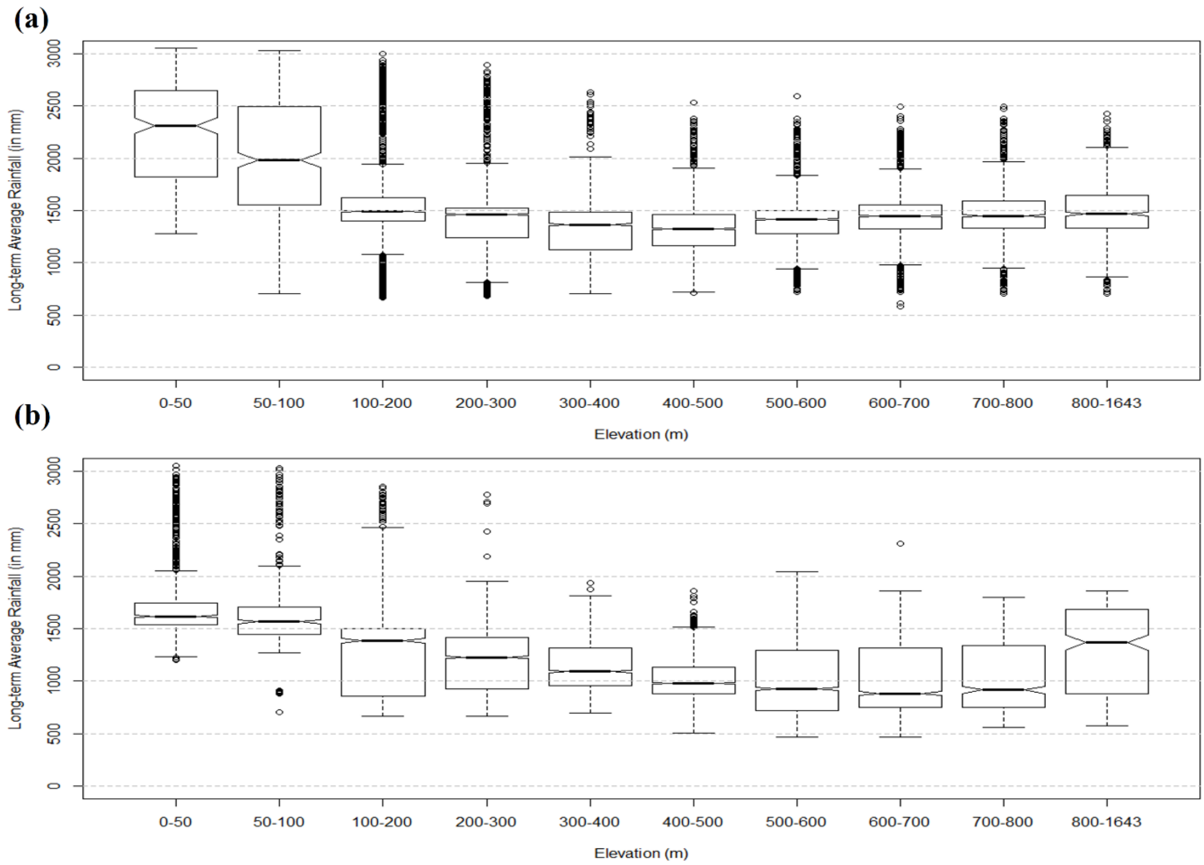

Figure 7. Rainfall variability in different elevation zones over forested region (a) and non-forested region (b).

3.4. Month-wise and state-wise rainfall variability

Figure 8 shows the spatial-temporal pattern of long-term average monthly rainfall over the central Indian landscape. During the winter months of January, February and March, the average rainfall is reduced to 63.13 mm and the western side of the continent remains drier than the eastern side. A similar pattern is observed during the summer months of May and June, but the average rainfall increased to 197.99 mm. During the monsoon season (June to September) the central Indian region received the maximum rainfall. During the monsoon, MH received much lower rainfall than the rest of the regions. The lowest rainfall was observed in the study region during December. Overall, the rainfall received over central India varied across the landscape, but a clear pattern of high rainfall was observed in the forested regions during the monsoon, which provides a clear indication of the role of forests in attracting rainfall (**Figure 8**). Among the states, MH exhibited the highest variance in rainfall, with the majority of the land area converted to agriculture, while CH and JH exhibited the least variance, where forest is well distributed and dense. **Table 4** shows area statistics of different ranges of rainfall in different months over central India. The long-term monthly average rainfall of the five states over 18 years is shown in **Table 5** and **Fig. S7**. OD's long-term average rainfall (1559.94 mm) was the highest over the 18 years, followed by CH (1421.14

mm), JH (1334.17 mm), MP (1100.98 mm) and MH (1102.73 mm). MP received around 91.76% of its rainfall during the monsoon, while MH and CH received approximately 87.96% and 86.79%, respectively, which shows a high dependency of these states on the monsoon. **Table 6** shows the long-term average annual rainfall, and rainfall received during monsoon. It was found that MP received more of its rainfall during the monsoon season than OD (91.76% and 81.50%, respectively), although OD received the maximum rainfall in a year. Therefore, examining the factors responsible for controlling the central Indian rainfall becomes necessary as the distribution of monsoon rainfall is not uniform across the study region. MH experienced the highest variability in rainfall and is prone to frequent drought, followed by MP, JH, and CH. The least variability was observed in OD (see Figs. **S8** & **S9**).

Table 4. Area statistics of long-term average monthly rainfall.

Rainfall (mm) classes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 -5	59.72	63.40	59.08	65.66	50.81	48.47	48.47	48.47	48.47	48.47	56.25	86.52
5 -20	34.28	25.44	24.96	20.16	30.53	0.24	0.00	0.00	0.00	4.44	33.00	13.48
20 -50	6.00	11.09	15.95	13.52	10.18	4.16	0.00	0.04	0.00	16.89	10.56	0.00
50 -100	0.00	0.08	0.00	0.66	6.77	13.43	1.07	1.05	0.00	23.24	0.19	0.00
100 -150	0.00	0.00	0.00	0.00	1.41	16.46	2.04	1.89	0.21	4.99	0.00	0.00
150 - 200	0.00	0.00	0.00	0.00	0.29	15.21	1.75	3.58	6.56	1.81	0.00	0.00
200 - 300	0.00	0.00	0.00	0.00	0.00	0.47	8.37	13.27	18.98	0.17	0.00	0.00
300 - 400	0.00	0.00	0.00	0.00	0.00	0.73	21.56	20.32	23.47	0.00	0.00	0.00
400 - 600	0.00	0.00	0.00	0.00	0.00	0.83	15.14	10.89	2.17	0.00	0.00	0.00
600 - 1000	0.00	0.00	0.00	0.00	0.00	0.00	1.61	0.49	0.14	0.00	0.00	0.00

Table 5. State-wise long-term monthly average rainfall (in mm).

State	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
CH	15.11	17.50	21.65	20.55	25.40	192.81	397.18	407.38	236.01	72.81	10.66	4.08
JH	14.90	19.25	17.79	25.11	56.62	195.23	348.06	320.11	238.42	90.27	5.87	2.54
MP	14.80	12.47	11.24	4.10	8.17	137.84	372.94	328.14	171.31	28.56	7.04	4.38
MH	5.69	5.06	9.10	9.37	18.33	208.75	305.58	261.41	194.20	61.83	18.78	4.61
OD	11.34	21.25	21.40	32.99	61.60	221.37	394.08	382.14	273.82	115.02	21.28	3.64

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Table 6. State-wise long-term average rainfall during and monsoon months.

State	Annual Rainfall	Monsoon Rainfall	Relative Monsoon Contribution (in %)
Chhattisgarh (CH)	1421.14	1233.37	86.79
Jharkhand (JH)	1334.17	1101.82	82.58
Madhya Pradesh (MP)	1100.98	1010.23	91.76
Maharashtra (MH)	1102.73	969.94	87.96
Odisha (OD)	1559.94	1271.42	81.50

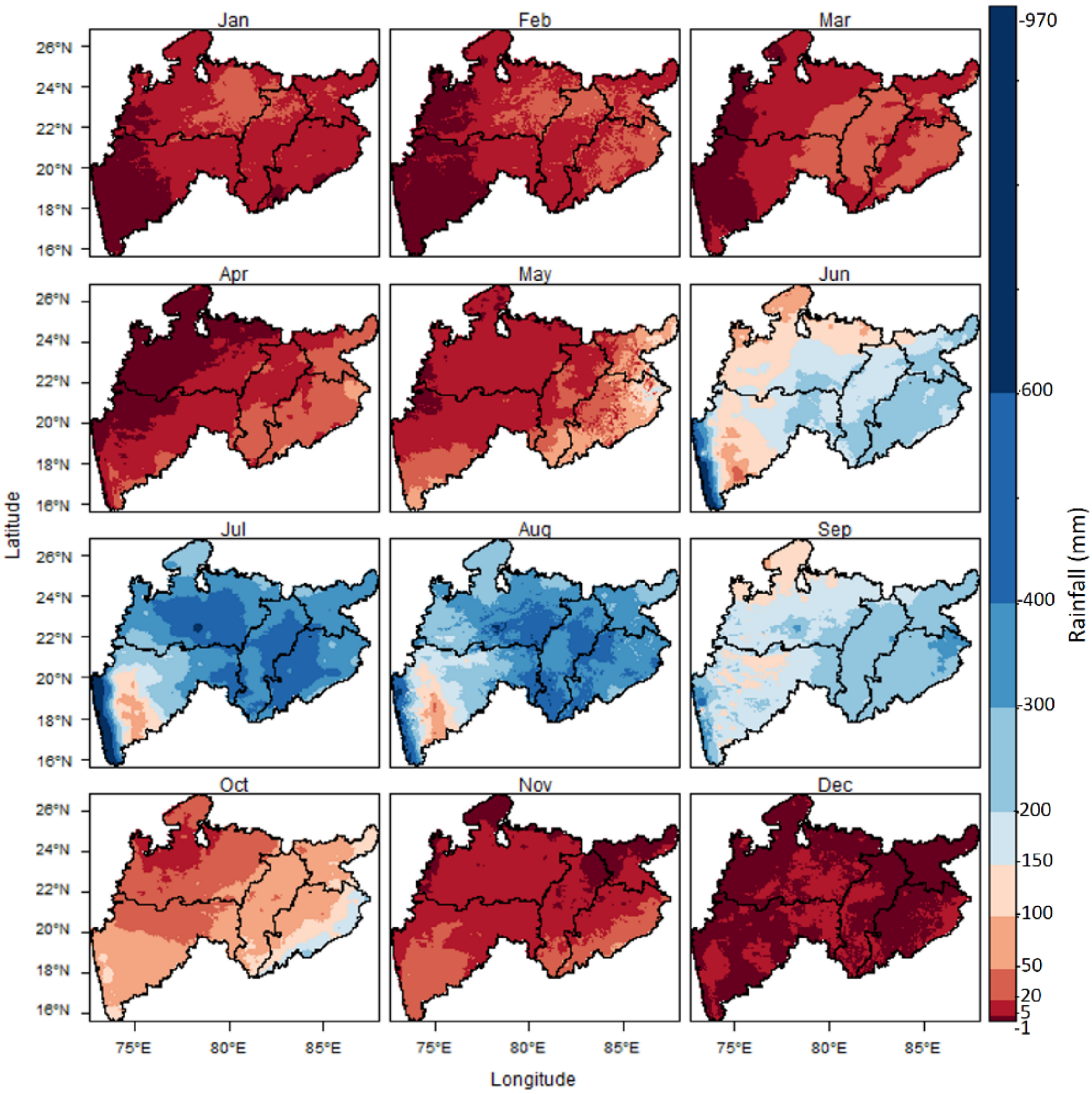

Figure 8. Temporal variability of long-term monthly average rainfall of 18 years.

The accumulated rainfall inside and outside forested area was analysed in (a) different months, (b) different states and (c) over the full study region. It was observed that the amount of accumulated monsoon rainfall observed during 2001 to 2018 in the states MH, MP, CH, JH and OD within forest (non-forest) are: 1051 (577), 769 (692), 890 (885), 786 (800) and 918 (910) mm km^{-2}, respectively. The accumulated monsoon rainfall observed within forest (non-forest) area in the buffer zones 0-50 km, 50-100 km, 100-150 km and 150-200 km from the western coast are: 1661 (1651), 1119 (830), 709 (501) and 612 (397) mm km^{-2}, respectively. Similarly, the accumulated monsoon rainfall observed within forest (non-forest) areas in the buffer zones 0-50 km, 50-100 km, 100-150 km and 150-200 km from the eastern coast are: 816 (838), 890 (902), 907 (876) and 911 (905) mm km^{-2}, respectively. Overall, the amount of rainfall observed during the monsoon within the forest (non-forest) area in the full study region was 245 (215) mm km^{-2} yr^{-1}. Interestingly, the total area of forest in the 0-100 km buffer in the western coast is 75% more than the eastern coast, and this can be attributed to the difference in rainfall in the eastern coast.

3.5. Spatio-temporal variability in rainfall in different experimental zones

To examine the spatial distribution and variability of rainfall in different areas, we demarcated the study area into different experimental zones (**Fig. 1a**) (i.e. FEZ, FEZ-Ad and FEZ-Ag) and different buffer zones within and outside forested regions based on the MODIS and CHIRPS time-series vegetation and rainfall data, as described in section 2.3.2.

3.5.1. Forest Experimental Zone (FEZ)

The variation in rainfall in different forest zones is depicted in **figure 9**. Of the 13 FEZs, zone FEZ1 received the maximum average rainfall (~1900 mm), which might be due to two factors such as its closeness to the western coast and the orographic effect of the Western Ghats topography. The zone FEZ12 received the lowest rainfall (~800 mm), which might be due to the low density of forests in that zone and its location far from coasts. The other zones FEZ2 to FEZ6, FEZ10, FEZ11 and FEZ13 also received high average rainfall (~1500 mm). On the other hand, FEZ7 and FEZ8 received relatively less rainfall (~1300 mm) and FEZ9 received around 1000 mm. The highest variance in rainfall was observed in FEZ1, FEZ9 and FEZ11, which might be due to the fragmentation of forest patches in these regions. The zones FEZ9 and FEZ12 seem to be sensitive to drought as they received less rainfall than all other zones. **Figure S10** reveals the inter-annual variability in the rainfall in all these 13 FEZs. During 2002, 2004, 2009, 2014 and 2015 there was an overall reduction in the rainfall in most of the zones, except FEZ1 and FEZ11 as these zones fall into high elevation regions and receive consistently the maximum rainfall in all years. It was observed that the size, density, fragmentation, elevation and distance from the coast of the forested zones affected the rainfall amount and variability.

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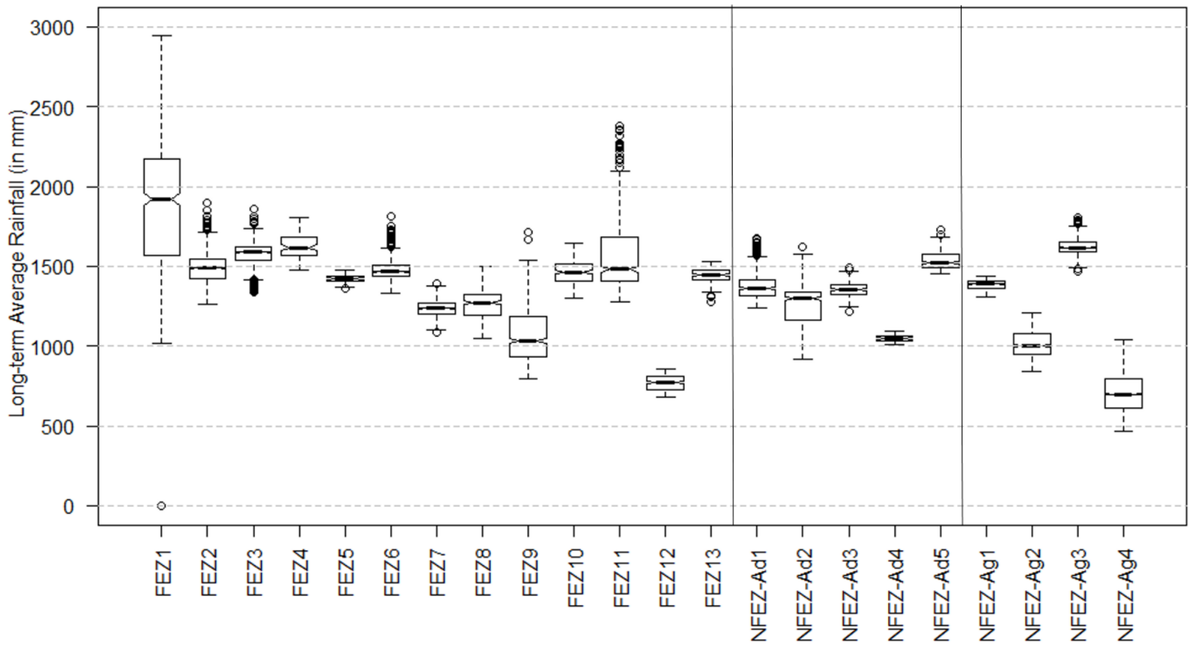

Figure 9. Long-term average annual rainfall variability within the experimental zones.

3.5.2. Non-Forest Experimental Zone-Adjacent (NFEZ-Ad)

The non-forest regions located adjacent to forests and surrounded by forested area have the benefit of receiving high rainfall because of their closeness to forests. All the 5 NFEZ-Ad zones received consistently high rainfall (>1000 mm) (**Fig. 9** and **S7**). NFEZ-Ad5 received the maximum rainfall (>1500 mm) because this patch is narrow, and it is the smallest in size, located close to the large forest patches of FEZ2 and FEZ3 (**see Fig. 1a & 9**). On the other hand, NFEZ-Ad4 received less rainfall (~1100 mm) than the other zones. NFEZ-Ad2 had the highest rainfall variability among all the zones. The reason could be its shape and extent over a large area where the surrounding forest patches are fragmented and varied in density **(Fig. 1a)**. All these NFEZs experienced a reduction in rainfall during the drought years similar to FEZ, but NFEZ-Ad4 seems to be more sensitive (**Fig. S**11).

3.5.3. Non-Forest Experimental Zone-Agriculture (NFEZ-Ag)

Of the four agricultural zones, NFEZ-Ag4 received the lowest rainfall (~700 mm) (**Fig. 9 & S12**). This zone in MH is a vast stretch of intensive agriculture where rainfall is highly erratic. In contrast, the NFEZ-Ag2 zone in MP received higher rainfall than NFEZ-Ag4 which might be due to the effect of adjacent forest patches. NFEZ-Ag3 received the highest average rainfall (~1600 m m) and the apparent reason could be its closeness to the eastern coast. High rainfall in NFEZ-Ag1 is likely due to the orographic effect supported by surrounding forest patches. Figure S8 reveals the inter-annual rainfall variability in these zones over 18 years. NFEZ-Ag4 & Ag2 are at the lowest receiving end and are sensitive to drought, and NFEZ-Ag1 & Ag3 profit greatly from the monsoon. Though

NFEZ-Ag4 falls in the rain-shadow region, the lack of forest patches in NFEZ-Ag4 compounds the situation of low rainfall occurrence here.

3.6. Spatio-temporal variability of rainfall in the buffer and core zones.

To gain more insight into the spatial distribution of rainfall, buffer analysis was carried out where buffer zones at 10 km intervals were created outside the edge of the forested areas. Also, buffer zones of 5 km interval were created inside the forested areas from the edges. **Figures 10** and **11** show the variability in rainfall in these two groups of buffer zones. The hypothesis is that rainfall should increase inside the forests and should decrease at increasing distance from forests. First, we estimated the average rainfall in different buffer zones located in different forested regions across the study area. Interestingly, a clear pattern of exponential reduction in rainfall was observed with increasing distance from forests at an average rate of -20 mm yr^{-1} km^{-1} over a 0-to-50 km range, and at the rate of -1.5 mm yr^{-1} km^{-1} over a 50-to-100 km range.

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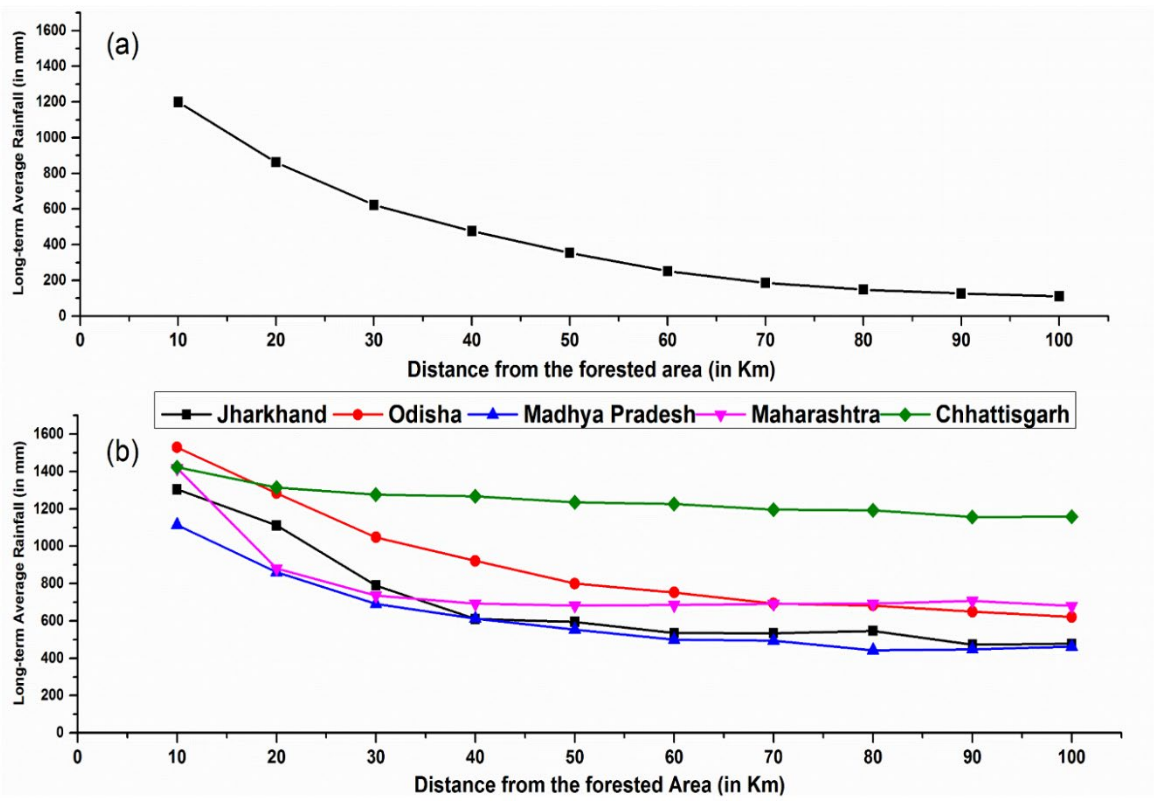

Figure10. Variability in the long-term average rainfall with respect to distance from forested area in the central Indian landscape (a) and in different states (b).

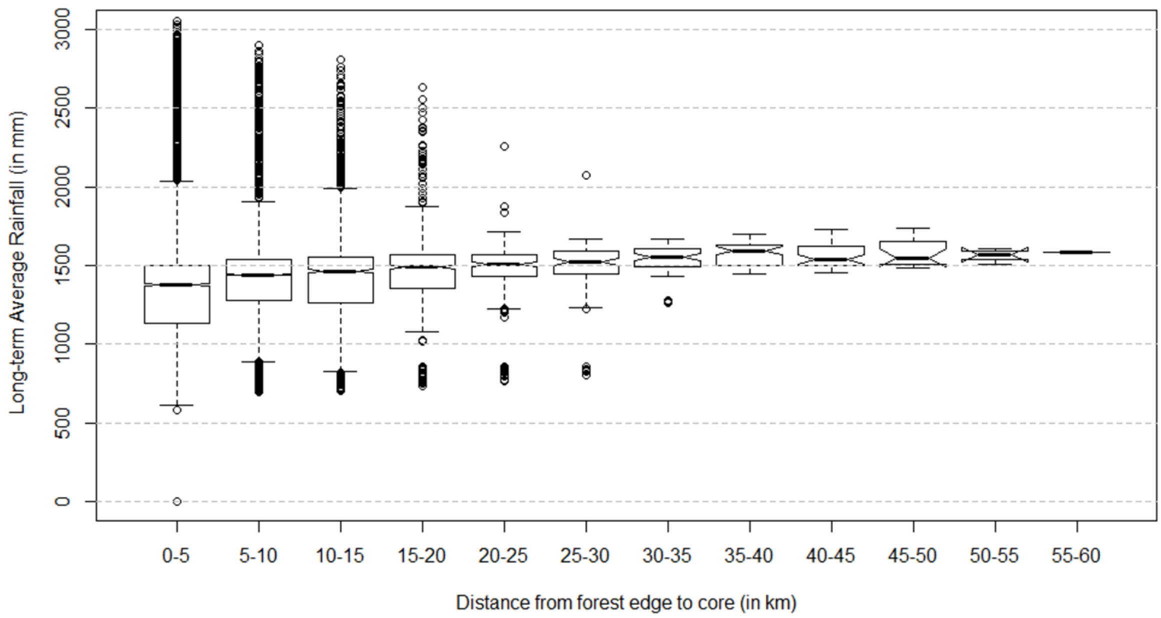

Figure 11. Variability in the long-term average rainfall at different distances within the forests (from edge to core).

3.7. ANOVA statistical analysis

The statistical null hypothesis was that there is no difference in the mean rainfall and its variability between the forested and non-forested areas, and across the different experimental zones (and, thus, forests do not contribute in bringing rainfall to the region). Therefore, ANOVA was performed to test the rainfall variability in different zones, and also in different years. We found that the mean rainfall variation was significantly different ($p<0.05$) between the experimental groups at inter and intra-year stratifications, and during extreme years like 2002 (dry year), 2011 (normal year) and 2013 (wet year). We found that FEZ4 and NFEZ-Ag3 experienced almost the same average rainfall of 1621.18 mm and 1620 mm, respectively, due to closeness to the coastal zone which supersedes the effect of forests on rainfall. Another two nearby experimental zones, FEZ8 and NFEZ-Ad2, experienced a similar average rainfall of 1256.06 mm and 1251.43 mm, revealing the benefit of being close to forested regions. **Tables S1, S2, and S3** provide the results from the ANOVA test for the different years. **Table 7** provides the ANOVA results for the rainfall variability between forested and non-forested pixels, intersected with four different spatial profiles across the landscape. All the ANOVA results confirm that the mean rainfall and variability are clearly different in the forested and non-forested zones and the null hypothesis is rejected and the alternative hypothesis is supported.

Table 7. Testing the influence of forest on rainfall within the forest area and outside forest area along different profiles using one-way ANOVA.

Summary		Rainfall outside Forest	Rainfall within Forest
Spatial Profile Line	Rainfall Occurrence		
AB Spatial Profile Line	Average	1236.69	1391.03
	SD	308.25	190.40
	Variance	95021.20	36255.56
	standard error	30.82	19.04
	F	27.04	
	F Critical	3.87	
	P-value	3.84E-07	(significant)
	N	120	164
CD Spatial Profile Line	Average	1245.02	1295.86
	SD	222.32	286.46
	Variance	49426.03	82057.74
	standard error	22.23	28.65
	F	2.08	
	F Critical	3.88	
	P-value	0.15	(not significant)
	N	83	197
EF Spatial Profile Line	Average	1046.79	1365.32
	SD	306.03	348.19
	Variance	93653.29	121233.30
	standard error	30.60	34.82
	F	99.76	
	F Critical	3.86	
	P-value	2.56E-21	(significant)
	N	185	259
GH Spatial Profile Line	Average	815.05	1151.72
	SD	183.06	592.99
	Variance	33512.03	351633.81
	standard error	18.31	59.30
	F	52.16	
	F Critical	3.87	
	P-value	3.81E-12	(significant)
	N	182	138

****Note:* SD = Standard Deviation, N= Total number of samples

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3.8 Profile analysis

To characterize the rainfall variability across the study area, we took four different profiles traversing different lengths and breadths of the study area. **Figures 12a and 13** show the spatial extents of these profiles along with rainfall. **Figure 12b** depicts the spatial distribution of forest density while **Figure 12c** depicts the forest and non-forest areas. These four profiles were intersected with the rainfall during normal (2011), dry (2002) and wet (2013) years, and plotted to understand the effect of presence of forest on rainfall (**Fig. 13**). It is clearly evident that an increasing pattern of rainfall (**Figures 13 a, b, c & d**) was observed while moving towards forested areas, and an exponential reduction was observed while moving away from forested regions (**Fig. S13**). These effects are dominant (**Figure 13 c, d**) in MH when the profile line crosses the locations where agriculture practices are followed over the vast region. **Table 7** shows the influence of forest on the different profiles tested using ANOVA. It is found that the rainfall pattern and its variability in profiles AB, EF and GH was significantly ($p < 0.05$) different over forest and non-forested areas. Interestingly, in the CD profile one can see a reduction in rainfall in the north-western region where the forest is fragmented and less dense, but in the agriculture region, covered by forest on all sides (in Chhattisgarh) and falling within the zone of influence of forest, the reduction was minimum. These rainfall-forest linked profile pictures **(Fig. 13a-d)** further confirm the influence of natural Vegetation on rainfall.

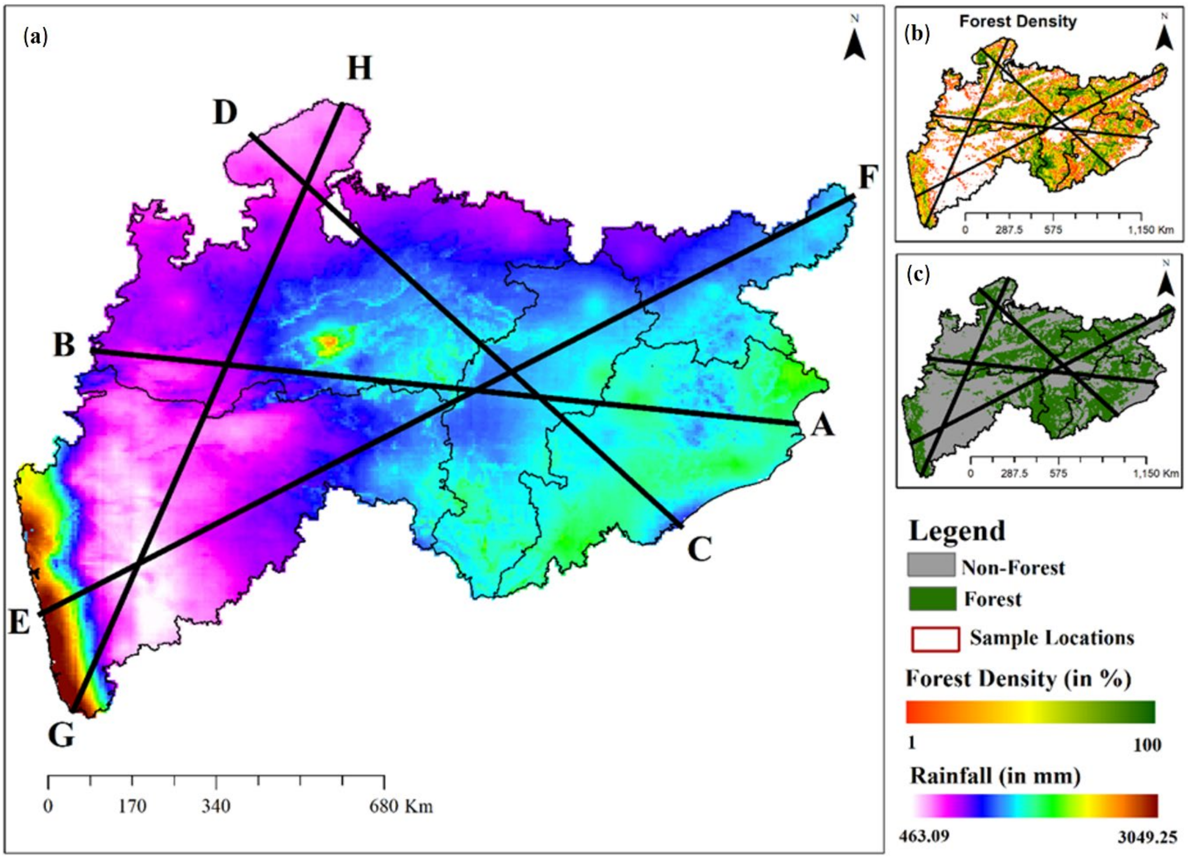

Figure 12. Rainfall and Vegetation variation along different directional profiles (AB, CD, EF and GH): (a) long-term average annual rainfall, (b) forest density and (c) forest and non-forest area.

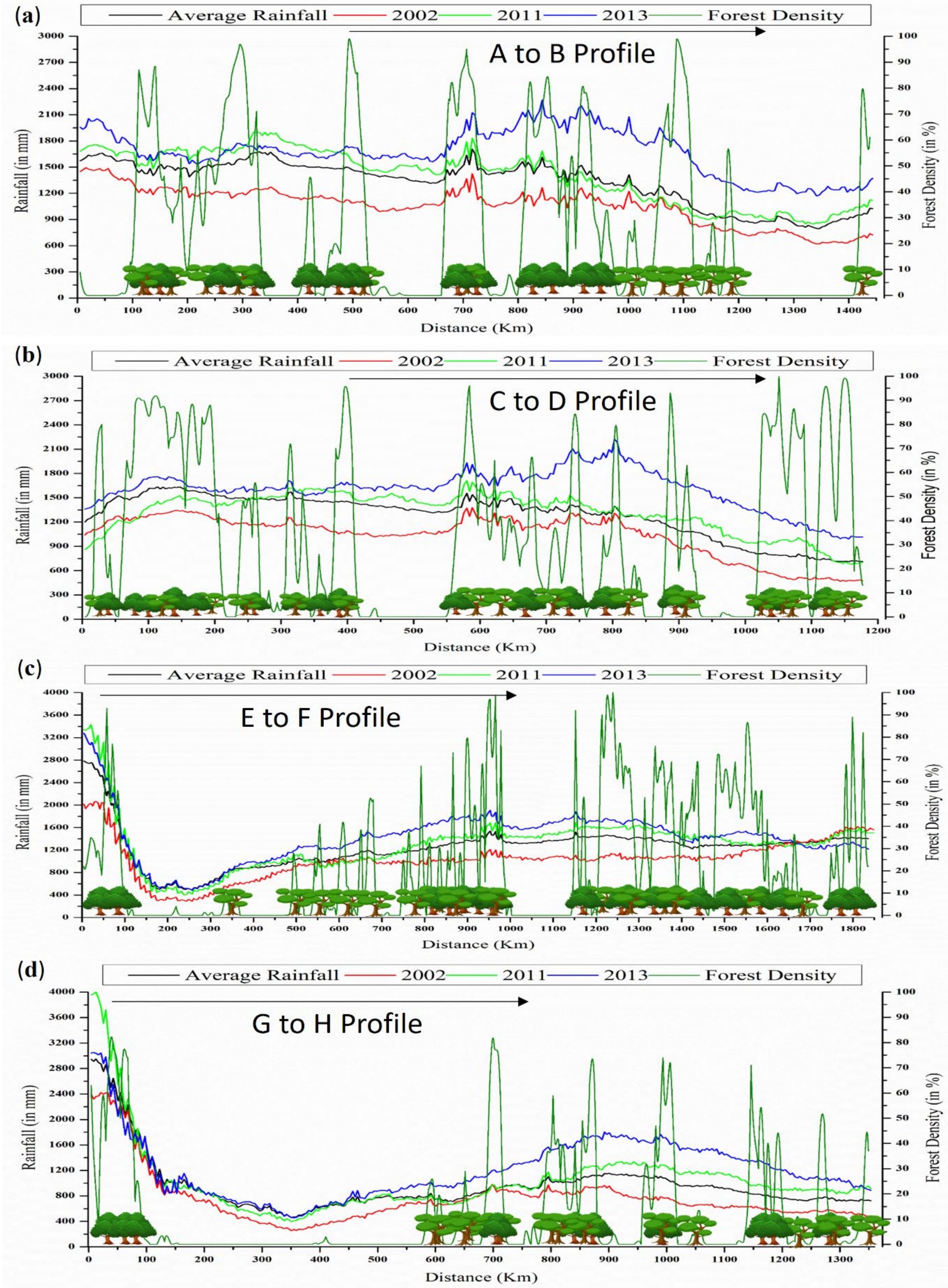

Figure 13. Rainfall variability during extreme rainfall years and the presence of natural Vegetation across the study area (as forest density in the secondary axis). (Note: The spatial extent of the profile lines is provided in Figure 12)

4. Discussion

The influence of forests in regulating the regional distribution of rainfall was realized very early by humans, indeed since the Indus civilization (Bhattacharya 2014; Sheil 2014). Creed et al. (2019) stressed that forests and water are an integrated system and, thus, there a global consensus on transboundary management policies is required for achieving the UN sustainable development goals. Meteorologically, various factors affect the distribution of rainfall intensity over India. For example, warming in the Arabian Sea, the Indian Ocean and the Bay of Bengal affect moisture transport mechanisms over central India (Jin and Wang 2017; Roxy et al. 2017). However, a full deterministic understanding of the spatial (and spatio-temporal) variation in rainfall has not yet been achieved. Roxy et al. (2017) questioned the mechanism behind the observed increases in extreme events over central India, noting that meteorological models are still not able to predict the frequent droughts observed. Various models, ground and satellite-based studies reported that forest-rainfall feedbacks are likely to influence water availability under climate change scenarios (Bergkampt et al. 2003; Spracklen et al. 2012; Staal et al. 2020a). Our findings revealed that rainfall decreased exponentially outwards from forest edges to non-forested areas, inline with reported increases with distance from the ocean (Makariaeva et al. 2009).

Pradhan et al. (2019) showed that, in north-eastern (NE) India, high evapotranspiration (ET) from forested regions supplies water vapour to the atmosphere during summer which may contribute to the high rainfall observed over forests in the NE during summer. However, in central India, moisture supply to the atmosphere through ET from the forested region is very low during the summer for two reasons: (a) plants are deciduous in nature and lack leaves in summer (already shed to avoid water loss), and (b) the region is water scarce in summer. For example, Meghalaya receives around 400 to 800 mm of rainfall in summer, but Madhya Pradesh receives only 100 to 200 mm. In central India, ET arises mainly from forests, primarily from two types; dry and moist deciduous. They are drought resistant and extract water from their deep and wide spreading rooting systems (Neptad et al. 1994). When the tropical deciduous forest starts greening in May-June ET increases and, hence, accelerates moisture supply inducing cooling on the clouds and causing subsequent rainfall in the region. Of four ways to cool the southwestern moisture-laiden winds (i.e. adiabatic, conductive, radiative and evapo-transparative cooling), two types are often observed in central India. One is through adiabatic cooling due to the Western Ghats and central hilly areas, and the other is evapotranspiration-induced cooling by natural Vegetation. To induce ET cooling, greening of the central Indian forests has to materialise before the actual arrival of the moist monsoon winds. Such an effect would be possible if the root system of natural Vegetation inherits temporally correlated genetic traits (Makarieva and Gorshkov 2007), hence, stressing the importance of native species in the local

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ecosystem. However, the exact triggering mechanism in the root system of trees requires ground-level and species-level detailed study which is out of scope of this research.

Further evidence of increased ET during the monsoon and post-monsoon, acting as a moisture feedback to maintain the balance of ground water, was also observed over central India (Goroshi et al. 2017). Kannemadugu (2019) observed that long-range convective transport of dry dust due to north-western winds contributes in increasing aerosol optical depth in central India during the pre-monsoon. However, southwestern winds, caused by a low pressure system over the Tibetan plateau, bring moist ocean winds to central India, and ET from natural Vegetation helps in condensing these moist winds. O'Connor et al. (2021) conducted a study on 14 biomes distributed across the globe and showed that a forest buffering effect on precipitation was found in 10 biomes. They observed that the tropical region receives ~50% of the precipitation due to the presence of forests. In another study based on a dynamic recycling model, Roxy et al. (2017) observed that forests contributed in capturing 29% of rainfall. Due to the continuous stretch of forest patches in MP, CH and OD a larger extent of precipitation-shed over India can be seen on the eastern side (**Fig. 4**).

Interestingly, we found that a higher magnitude of rainfall was observed consistently over the forested region, on an inter-annual basis (**Fig. 3 and 4**), and higher frequency of low rainfall was observed outside the forested region. It was found that inter-annual rainfall variability was uniform inside the forest area, while the rain was unevenly distributed outside the forested area. During the drought years (2002 and 2015), the RF variability was low in forested areas, but high in non-drought years (2011 and 2016). Interestingly, the rainfall variability was high outside the forest area irrespective of wet or drought conditions and year (**Fig. S2**). On the other hand, it was observed that the Positive Indian Ocean Dipole (IOD), which brings more monsoon rainfall over India during the months of July and August (Anil et al. 2016), was associated with rainfall over the forested region (**Fig. 8**).

Remote sensing-based NDVI data revealed greening trends across the globe (Zhu et al. 2016; Chen et al. 2019) and over central India Singh et al. (2021) which is expected to increase ET over the study area and, hence, increase rainfall intensity. Knox et al. (2011) conducted a similar study to the present one to characterize the variability in precipitation over forest areas, non-forest areas and forest edges in the Amazon. They found that rainfall tends to be influenced by the presence of natural Vegetation, supporting the results presented here. In this research, the mean rainfall in the different elevation classes with forests was found to be consistently around 1500 mm with less variability than in the non-forested area where the mean rainfall was around 1000 mm. Makarieva et al. (2013) showed that tropical forests experienced less rainfall variation at the centre of continents or landscapes, located far away from the oceans. However, rainfall magnitude is greater in elevated regions of the

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world (IPCC 2014). Zeng et al. (2015) linked changes in rainfall to elevation in the Sichuan province of China, in monthly, seasonal and annual rainfall events. Similarly, in this study, the effect of relief on the rainfall distribution was observed, and the 800-1643 mm elevation class received maximum rainfall irrespective of the presence of forests. However, the presence of forests induced more rainfall in the 300 to 800 m elevation range.

The average rainfall was found to decrease exponentially with an increase in distance from forest edges. Such a decrease might vary due to transpiration differences at the edges due to variation in land cover composition (Giambelluca et al. 2003). Makarieva and Gorshkov (2007) explored rainfall variability with distance from forests. They obtained samples from various parts of the world, but did not include the Indian Subcontinent. Srivastava et al. (2017) reported intra-seasonality rainfall variability, and observed a relationship between evaporation, soil moisture and rainfall. Although the central Indian forest is a fragmented landscape, its role in capturing the monsoon rainfall is relatively similar to that of any other forest, be it in the Amazon or Congo, as well as maintaining a balance in the hydrological cycle and multiple ecosystem services.

In this research, it was found that the long-term average rainfall was higher in the eastern half of the study area than the western half, under different NDVI classes. On the other hand, the rainfall variability was greater in the western side as shown in **figures S4 & S5**. Interestingly, all forested sample zones experienced different amounts rainfall despite falling into the same or different climate zones, which could be due to differences in forest density, species type or understory composition. Also, the zones adjacent to forested regions experienced a similar magnitude of average rainfall (e.g. NFEZ- Ad1 & Ad3, **Fig. 9**). Also, meteorologically, differences in differential heating across heterogeneous land surfaces, evaporation rates, atmospheric circulation and water availability, could lead to variability in rainfall and cloud formation (Bonan 2008; Knox et al. 2011; Spracklen et al. 2012). As per Makarieva and Gorshkov's (2007) hypothesis, a transitional increase in rainfall towards inland over the forested landscape from the eastern and western coast was observed in this research. The spatial profiles AB and CD in **Figure 12** revealed a clear increase in rainfall associated with forests, likely due to the ET effect described above, and a decrease towards the coast and the MP borders. On the other hand, the spatial profiles EF and GH showed the orographic effect on rainfall due to the presence of the Western Ghats (Tawde and Singh, 2014; Phadtare et al., 2022). The rainfall on the rain shadow side was lower, but started increasing towards the forest areas (**Fig. 13**).

Reduced rainfall intensity and high rainfall variability have been linked to deforestation in various parts of the world like the Amazon and African Sahel, and a weakening of the monsoon (Bonan 2008; Staal et al. 2020b). In this research, we observed that rainfall is consistently high in regions with high forest density. Results from

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various studies imply that increasing rates of global deforestation and degradation would reduce the forest density which, in turn, is likely to affect rainfall intensity. Recent droughts in the Amazon region and reduced water depth downstream could be linked to increased deforestation and fragmentation reducing the cumulative tree projection area and volume of moisture transport leading to a reduction in net condensation volume in the Amazon basin (Chen et al. 2009; Atkinson et al. 2011; Lewis et al. 2011). Spracklen et al. (2012) examined the rainfall over tropical regions and reported that moist air passing over extensive vegetative areas produced at least twice the rainfall compared to less forested areas. This is also true in the present study because of the high leaf area index, which maintains high evapotranspiration fluxes in the continuous intact natural undisturbed forested area (**Fig. 13**) (Bonan 2008; Sheil and Murdiyarso 2009; Knox et al. 2011; Ellison et al. 2017). Relief and altitude differences cause adiabatic expansion of moist air, which condenses after reaching a certain height (Makarieva and Gorshkov 2007; Ellison et al. 2017).

Rainfall variability in central India is not uniform, either spatially or temporally, even though the south western moist winds blow over the entire central Indian landscape. The results of this study suggest, in particular, that the presence of deciduous forests in central India plays an important role in generating precipitation through condensation services. Considering its major role in condensation, it is vital to conserve, manage and protect the large deciduous forests of the central Indian landscape to minimise the impact of future climate change on the region and sustain society. Without awareness of this fragility, and actions to protect the forests, it is possible that the monsoon system over central India may experience a regime shift under large-scale fragmentation and/or deforestation of this forested landscape. We recommend further detailed investigation, and declaration of the central Indian forested landscape as a Monsoon Hotspot to protect it from further degradation due to pressure from climate change, increasing population and human disturbances. We also recommend further studies on large-scale regional eco-hydrology and estimation of the precipitating effect of major ecological reserves.

5. Conclusion

Tropical forests balance the regional climate and help in reducing warming during the summer months. In the drought-prone central Indian region the valuable ecosystem services of forests, such as biodiversity conservation and ecotourism, as well as the aforementioned adjustments to the micro-climate and water storage, make them a crucial element of the biosphere. This research investigated the inter-annual rainfall variability over the forested and non-forested landscapes of central India on a monthly and inter-annual basis using 18 years of time-series rainfall data. We investigated the association of rainfall with forests under various conditions, with the

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ultimate aim of understanding the possible influence of forests on the spatial pattern of rainfall. We found that the long-term average rainfall was higher in the forest rich eastern region than the agriculture-dominated western region. However, focusing on forests only, rainfall in the eastern coastal region (<100 km from coastline) was found to be less than in the western coast. The highest rainfall variability was observed in the agriculture-dominated MH whereas the least rainfall variability was observed in the forest-dominated CH and OD.

In summary, we suggest that rainfall over central India is controlled majorly by two factors: (a) the orographic effect and (b) evapotranspiration from natural Vegetation. The high rainfall in the western aspect of the Western Ghats region is due to a dominant orographic effect, and the reduced rainfall in the agriculture region of MH is due mainly to its disadvantaged position in the leeward rain-shadow. A buffer analysis confirmed that core areas inside forests receive higher rainfall than the edges and, crucially, rainfall decreases outwardly with distance from the forested areas. Moreover, as illustrated by the spatial profiles of rainfall, the presence of vegetation exhibited a large correlation with rainfall occurrence. It is possible that the distribution of forests induces the condensation of the moisture-laden monsoon wind over tropical central India, in addition to other meteorological variables. However, vegetation-climate feedback mechanism is complex as there are many terrestrial and atmospheric factors control monsoon rainfall distribution in India, and forest could be one of the important factor. This research highlights the potential role of forests in regulating the spatial distribution of rainfall in the central Indian landscape. Further research on this critical regulatory ecosystem service is required.

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Author contribution

BS and CJ designed the study, carried out data analysis and wrote the manuscript. VSR, PMA, MDB, CPS, JD and PSR participated in logical discussion for improving the concepts, data analysis and contributed in editing

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and enhancing the write-up. All authors discussed results, discussion and conclusion. All the authors have given approval to the final version.

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Data availability The data analysed to carry out the current study are freely available from the LPDAAC (Land Processing Distributed Active Archive Center (https://lpdaac.usgs.gov) The monthly precipitation dataset of Climate Hazards Group Infra-Red Precipitation with Station data (CHIRPS version 2.0) is also freely available for downloading from 1981 onwards(ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRP/month-ly). Data used in this research cab be available from the corresponding author on reasonable request.

Code availability The open source R computing and analysis software was used in this research. Figures generated using R codes are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval Not applicable.

Consent to participate The authors declare that they all participated in the preparation of final draft of the manuscript and contributed accordingly.

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