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Exploring Temporal Rainfall Variability and Trends Over a Tropical Region Using Tropical Rainfall Measurement Mission (TRMM) and Observatory Data

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Abstract

Kerala is the gateway of the Indian southwest monsoon. The Tropical Rainfall Measurement Mission (TRMM) rainfall data is an efficient approach to rainfall measurement. This study explores the temporal variability in rainfall and trends over Kerala from 1998-2019 using TRMM data and observatory data procured from India Meteorological Department (IMD). Direct comparison with observatory data at various time scales proved the reliability of the TRMM data (monthly, seasonal and annual). The temporal rainfall converted by averaging the data on an annual, monthly and seasonal time scale, and the results have confirmed that the rainfall estimated based on satellite data is dependable. The station wise comparison of rainfall in monsoon season provides satisfactory results. However, estimation of rainfall in mountainous areas is challenging task using the TRMM. In the basins of humid tropical regions, TRMM data can be a valuable source of rainfall data for water resource management and monitoring with some vigilance. In Kerala, the study found an insignificant increase in the southwest monsoon and winter season rainfall during last two decades. The rainfall over Kerala showed uncertainty in the distribution of monthly, seasonal and yearly time scales. This study provides a preview of recent weather patterns that would enable us to make better decisions and improve public policy against climate change.

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1 INTRODUCTION

The Kerala state is gateway of Indian monsoon (Joseph *et al.*, 1994). The southwest monsoon irrigates the majority of Kerala's cropland. The onset of the monsoon dictates the timing of crop sowing because the amount of rainfall influences productivity. Because of the higher geographical variability of rainfall in a tropical region like Kerala, rainfall measurement, monitoring, and analysis are essential. However, the current rainfall observation network is insufficient to monitor the rainfall. It might be challenging to set up and maintain weather stations in remote locations. The highly dynamic nature of precipitation in terms of amount and intensity over a given area makes determining its geographic distribution difficult (Sharma *et al.*, 2012). However, meteorological satellites can provide a precise spatial distribution of rainfall. TRMM (Tropical Rainfall Measurement Mission) is a research satellite built by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) as part of their joint space mission (Bookhagen, 2010; Sharma *et al.*, 2012). It uses space-borne radar to detect the precise estimations of near-surface rainfall. The TRMM intended for better recognizing the distribution and variability of rainfall in the tropics as part of the current climate system. It can provide reliable rainfall estimates

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with adequate validation of rainfall (Gu *et al*., 2010; Chang *et al*., 2013; Tarek *et al*., 2017). David (2020) found that comparing annual TRMM data to average rainfall readings from the India Meteorological Department (IMD) yields a 0.85 correlation coefficient, indicating that the estimation is trustworthy.

Studies on rainfall variability and trends have been conducted by various researchers worldwide (Nicholson and Grist, 2001; Murphy and Timbal, 2007; Nouaceur and Murarescu, 2020). Parthasarathy *et al*. (1995) studied the Indian monsoon rainfall for long-term trends over the country and the subdivisions. Thomas *et al*. (2015) and Sreelash (2018) studied seasonal and annual rainfall trends over Kerala during the last century. The long-term tendencies of precipitation over Kerala state were studied by Soman *et al*. (1988), Krishnakumar *et al*. (2009), Pal and Al-Tabbaa (2009) and Thomas and Prasannakumar (2016). The yearly and southwest monsoon season rainfall amounts in Kerala have dropped over the previous century (Guhathakurta and Rajeevan, 2008; Krishnakumar *et al*., 2009). Nikhil Raj and Azeez (2010) showed that climate change affects rainfall variation locally and globally. They evaluated the region's annual rainfall, southwest monsoon and pre-monsoon rainfall, indicating a significant decline in rainfall over the last years. The annual and seasonal rainfall trends in most parts of Kerala are also showing a considerable decline. According to Nair et al. (2014), the declining trend in rainfall and global anomalies linked to greenhouse gas emissions from increased petroleum consumption, land-use variation due to developmental activities and deforestation, and atmospheric pollutants linked to transportation facility development.

Researchers are facing the scarcity of rainfall data due to unavailability and higher costs especially for weather stations in remote areas. The TRMM data can generate the daily rainfall data. Therefore, this study tries to estimate the variability and trends over Kerala during 1998-2019 using TRMM data. The observatory data used to find out the dependability of the TRMM data. We used both IMD and TRMM data simultaneously to compare the trends and variability. Statistical techniques, the Mann-Kendall test and Sen's slope used to evaluate annual, monthly, and seasonal rainfall variability and trends. Numerous researchers have studied the trends and variability of rainfall over Kerala based on data for last 100 years or longer but not for the recent years. Therefore, the present study focused on analysis of monthly, yearly and seasonal variability and trends in rainfall during the last 22 years (1998-2019) over Kerala state. It will be beneficial to understand the most recent climate changes, and it will be helpful to the state government for adaptation of management strategies to ameliorate the harmful effects of climate change.

2 STUDY AREA

Kerala state is located between 8.25º N and 12.83º N latitudes and 74.83º E and 77.50º E longitudes (Figure 1) on southwestern coast of India. This tropical state distinguished by its terrain, bounded on the West by the Arabian Sea, a portion of the Indian Ocean, and on the East by the Western Ghats, which reach heights of 500-2700m and are home to forty-four rivers. Kerala divided geographically into three regions: the highlands, which descend from the Western Ghats, and the midlands, consisting of sloping hills and valleys that form an uninterrupted coastline with several scenic backwaters connected to canals and rivers. The monsoon seasons (June-September and October-November) and summer (February-May) are the most significant seasons here, whereas winter brings a modest temperature fall from the typical range of 28 to 32°C. The long-term average annual rainfall of Kerala is approximately 3000 mm. The majority of population in Kerala relies on agriculture for their living, either directly or indirectly. Paddy, coconut, pepper, cashew, cassava, and plantation crops (rubber) are the principal crops farmed in the state. Kerala's economy is based on agriculture, with cash crops such as coconuts, rubber, tea and coffee, pepper and cardamom, cashew, areca nut, nutmeg, ginger, cinnamon, cloves, and other spices giving the state's agriculture a distinct flavor. Handloom, handicraft, bamboo, coir, Khadi and village, cashew, tourism, and other industries dominate Kerala.

3 DATA AND METHODS

The study depended solely on TRMM and IMD rainfall data. The daily accumulated precipitation data results from the TRMM Multi-Satellite Precipitation Analysis (TMPA) data collected every three hours (3B42) (Huffman *et al*., 2016). It covers daily rainfall data from 50º S to 40ºN at a 0.25º x 0.25º spatial resolution. The 3B43 dataset is a monthly product of the 3B42 dataset. This product derived using TRMM-adjusted integrated microwave infrared precipitation rates and root-mean-square error estimates. TRMM three hourly and monthly rainfall data can be freely accessible, and it is available on the website maintained by NASA. In this study, the TRMM daily rainfall was calculated using area-averaged gridded data. We have selected the area-averaged gridded rainfall data for the fourteen districts of Kerala where the IMD observation networks are available. It will increase the accuracy of TRMM data while comparing it with IMD observatory rainfall. The area-averaged daily precipitation data for 14 districts retrieved and used to figure out the average monthly, seasonal, and annual rainfall over Kerala. IMD Monthly rainfall data for Kerala was obtained from the IITM publication "Monthly, Seasonal, and Annual Rainfall Time Series for All-India, Homogeneous Regions, and Meteorological Subdivisions: 1871-2016" (Kothawale and Rajeevan, 2017), and for 2017 to 2019 data was collected from the IMD publication "Rainfall Statistics of India - 2012 to 2019". Statistical analysis employing standard parameters used to evaluate the satellite data to the IMD observatory data. Among these, the Pearson correlation coefficient, which used to determine the linear relationship between two data sets. Additionally, the bias factor (Duan *et al*., 2012) and the Root Mean

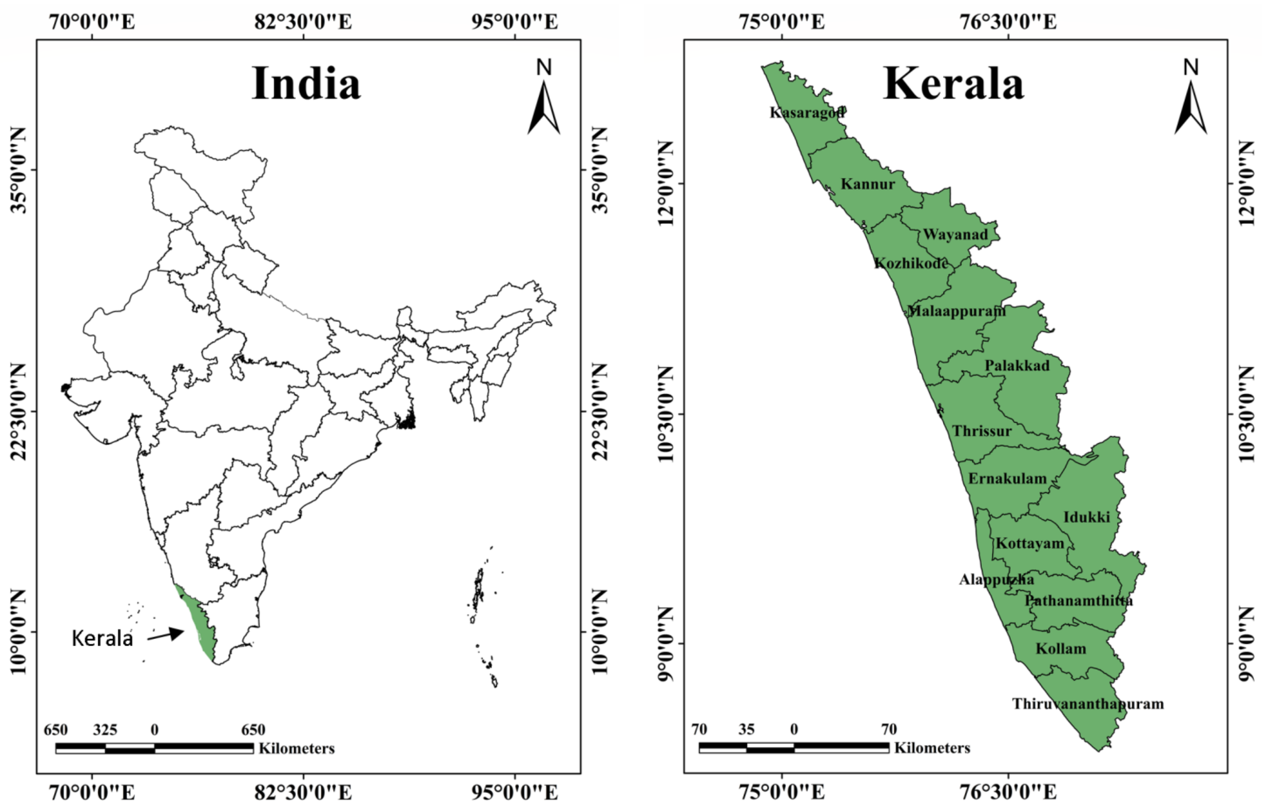

Figure 1. Study area: Kerala state of India

Square Error (RMSE) are used to assess the difference in TRMM and IMD observatory data.

Daily rainfall data (1998 to 2019) used to analyze trends, variability, and mean rainfall patterns. The analysis of rainfall data separated into four broad categories: yearly, monthly, seasonal, and decadal time scales. First, the daily rainfall data converted to monthly data. The Pre-monsoon (March to May), Southwest Monsoon (June to September), Post-monsoon (October to November), and winter (December to February) are the prominent seasons considered. Then, monthly rainfall data divided into two groups to determine rainfall variability across two periods: 1998-2008 and 2009-2019. To compare the spatial dependence and station wise performance of TRMM data, we compared the monsoon season rainfall for 14 stations. The mean, standard deviation (SD) and coefficient of variation (CV) used to determine rainfall patterns and variability. The Mann-Kendal test and Sen's slope used to determine the magnitude of annual, monthly, seasonal, and decadal rainfall trends. For all rainfall trends, the p-value used to determine statistical significance. There is some discrepancy between the results of both the data sets. Therefore, the trend and variability analysis derived from the IMD data considered as acceptable results.

4 RESULTS AND DISCUSSION

4.1 Comparison of Rainfall Data

4.1.1 Comparison of Annual Rainfall Data

The TRMM 3B42 V-7 rainfall products compared to annually averaged observatory data. The comparison in Table 1 shows that the TRMM values for annual average rainfall match the observatory data very well. The correlation coefficient (r) and root mean square error (RMSE) for annual average daily rainfall were determined to be 0.876 and 286.8 mm, respectively. The regression plot with 95% confidence intervals shows that the majority of points lie inside the interval. It indicates that both the data sets are highly correlated (Figure 2). The mean, SD, and CV for the observatory data are 2722.3mm, 420.9mm, and 15.5%, respectively, whereas, for TRMM data, they are 2515.5mm, 351.1mm, and 14%.

The bias parameter indicates the extent to which the measured value is over- or under- estimated. A negative bias value obtained for most of the year in this investigation, indicating that the TRMM underestimates the observatory data (Table 1). The lower negative bias value emphasizes that the TRMM slightly underestimates the actual rainfall. Tarek *et al.* (2017) also revealed that the TRMM annual average rainfall outcomes projected to generate similar findings to rain-gauges on a macro scale.

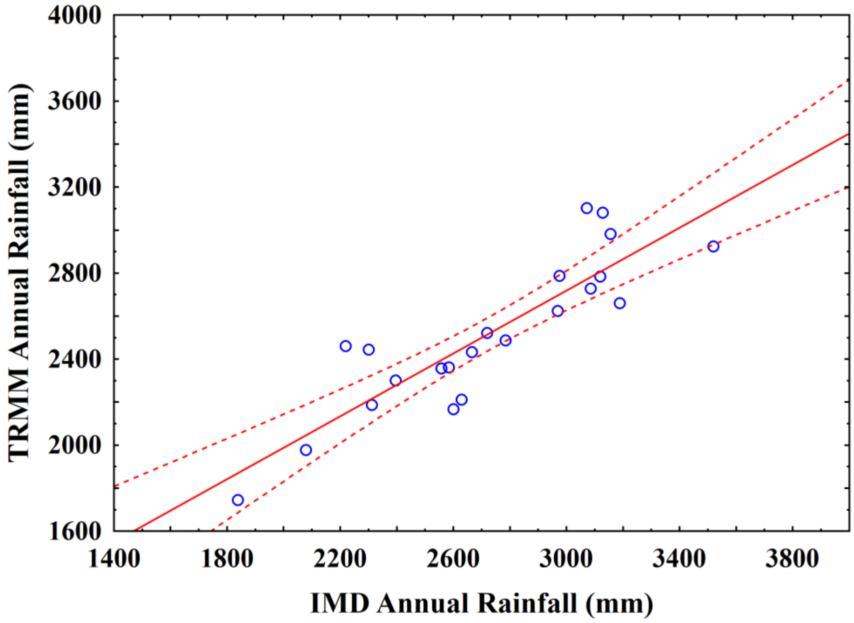

Figure 2. Regression plot of the average annual accumulated rainfall recorded at observatory against TRMM data (1998-2019)

4.1.2 Comparison of Monthly Rainfall Data

Furthermore, the TRMM 3B42 V-7 total monthly rainfall data series compared to observatory data throughout the study period (Figure 3). Both trajectories are reasonably similar, indicating that the TRMM data is judiciously close to the value of the observatory data. However, a comparison of monthly rainfall averages demonstrates that the TRMM 3B42 V-7 often underestimates observatory rainfall data. For example, as illustrated in Figure 3, significant underestimations seen in peak values during the monsoon seasons of 2001, 2002, 2004, 2006, 2013, and 2019. Despite these discrepancies, the correlation coefficient (r) and root mean square error (RMSE) for monthly average daily rainfall found to be 0.989 and 42.70 mm, respectively, signifying that the monthly TRMM data is sufficiently reliable.

Figure 4 depicts the average monthly rainfall for both datasets from 1998 to 2019. The bias value indicates that the TRMM 3B42 V-7 data tend to overestimate rainfall from January to April and November while underestimating rainfall from June to September. However, both datasets closely match rainfall in October and December. June is the month with the most significant underestimation. In general, it can be concluded that the TRMM products reliably reflect monthly records.

Table 1. Annual rainfall from observatory and TRMM data

Year	IMD (mm)	TRMM (mm)	Bias
1998	3070.7	3103.8	0.0
1999	2974.2	2787.6	-0.1
2000	2219.0	2461.4	0.1
2001	2628.9	2212.8	-0.2
2002	2600.0	2167.7	-0.2
2003	2311.7	2187.2	-0.1
2004	2719.7	2522.9	-0.1
2005	2300.7	2445.0	0.1
2006	3155.8	2982.8	-0.1
2007	3128.2	3081.6	0.0
2008	2395.5	2300.8	0.0
2009	2584.0	2363.1	-0.1
2010	3085.0	2728.1	-0.1
2011	2784.4	2487.2	-0.1
2012	2078.4	1977.8	0.0
2013	3188.5	2661.1	-0.2
2014	2968.2	2624.5	-0.1
2015	2557.6	2357.4	-0.1
2016	1837.4	1745.7	0.0
2017	2664.9	2432.5	-0.1
2018	3518.9	2924.8	-0.2
2019	3119.2	2784.3	-0.1
Mean	2722.3	2515.5	-0.1

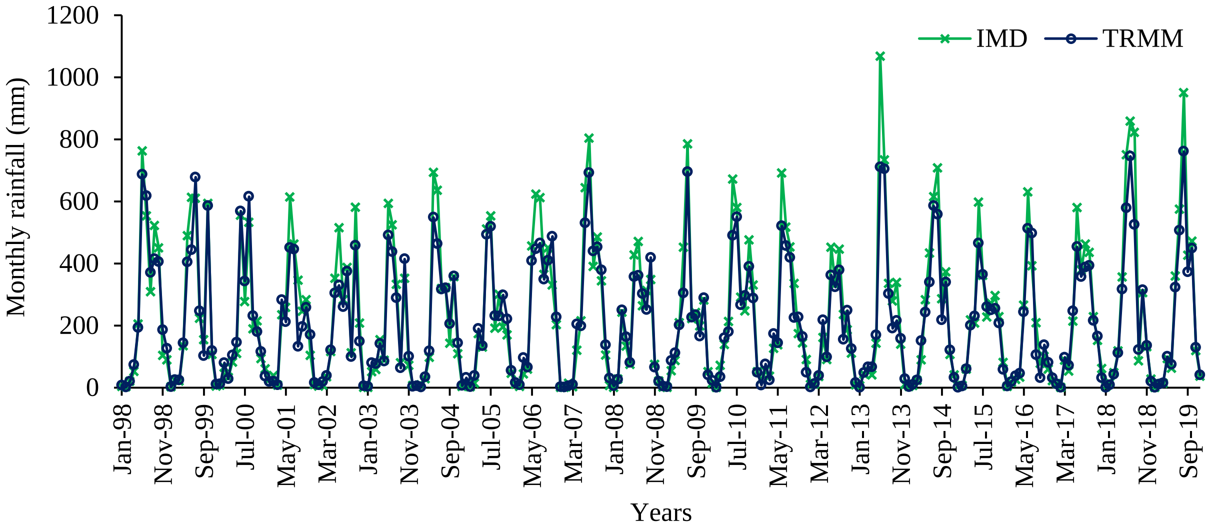

Figure 3. Monthly rainfall recorded at observatory and TRMM data

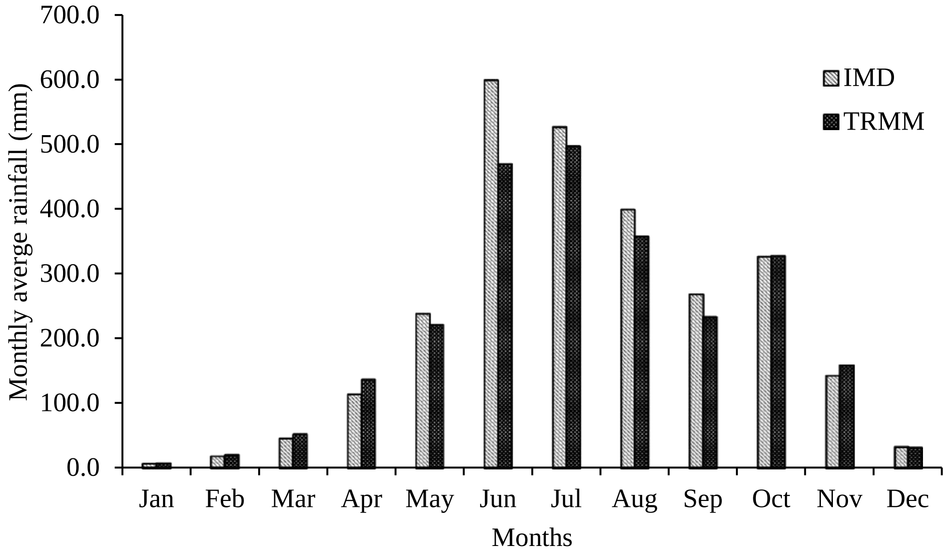

Figure 4. Average monthly rainfall recorded at observatory and TRMM data (1998-2019)

4.1.3 Comparison of Seasonal Rainfall Data

Another comparison made between TRMM 3B42 V-7 rainfall products and observatory data based on seasonal classification. The comparison of the two datasets for Kerala's four different seasonal average rainfall levels shown in figure 5. The TRMM data for winter, pre-monsoon, southwest monsoon and post-monsoon is more consistent with the observatory data, with correlation coefficients of 0.855, 0.963, 0.899, and 0.834 with RMSE values of 19.57, 50.42, 286.85, and 85.11 mm, respectively. The presence of a high R-value suggests that TRMM can follow the trend, whereas the RMSE shows the presence of under-or over-estimation. TRMM consistently underestimates observatory rainfall data during the southwest monsoon, with an average bias of -0.13.

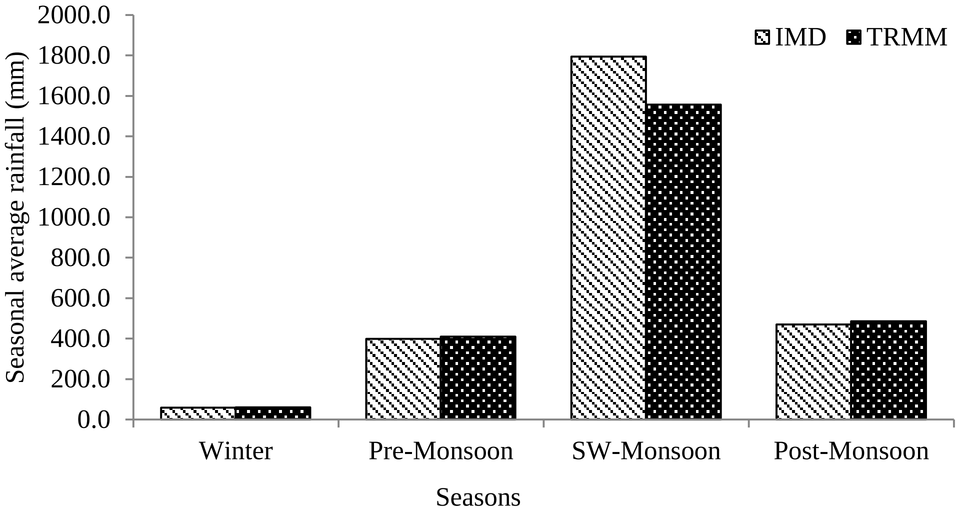

Figure 5. Seasonal average monthly rainfall recorded at observatory and TRMM data (1998-2019)

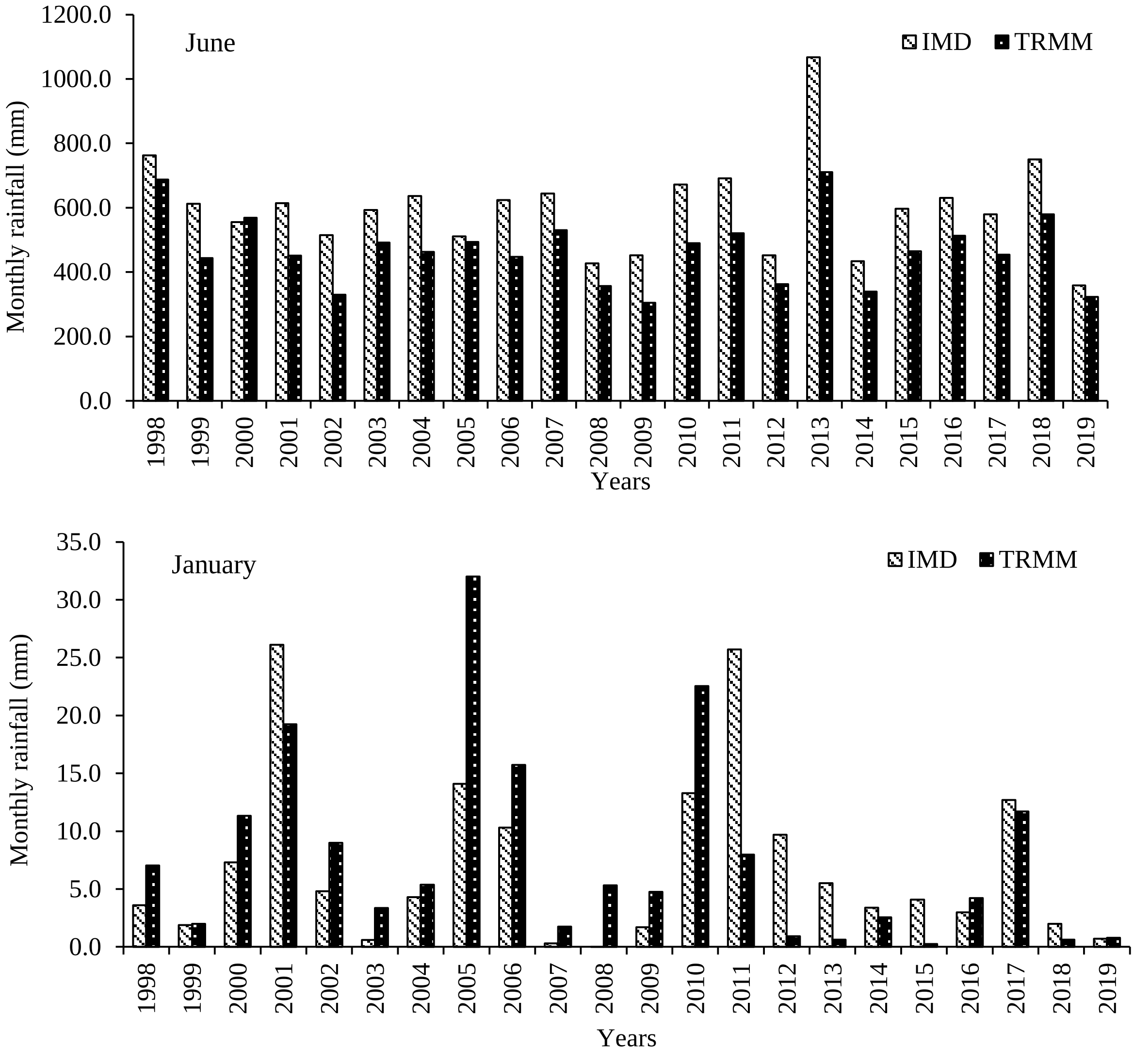

Figure 6. Average rainfall recorded at observatory and TRMM data for highest (June) and lowest (January) months (1998-2019)

4.1.4 Comparison of Highest and Lowest Rainfall Month

Moreover, the TRMM 3B42 V-7 total monthly rainfall data compared to observatory data for the study period's peak and lowest rainfall months (Figure 6). June is the wettest month, while January is the driest. Thus, TRMM underestimates total rainfall in June and overestimating in January months. The TRMM data for the month with the highest and lowest rainfall values agrees better with the observatory data, with R values of 0.871 and 0.618 with RMSE values of 149.3 and 6.78 mm, respectively. The TRMM delivers more reliable estimated estimations during the month with the highest rainfall than during the month with the lowest rainfall.

4.1.5 Comparison of Station Wise Data and Spatial Pattern

Kerala is a complex terrain with significant topographical changes, especially from the West (Arabian Sea) to East (Western Ghat) directions with an average width of approximately 70 km. In this short distance, we can observe seashore, plains and hills. Some regions are below sea level (Kuttanadu region) to 2695 m (Anamudi peak) above sea level. To compare station wise monsoon season rainfall, we selected 14 major IMD stations (Figure 7), representing each district for the last ten years (2009-2019; the year 2011 has no district wise rainfall station data available). Rainfall readings are frequently sensitive to location and altitude. It is decided to explore the TRMM rainfall features in relation to the terrain topography and elevation. The seasonal distribution (South-West Monsoon) and performance evaluated for 14 different topographical gauge locations. District wise prominent station names and their corresponding IMD, TRMM, bias value and elevation from mean sea level described in table 2. While analyzing the spatial pattern, it identified that the amount of monsoonal rainfall increases from South (Thiruvananthapuram -807 mm) to North (Kasaragod - 2725 mm) gradually. It indicates that the Northern part of Kerala receives more rainfall than the Southern part. Similarly, Simon and Mohankumar (2004) reported that the North region receives more rainfall than the South region and stated that apart from the hilly region, the coastal region also receives abundant rainfall. The station data and TRMM data comparison obtained reasonable similarity with a correlation coefficient of 0.85, coefficient of determination of 0.72 (Figure 8) and RMSE of 453.02 mm. The bias value indicates that in most cases, TRMM underestimates the station data. A higher bias value was obtained primarily for higher elevation stations of Pathanamthitta (-0.3), Idukki (-0.4), Wayanad (-0.3) and one lower elevation station, Kozhikode (-0.3). The TRMM outcomes are sometimes diverge, especially during the monsoon, and it has several significant underestimations in assessing values at the higher elevation stations viz., Pathanamthitta (101 m), Idukki (900 m) and Wayanad (1018m) compared to the lower elevation stations (<80 m) (Figure 9).

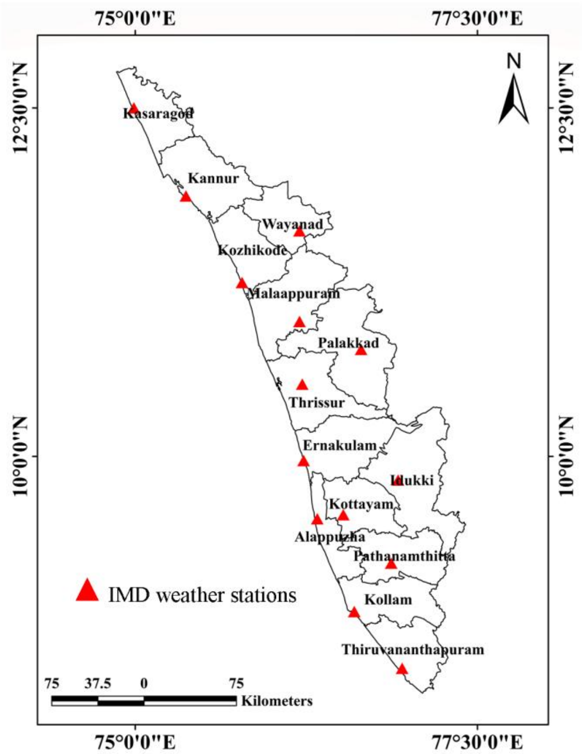

Figure 7. Weather stations of IMD in Kerala

However, the research revealed that obtaining rainfall amounts in mountainous areas was challenging using the TRMM satellite data. Both Almazroui (2011) and Milweski *et al*. (2015) have recognized the significance of undulating topography in influencing satellite and rain gauge accuracy. They all exposed a low level of agreement between TRMM and rain gauges at the high altitudes. While the TRMM satisfactorily predict the rainfall data for entire lower elevation stations except for Kozhikode station (10m). When there is much convection over land, the TRMM precipitation radar algorithm likely underestimates the amount of precipitation (Iguchi *et al*., 2009; Kozu *et al*., 2009). Kumar *et al*., (2020) observed the dynamic characteristics of convective systems that resulted in widespread rainfall over west coast of Kerala. However, dense clouds around India's West coast (8-20º N) indicate convective activity linked with low-pressure systems and active monsoon conditions in the southwest monsoon zone. Additionally, the higher level of emission from land obstructs the signal received by satellite sensors. As a result, an efficient statistical correction scheme may include stratifications for convective and stratiform precipitation, as well as rainfall over ocean and land (Chang *et al*., 2013). It may be the reason for the underestimation of station data of Kozhikode and some lower elevation station data by TRMM. However, because only ten years of station wise precipitation data were available, a fair conclusion could not be drawn in this context. Hence, a further detailed study using daily station wise data is necessary.

Table 2. Seasonal rainfall recorded at IMD stations and TRMM data

Station	IMD (mm)	TRMM (mm)	Bias	Elevation* (m)
Thiruvananthapuram	807.2	691.1	-0.1	12
Kollam	1281.0	1009.5	-0.2	12
Pathanamthitta	1543.1	1072.7	-0.3	101
Alappuzha	1529.8	1701.9	0.1	5
Kottayam	1887.7	1544.7	-0.2	25
Idukki	2401.1	1376.1	-0.4	900
Ernakulam	2144.1	1824.0	-0.1	3
Thrissur	1979.0	1833.1	-0.1	12
Palakkadu	1652.0	1421.9	-0.1	80
Malappuram	1990.6	1551.4	-0.2	75
Kozhikkodu	2690.6	1909.1	-0.3	10
Wayanadu	1968.9	1433.2	-0.3	1018
Kannur	2614.1	2344.3	-0.1	20
Kasaragod	2725.7	2562.2	-0.1	24

* Approximate elevations derived from Google Earth Pro.

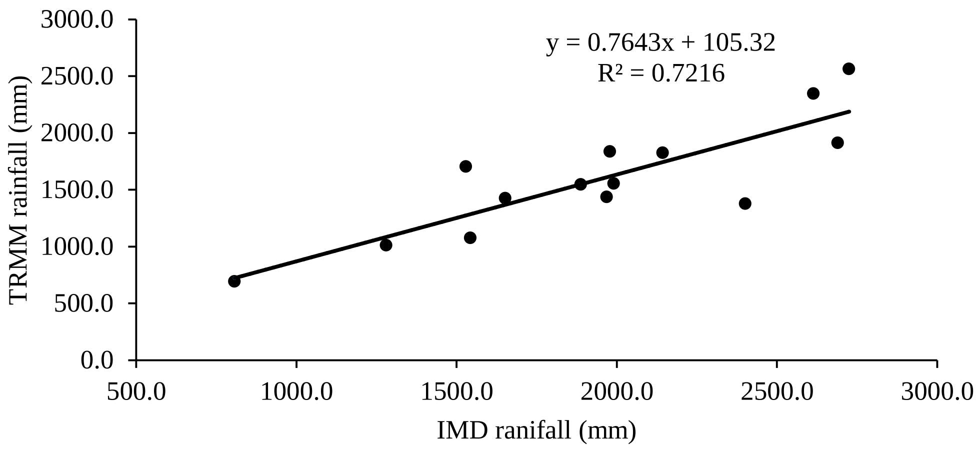

Figure 8. Scatterplot between the rainfall recorded at IMD stations and TRMM data in Monsoon season (2009-2019)

4.2 Rainfall Characteristics

Between 1998 and 2019 (Table 3), the yearly average rainfall in Kerala, according to TRMM, was 2515 mm, with a standard deviation of 351.1 mm. While observatory data indicates it about 2722.3 mm and a standard deviation of 420.9 mm. TRMM measured seasonal rainfall of 410.6 mm, 1557.6 mm, 486.6 mm, and 60.6 mm during the pre-monsoon, southwest monsoon, post-monsoon, and winter seasons, respectively, while observatory data indicates 399 mm, 1794.5 mm, 470.1 mm, and 58.7 mm, respectively. Annual rainfall has a coefficient of variation about 14% for TRMM data and 15.5% for IMD data, indicating that the rainfall very consistently. July has the highest TRMM rainfall (496 mm) and accounts for 19.75% of the yearly rainfall (2515.5 mm), followed by June (18.66 per cent). August and September are the rainiest months, accounting for 14.2% and 9.3% of yearly precipitation, respectively. January has the least rainfall (7.7 mm) and contributes barely 0.3% to the yearly precipitation. According to IMD data, June (599.2 mm) is the wettest month, while January (7.1 mm) is the driest. This discrepancy is due to the underestimation of observatory rainfall by TRMM sensor.

For IMD data, in January and March (106%), the coefficient of variation was at its maximum, followed by February (105.4%) and December (89.3%), and the lowest in June (24.8%) and July (32.1%). The southwest monsoon (June-September) accounts for 65.92% of yearly precipitation. Pre-monsoon (March-May), post-monsoon (October-November), and winter (December-January) rainfall contribute 14.66%, 17.27%, and 2.16% to the yearly total, respectively. Seasonal rainfall throughout the monsoon season (June-

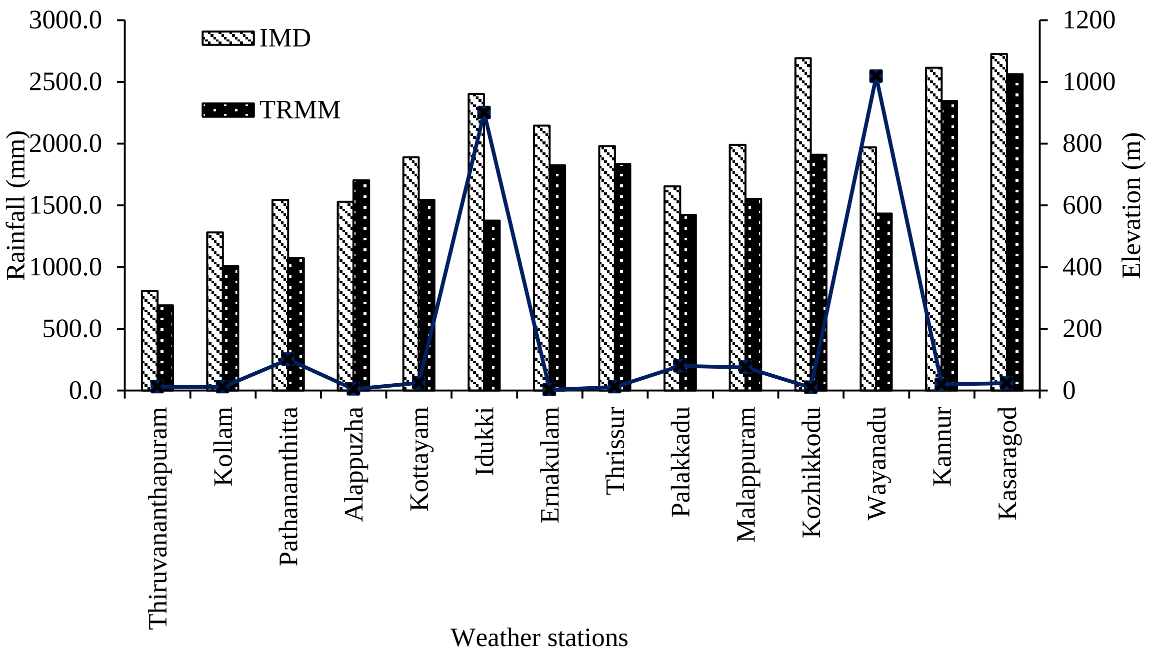

Figure 9. Rainfall recorded at IMD stations and TRMM data in Monsoon season (2009-2019) with the elevation

September) is consistent, with a coefficient of variation of 20.1% for both data sets. Meanwhile, rainfall in the winter is unpredictable due to the higher coefficient of variation (65.1%).

4.2.1 Annual Trends

Between 1998 and 2019, the TRMM-derived mean annual rainfall across Kerala exhibited an insignificant decreasing trend. The Mann Kendall test yields a -9 S value. The magnitude of the trend determined by Sen's slope is of -2.47 mm/year. At the same time, IMD observatory data from 1998 to 2019 over Kerala revealed an insignificant increasing trend. A positive S value of 21 obtained through the Mann Kendall test. The trend's magnitude determined by Sen's slope of 10.05 mm/year. The discrepancy is due to the underestimation of rainfall during the rainy months and overestimated during the drier months.

Figure 10 shows that the TRMM under predicts the rainfall in most cases, and the trend line of TRMM data is slightly decreasing, while the IMD data is relatively stable. The primary cause of the disparities in the two data sets is an underestimation of rainfall. It shows that the TRMM data can follow the trend of observatory data in most years. However, it is essential to note that no significant trend observed in the annual scale of rainfall during 1998-2019. As stated above, the validation of the data set is necessary for the TRMM studies in Kerala.

4.2.2 Monthly Trends

Individual monthly rainfall behaviour examined using the Man-Kendall test and Sen's slope (Table 4). It is worth noting that rainfall in January exhibited a declining trend that was statistically significant at the 0.05 level for the TRMM data, whereas observatory data showed a decreasing trend but was not statistically significant. March, July, August, September, and December rainfall had an insignificant increase in TRMM and observatory data. January, February, April, May, June, and October rainfall revealed a declining trend that is statistically insignificant for both TRMM and observatory data. In November, the observatory data indicated an increasing trend, while the TRMM data indicated a decreasing trend, and both data indicated an insignificant trend.

Considering observatory data (IMD) from 1998 to 2019, there was a drop in June's contribution to yearly rainfall (24 to 22 %) from 1991 to 2005 (Table 5). When comparing to rainfall data for June, the contribution of rainfall is more stable in July. At the same time, rainfall contributions increased in August (12.2 to 14.7%) and September (7.6 to 9.9%). A slight decrease in the yearly rainfall contribution observed throughout October and November. Over Kerala, the percentage rainfall contribution during the southwest monsoon increased while the post-monsoon season is decreasing and relatively consistent during the pre-monsoon and winter seasons. Recent decades have seen the development of these phenomena.

Table 3. Monthly and seasonal means of rainfall over Kerala (1998-2019)

	IMD-Rainfall				TRMM-Rainfall			
Month/ Season	Mean (mm)	SD (mm)	CV (%)	Contribution (%)	Mean (mm)	SD (mm)	CV (%)	Contribution (%)
January	7.1	7.5	106	0.26	7.7	8.3	107.5	0.31
February	18.6	19.6	105.4	0.68	20.8	26	124.9	0.83
March	46.1	48.8	106	1.69	52.3	51.5	98.5	2.08
April	114.2	53.3	46.7	4.2	137.2	59.1	43	5.45
May	238.7	154.6	64.8	8.77	221.1	118.3	53.5	8.79
June	599.2	148.5	24.8	22.01	469.4	108.7	23.2	18.66
July	527.1	169.3	32.1	19.36	496.8	145.9	29.4	19.75
August	399.5	199.2	49.9	14.67	357.5	154.3	43.2	14.21
September	268.7	133.3	49.6	9.87	233.9	117.4	50.2	9.30
October	327	129.5	39.6	12.01	327.6	117.5	35.9	13.02
November	143.1	69	48.2	5.26	159	58.5	36.8	6.32
December	33	29.5	89.3	1.21	32.1	26.8	83.3	1.28
Winter	58.7	38.2	65.1	2.16	60.6	34.6	57.0	2.41
Pre-Monsoon	399	152	38.1	14.66	410.6	117.3	28.6	16.32
SW-Monsoon	1794.5	374.4	20.9	65.92	1557.6	313.7	20.1	61.92
Post-Monsoon	470.1	155	33	17.27	486.6	126.1	25.9	19.34
Annual	2722.3	420.9	15.5	100	2515.5	351.1	14	100

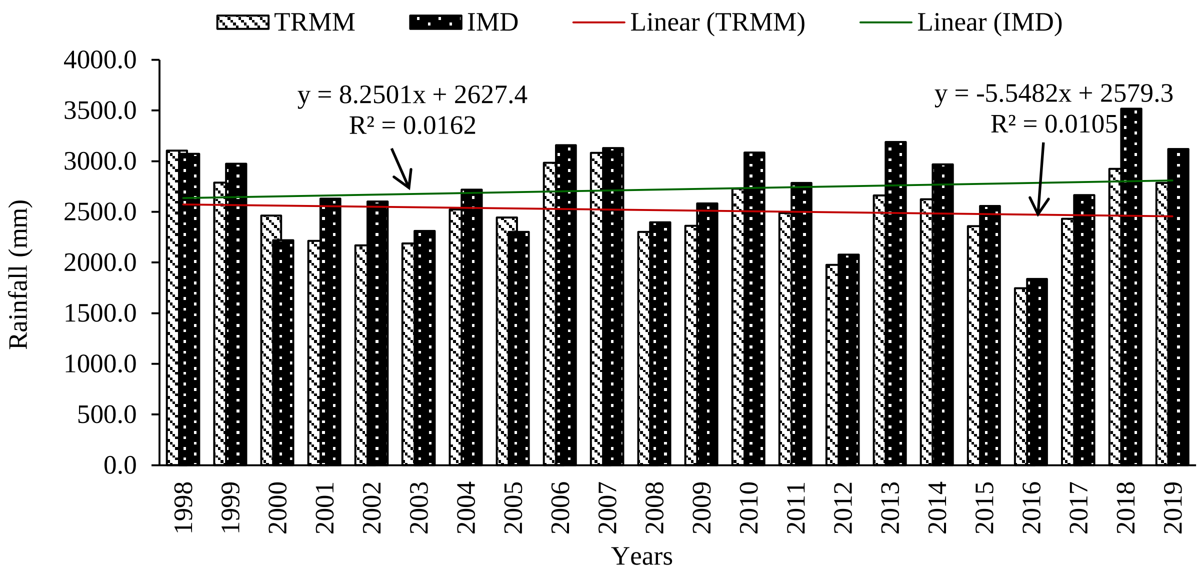

Figure 10. Annual rainfall trends over Kerala (1998 to 2019)

Table 4. Man-Kendall test Sen's slope statistics of monthly and seasonal rainfall

	IMD		TRMM	
Month/ Season	Mann-Kendall (S)	Sen's Slope (Q)	Mann-Kendall (S)	Sen's Slope (Q)
January	-23	-0.1	-76	-0.32*
February	-21	-0.29	-0.29	-0.38
March	49	1.21	39	0.93
April	-23	-1.29	-19	-1.16
May	-15	-1.63	-1	-0.21
June	-13	-1.21	-13	-2.01
July	37	5.45	31	3.15
August	53	9	39	6.1
September	15	4.2	5	1.12
October	-47	-4.37	-59	-6.94
November	39	1.2	-11	-0.79
December	51	1.23	39	0.94
Winter	1	0.13	-31	-0.73
Pre-Monsoon	-25	-6.44	-31	-4.67
SW-Monsoon	41	17.82	29	11.84
Post-Monsoon	-17	-2.02	-65	-7.91**

* Significant values at a<0.05, ** Significant values at a<0.1

4.2.3 Decadal Trends

The monthly rainfall data is divided into two sections to determine the variability and trend of rainfall over two time periods: 1998-2008 and 2009-2019 (Figure 11). Between 1998 to 2008, yearly rainfall decreased at a rate of 3.27 mm/year and 5.50 mm/year for observatory data and TRMM data, respectively, with a Man-Kendall value of -3 and -1. It is also worth noting that rainfall increased between 2009 and 2019 using both observatory and TRMM data, with a Mann-Kendall S value of 7 for both and a rate of 24.58 mm/year and 34.50 mm/year, respectively. However, the trend found throughout these periods is statistically insignificant. Extreme precipitation events have strengthened the frequency and intensity in India over the previous few decades (Roxy *et al.*, 2017) and the frequency of land falling tropical cyclones over the Arabian Sea has been increasing (Mohapatra, 2021). Thus, it could be the rising trend in rainfall over recent years. In addition, Mukherjee *et al.* (2018) observed an increase in heavy rainfall in India due to anthropogenic global warming, using data from the coupled model inter-comparison project 5 (CMIP5).

To explore the recent rainfall trend over Kerala, the most recent years, viz. 2009 to 2019 monthly, seasonal, and yearly rainfall, were analyzed using mean, SD, CV and percentage of contribution of annual rainfall (Table 6). The percentage contribution of rainfall during southwest rainfall increased from 1871 to 2005 (base period), while the post-monsoon and pre-monsoon showed a slight decrease compared to the base period. Compared to the base period, the months of August and October show a slight decrease in percentage contribution, while the rest of the month shows an approximately equal contribution to rainfall. The vital variation observed in the case of the variability of monthly and seasonal rainfall. The CV during the June, August, October months and the SW-monsoon and post-monsoons are increasing. It indicates that the consistency of rainfall during these months and seasons has decreased in the last decade, which means that uncertainty is increasing. At the same time, it is worth noting that annual rainfall is increasing compared to the baseline period. The frequent drought and flood years are the primary causes of these variations.

The increase in southwest monsoon rainfall and decreasing post-monsoon season rainfall during 1998-2019 is a significant finding in this study. The increase in rainfall more pronounced from July to September but not in June during the monsoon season. However, this trend is statistically insignificant. All other studies concur with Kerala's southwest monsoon rainfall is on the decline (Soman *et al.*, 1988; Rupa Kumar *et al.*, 1992; Guhathakurta and Rajeevan, 2007; Krishnakumar *et al.*, 2009). However, this study shows an increasing insignificant trend. The pivotal factor is that all of these analyses take the long-term climate of the 20^{th} century into account. Moreover, tropical cyclones have increased in frequency by a factor of two over the Bay of Bengal and Arabian Sea (Singh *et al.*, 2001;

Mohapatra, 2021). As a result, it could cause the current insignificant increase in the trend of rainfall.

4.3 Seasonal Trends

4.3.1 Winter (December, January and February)

The TRMM data show a decreasing trend in winter rainfall, while the observatory data show a rising trend, which is not statistically significant (Figure 12a and 12b). The only season in which contradictory results received is the winter season. When observatory data (IMD) from 1998 to 2019 analyzed, the rainfall contribution from 1991 to 2005 remained relatively constant (2.4 to 2.2%) (Table 5). It also identified that TRMM overestimates rainfall in these months.

4.3.2 Pre-Monsoon (March, April and May)

During 1998 and 2019, both observatory and TRMM data indicated a reduction in pre-monsoon rainfall. The rainfall trend observed to be slightly decreasing during this period (Figure 12). However, when comparing winter rainfall (observatory data) from 1991 to 2005 to the current time, the pre-monsoon rainfall appears to be very consistent (14.4 to 14.7%) (Table 5).

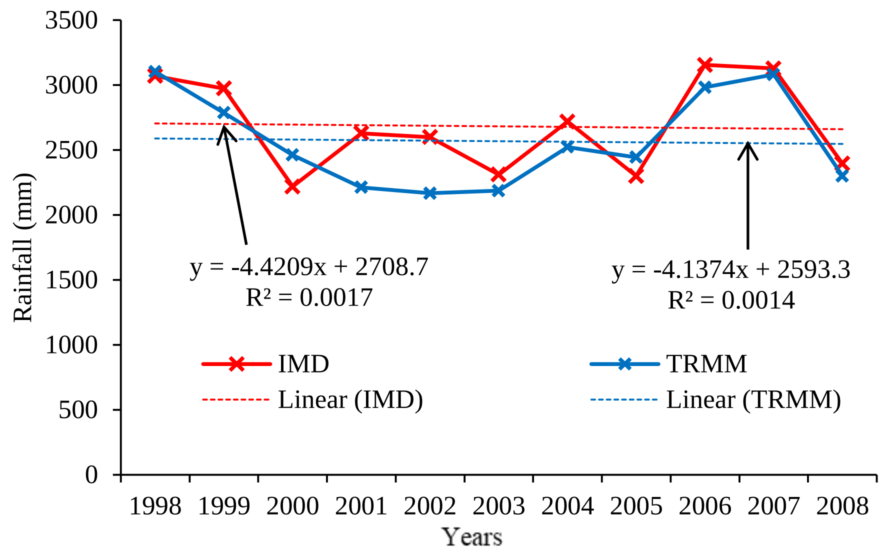

Figure 11a. Annual rainfall trends over Kerala during 1998 to 2008

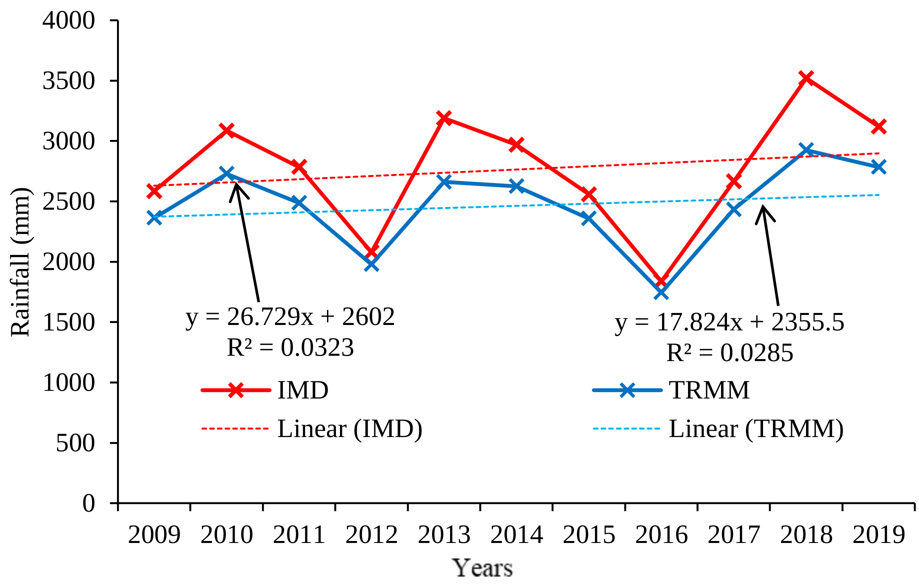

Figure 11b. Annual rainfall trends over Kerala during 2009-2019

4.3.3 Southwest Monsoon (June, July, August and September)

The southwest monsoon rainfall has increased over the last few years (1998-2019) (Figure 12). Concurrently, the TRMM and observatory data showed increased rainfall, with Mann-Kendall values of 29 and 41, respectively. According to Sen's slope, an increase of 17.8 mm for TRMM data and 11.8 mm for observatory data were observed. However, the study reveals that the growing trend is not statistically significant. Southwest monsoon rainfall increased from 63.6 per cent in 1991-2005 to 65.6 per cent in 1998-2019.

4.3.4 Post-Monsoon (October-November)

The Man-Kendall test found that seasonal rainfall during the post-monsoon period is significant at the 0.1 level, and a decreasing trend observed for TRMM data but not for observatory data. Additionally, it indicated that a reduction of 7.91 mm/season occurred during this period. As a result, post-monsoon rainfall decreased from 19.5 to 17.3% of annual rainfall over the current period compared to 1991-2005 for the observatory data.

Table 5. Seasonal rainfall contribution to annual rainfall during 1998 to 2019 and 1991-2005

	Krishnakumar et al. (2009)	IMD	TRMM
Month/ Season	1991-2005 (%)	1998-2019 (%)	1998-2019 (%)
June	24.0	22.0	18.7
July	19.7	19.4	19.8
August	12.2	14.7	14.2
September	07.6	09.9	09.3
October	13.3	12.0	13.0
November	06.3	05.3	06.3
Winter	02.4	02.2	02.4
Pre-Monsoon	14.4	14.7	16.3
SW-Monsoon	63.6	65.6	61.9
Post-Monsoon	19.5	17.3	19.3

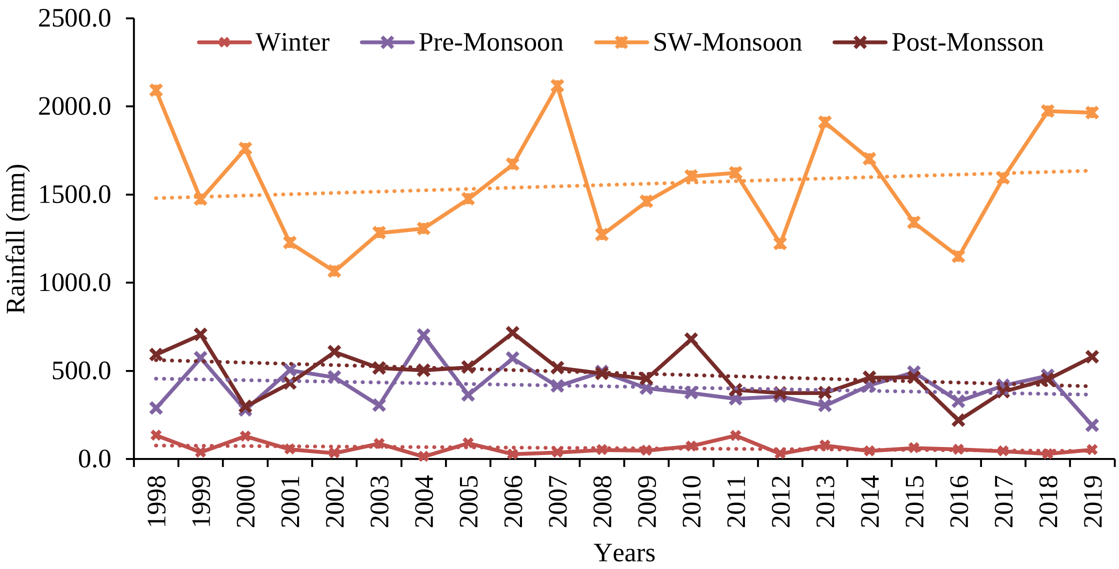

Figure 12a. Time series of seasonal rainfall derived from TRMM

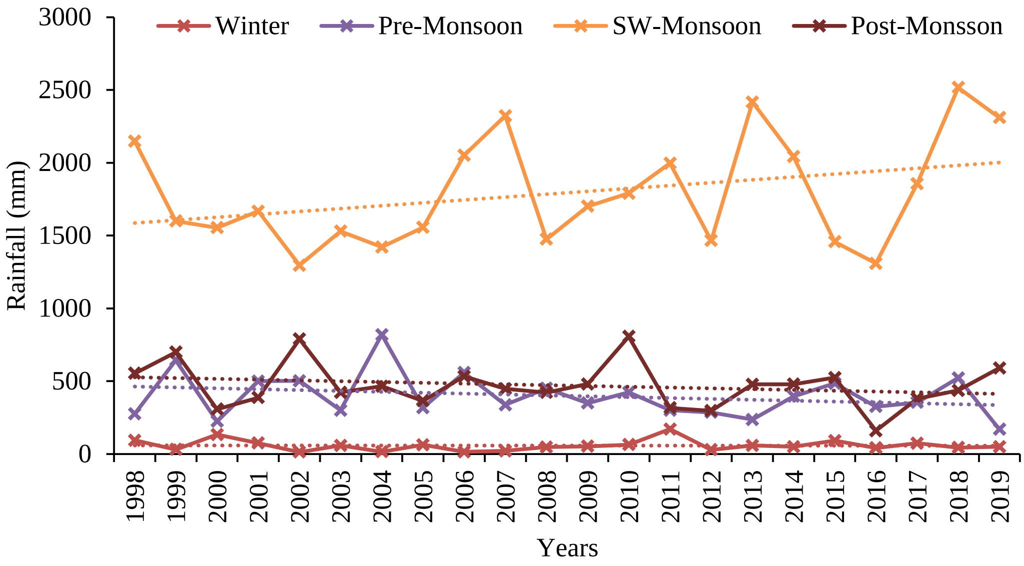

Figure 12b. Time series of seasonal rainfall derived from recorded data at IMD stations

Table 6. Monthly and seasonal means of rainfall during 1871 to 2005 and 2009-2019

	IMD-Rainfall (1871-2005)				IMD Rainfall (2009-2019)			
Month/ Season	Mean (mm)	SD (mm)	CV (%)	Contribution (%)	Mean (mm)	SD (mm)	CV (%)	Contribution (%)
January	12	17	146.1	0.26	7.4	7.5	100.6	0.27
February	17	19	115.4	0.68	15	17.8	118.8	0.54
March	36	28	78.5	1.69	46.4	22	47.5	1.68
April	112	52	46.5	4.2	105.2	55	52.3	3.81
May	246	159	64.6	8.77	198.2	86.3	43.5	7.18
June	684	194	28.4	22.01	607.9	196.3	32.3	22.01
July	632	209	33.2	19.36	557	181	32.5	20.16
August	373	157	42	14.67	466.1	255.1	54.7	16.87
September	224	122	54.7	9.87	265.5	113.8	42.9	9.61
October	288	108	37.5	12.01	286.1	122.1	42.7	10.36
November	156	85	54.4	5.26	164	82	50	5.94
December	38	39	102.1	1.21	43.6	26.8	61.6	1.58
Winter	65.3	65.3	14.4	2.16	66	38.4	58.2	2.39
Pre-Monsoon	393.7	393.7	41.5	14.66	349.8	103.9	29.7	12.66
SW-Monsoon	1913.5	377.7	19.7	65.92	1896.5	403.8	21.3	68.65
Post-Monsoon	444.1	138.4	31.2	17.27	450.1	169	37.5	16.29
Annual	2722.3	420.9	14.4	100	2762.4	493.4	17.9	100

5 CONCLUSION

This study aims to identify the variability and trend of rainfall over Kerala during the last two decades. The IMD observatory data and TRMM data used as the primary data for this study. It also aims to identify whether TRMM derived data is reliable for the studies conducted in Kerala. The observed results indicate that the Tropical Rainfall Measuring Mission (TRMM) 3B42 V-7 data correlates well with the observatory data on the monthly, seasonal, and annual scales. The study's primary limitation is that the authors did not validate the daily TRMM data against the daily IMD rain gauge data at a specific site due to a lack of daily gauge data. The amount by which the TRMM products deviated from the observatory's data was determined using statistical analysis. On a broad scale, it noted that the TRMM performs satisfactorily in calculating rainfall compared to observatory data. Apart from annual average rainfall data, the TRMM has excellent seasonal estimation accuracy. The correlation coefficient and root mean square error calculated from the two datasets are in excellent agreement. Therefore, the TRMM 3B42 V-7 data quality is reliable for assessing Kerala's average rainfall from 1998 to 2019. The station wise monsoon season comparison suggests that TRMM has difficulty in capturing higher elevation station data. The convective precipitations that occur during the monsoon season also may be a reason for underestimation. However, due to the limitations of only having a few years of station precipitation data, a proper conclusion can never reached in this case.

The TRMM results are comparable to those obtained from observatory data. Before conducting the study, it is necessary to validate the TRMM data. The yearly rainfall, winter season and November rainfall have a contradictory trend that differs from the IMD observatory data, whereas the rest exhibit a similar tendency. What matters is that none of the trends was statistically significant. However, this study has a significant finding that the insignificant increase in southwest monsoon rainfall while decreasing in the post-monsoon season during 1998-2019. In the last decade, the annual and monsoon rainfall has shown an insignificant increasing trend. This study expected to aid in defining and assessing agricultural planning, the threat of flooding and droughts and other changes associated with the state of Kerala's climate change mitigation and adaptation strategies. It will aid the government and policymakers in their decision-making and planning processes. Investigating temporal variations in weather parameters, especially in places heavily reliant on rain-fed agriculture, is crucial in evaluating climate-induced shifts and designing practical adaptation methods. This study will help the government to decide policies for the agricultural and allied sectors.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ABBREVIATIONS

CV: Coefficient of Variation; **IMD**: India Meteorological Department; **JAXA**: Japan Aerospace Exploration Agency; **NASA**: National Aeronautics and Space Administration; **RMSE**: Root Mean Square Error; **SD**: Standard Deviation; **TMPA**: TRMM Multi-Satellite Precipitation Analysis; **TRMM**: Tropical Rainfall Measurement Mission.

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