AN ANALOGY OF THE RAINFALL TREND OVER THE WESTERN GHATS AND THEIR SURROUNDINGS

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Abstract. The study examines the monthly variation of rainfall in lower atmospheric level of different locations in Western Ghats (W.G.), and its nearby cities in the states of Kerala, Karnataka, and Tamil Nadu. It uses high resolution gridded rainfall data from India Meteorological Department (IMD) with a resolution of $0.25^0 \times 0.25^0$ (approximately 25km×25km), which are used to analyze the trend of changing climate on the distribution of rainfall (measured in millimeters) in different topographical zones of the Western Ghats and their nearby cities in India, from 2016 to 2023. Additionally, datasets of wind direction from the power access data portal of NASA's MERRA-2 and intensities of El Niño & La Niña reports from the Golden Gate Weather Services portal were also taken into account for this study. Daily rainfall data have been analyzed as monthly, seasonal, and annual variations. It indicates that there is an increase in pre-monsoon, post-monsoon and winter rainfall, while monsoon rainfall decreased in the selected study areas. It has been observed that Karkala in Udupi received the highest mean rainfall in the month of August, and Parameshwarpuram in Nagercoil received minimum mean rainfall in the same month over Western Ghats (W.G.). Also, based on the variation of rainfall trend in the selected regions, the locations can be classified as low rainfall, moderate rainfall, and heavy and/or very heavy rainfall region with reference to the Western Ghats (W.G.).

Key words: rainfall, wind speed, monsoon season, oceanic Niño effects

1. INTRODUCTION

The Western Ghats (W.G.) of India, are considered to be one among the world's 'hottest' biodiversity hotspots and a UNESCO World Heritage site (Sateesh, 2020). This mountain range, which extends from north to south with a narrow zonal width and a precipitous western face, runs parallel to the western coast of India. The Western Ghats, start from Songadh town of Gujarat, continue through Maharashtra, Goa, Karnataka, Kerala and are ending in Marunthuvazh Malai in Tamil Nadu, covering a total area of around 160,000 square kilometers, and having an average elevation of 1,200 m (3,900 ft). The climate in the Western Ghats varies with the altitudinal graduation with an annual temperature of 15^0 C and it is witnessed that the temperature even reaches freezing point during winter months. The 1,600 km long Western Ghats mountains of peninsular India act as a barrier, and interact with the southwest monsoon in a manner that strongly influences the exceptionally varied climate pattern of the Deccan. These mountain ranges receive abundant precipitation, with an average annual rainfall of about 380 cm year^{-1} on the windward side (Rao, 1976). The W.G. play a key role in regulating Indian climate through regional climate modifications (Varikoden *et al.*, 2019). Numerous studies have been carried out in the Western Ghats in Kerala (Roy Bhowmik and Durai, 2008; Sijikumar *et al*., 2013) and minimal comprehensive analyses of rainfall have been carried out (Venkatesh *et al.*, 2021). The northern and central part of the Western Ghats is sensitive to climate change and it has been reported that an increase in temperature could cause high intensity rainfall (Gopalakrishnan *et al.*, 2011). Chandrashekar *et al.*, (2017) analyzed the long-term seasonal spatio-temporal variation trends of high resolution (0.25°×0.25°) gridded daily precipitation data provided by the Indian Meteorological Department (IMD) over the Western Ghats and the coastal region of Karnataka and reported this area as vulnerable to climate change risks. The south-west monsoon is the main source of rainfall for the Western Ghats region (Pai *et al.*, 2014). The onset of south-west monsoon from the southern tip of peninsular India especially hits the Western Ghats at the end of May, playing a key role in regulating the Indian climate through regional climatic modulations (Varikoden *et al.*, 2019). It spreads across the country within 10 to 15 days (Pascal, 1986), then gradually retreat from northern India by late September, reaching the southern tip of the peninsula by early December. A sharp environmental gradient is observed on the immediate back slope of the Ghats, where total annual rainfall can drop from 6000 millimeter to 600 millimeter over an area of about 80 square kilometers.

This is vigorously reflected in natural habitats like landforms, soil, vegetation and crop patterns, and raises the question of the relationship between the history of the mountain barrier uplift at geological time-scale, the history of the South Asian monsoon circulation, and the current climatic pattern as seen today. It is recorded that climate warming has changed the rainfall patterns in recent period (Knight and Harrison, 2012; Li *et al.*, 2020; Wu *et al.*, 2020). Precipitation trends in the northern and the southern regions of Western Ghats suggest possible reasons for this phenomenon, with an estimated average rainfall trend of + 0.3-millimeter day^{-1} decade^{-1} in the northern and − 0.39-millimeter day^{-1} decade^{-1} in the southern region of the Western Ghats for the 1931 to 2015 period (Venkatesh *et al.*, 2021). Mishra *et al.*, (2020) and Shou and Lin., (2020) discussed the rainfall statistics from the last 50 to 100 years in many locations around the globe, showing that the average annual number of rainy days has decreased, but the number of days with heavy rainfall has increased. Therefore, monitoring the changes in the rainfall trends in the Western Ghats is necessary for understanding regional climate shifts.

2. MATERIALS AND METHODS

2.1. Description of Study Area

Although the Western Ghats Mountains start from Gujarat and run through the states of Maharashtra, Goa, Karnataka, Kerala and Tamil Nadu between the latitudes 8° to 21° N, and the longitudes 70° to 78° E (Fig. 1), they can be classified as Northern in Maharashtra, central in Karnataka and southern Western Ghats in Kerala. The Nilgiris Mountains of Tamil Nadu span the Western and Eastern Ghats which lie near the Moyar River, from the Karnataka Plateau to the north (Fig. 1). We have chosen the locations of Western Ghats in Tamil Nadu, Kerala and Karnataka between the latitudes 8.25° to 14.75° N, and the longitudes 74° to 78.75° E, namely Kilamalai RF (reserve forest), Mundathurai WLS (wild life sanctuary), Mathikettansolai, Vallaparai, Mettupalayam, Nilgiris, Sathya Mangalam, Mettur Ghats from Tamil Nadu, Ranni forest, Idukki WLS (wild life sanctuary), Ghats of Trissur, Anamalai Hill (Anamudi highest peak of about 2695 m elevation), Palakkad WLS (wild life sanctuary), Ghats of Vadakara in Kerala and Bandipore, Nagarahole Hills, Tala-Kaveri and Ghats of

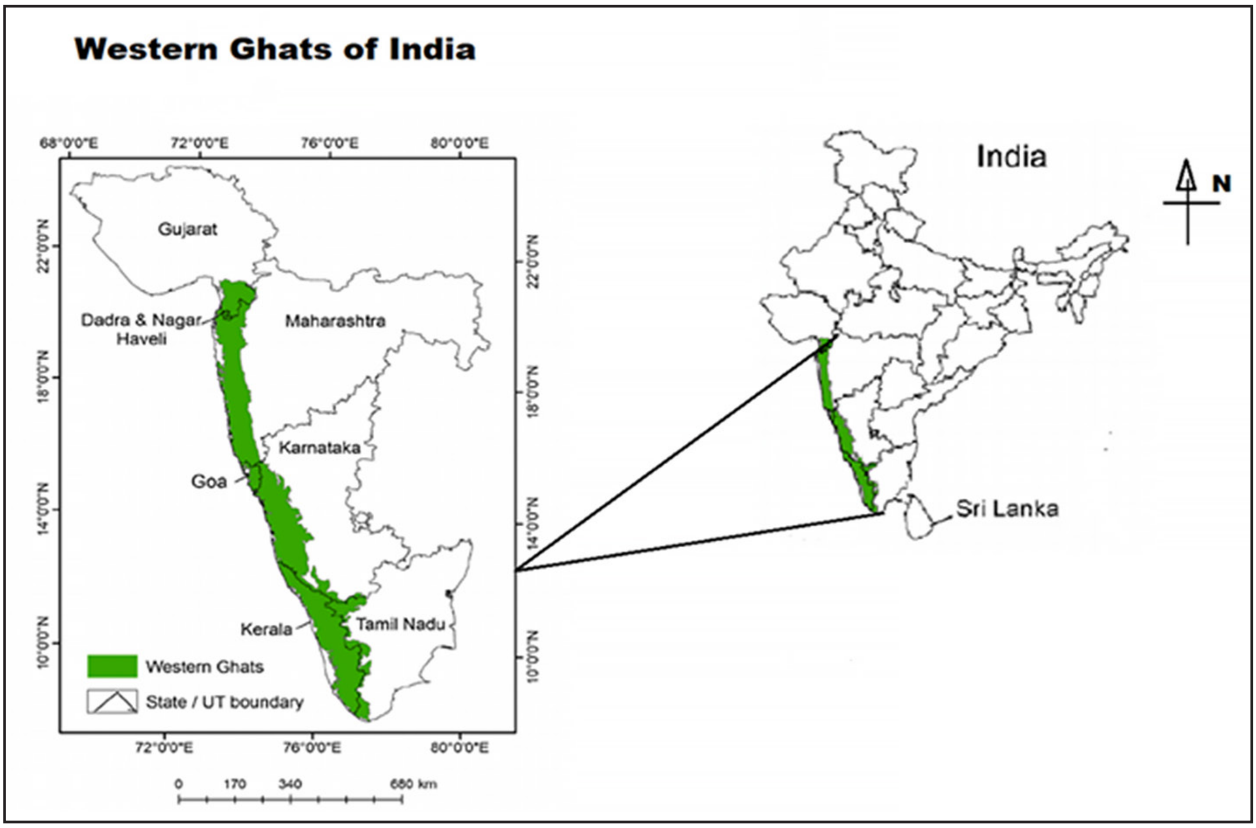

Fig. 1. Western Ghats of India (*Researchgate.net by Dr. Sudhakar Reddy. C*).

Chamarajanagar, Dakshin Kannada, Hassan, Chikkamagaluru, Udupi, Shimoga, Uttara Kannada, and Davanagere of Karnataka, respectively. Nearby towns, especially those within a radius of less than 100 km from the Western Ghats (W.G), are Karungal, Aralvaimozhi and Parameshwarapuram.

The nearby cities, particularly those within a radius of less than 100 Km from the Western Ghats, were chosen for the study. These are Karungal, Aralvaimozhi and Parameshwarapuram of Kanyakumari district, Nanguneri, Ambasamudram, Palayamkotai and Tirunelveli town from Tirunelveli district, Uthumalai, Sankarankovil and Kuruvikulam from Tenkasi district, Andi Patti and Theni town from Theni district, Peraiyur, Tirumangalam, Avarangulam, Pochi Patti hill, Vadipatti and Melur from Madurai district, Kodaikanal, Athoor, Chinapatti, Natham, Palani, Oddanchatram and Dindigul town from Dindigul district, Udumalaipetai, Madathukulam, Dharapuram, Palladam, Kangayam, Velankovil and Avinashi from Tirupur district, Soolakal, Karamadai and Coimbatore town from Coimbatore district, Perundurai, Madakkurichi, Sathya Mangalam and Gobichettipalayam from Erode districts from Tamil Nadu, Trivandrum town, Vakala and Kumily from Trivandrum district, Puthussery, Palakkad town, Shoranur, Pakkanji, Chittur and Mannarkkad from Palakkad district, Edamann and Kollam from Kollam district, Mavelikarra from Alappuzha district, Tiruvalla and Manimala from Pathanamthitta district, Vaikom and Kottayam from Kottayam district, Idukki town, Cumbummatu, Irunnoor from Idukki district, Trissur, Ernakulam, Kolenchery, Kadavoor and Idamalayar from Ernakulam district, Kayyoor, Thalasseri, Pavannur, Edoor, Cheemeni, Udayagiri, and Kasaragod town from Kasaragod district, Ponnai, Kottakal, Mukurthi, Nilambur hills and Malappuram town from Malappuram district, Arikkulam and Vanaparvam from Kozhikode district, Peechamcode and Wayanad from Wayanad district, Chamarajanagar, Srimangala and Kodagu from district Kodagu, Ambalare, Diddahaali, Mavinikare and Mysuru from Mysuru district, Hullambali, Pandavapura, Mandya, Nagamangala, Maddur and Ambigarahalli from Mandya district, Ramanagaram and Magadi from Ramanagaram district, Sendragaya, Moodabedri, Belthangady, and Beltangadi from Dhakshin Kannada, Puttur, Bantra, Pangala and Yadtadi from Udupi, Koratikere and Hale Kallahalli from Chitra Durga, Bangalore Urban, Arkalgud, Holenarasipura, Hassan, Chakkanahalli, Channarayapatna, Belur, Arasikere, Battihalli and Konanur from Hassan and Kunigal, Tiptur, Tumkur and Hebbur from Tumkur.

2.2. Data and Analysis

The study utilizes high spatial resolution (0.25° x 0.25°) gridded daily rainfall (Bejagam *et al.,* 2023), measured in millimeters, between 2016-2023, across 135x129 grid points over India, sourced from the Indian Meteorological Department (IMD), Pune. The first data in the record is at 8.5^{0}N and 76.25^{0}E, and so on. The last data record taken for analysis corresponds to 14.5^{0}N and 77.25^{0}E. (Guhathakurta *et al.*, 2011)

According to IMD's criteria, "Rain rate (rain intensity) = (mm^3 of rain) / (mm^2 rain gauge opening area) / (hour) = mm/hr (mm per hour)" (Table 1).

- **Light rain**: Defined as a rain rate of less than 2.5 mm/hr (under 0.1 inches/hour) or less than 0.04 mm/min (below 0.0007 inches/min). For a rain gauge with a 0.1 mm resolution, this equates to 25 tipping bucket activations per hour (25 pulses/hour).
- **Moderate rain**: Characterized by a rain rate of 2.6 to 7.5 mm/hr (0.1 to 0.3 inches/hour) or 0.04 to 0.125 mm/min (0.0017 to 0.005 inches/min), corresponding to 26 to 75 tipping bucket activations per hour (26 to 75 pulses/hour) for a 0.1 mm resolution rain gauge.
- **Heavy rain**: Describes a rain rate exceeding 7.6 mm/hr up to 50 mm/hr (0.3 to 2 inches/hour), or 0.125 to 0.83 mm/min (0.005 to 0.033 inches/min), which results in 76 or more tipping bucket activations per hour (76+ pulses/hour) for a 0.1 mm resolution rain gauge.
- **Violent rain**: Sometimes used to denote exceptionally high precipitation rates over 50 mm/hr (>2 inches/hour) or over 0.83 mm/min (>0.033 inches/min), leading to 500 or more tipping bucket activations per hour (500+ pulses/hour), or more than 8 pulses per minute.

The years 2020 and 2021 recorded that most of the rainfall is received from the southwest (June to Sept.) with maximum rainfall rate in the months of August and September, as in the last 8 years. The Table 2 below shows the total annual rainfall (RF) in mm versus total number of days with rainfall from 2016-2023 for the selected study region of three states.

Table 1. Rainfall Classification, IMD's criteria.

1.	Heavy Rainfall	64.4 mm <RF<124.4mm
2.	Very Heavy Rainfall	124.4mm<RF<224.4mm
3.	Extremely Heavy Rainfall	RF>244.4mm
4.	Within the normal range	• Light – RF<2.5mm/h • Moderate -2.5mm<RF<7.6-10mm/h • High – 7.6mm<RF<50mm/h • Violent- RF>50mm/h

Table 2. Total Annual Rainfall.

Table 2.1. Study regions of Karnataka

St. No.	Long⁰ deg.	Lat⁰ deg.	Location	2016/366		2017/365		2018/365		2019/365		2020/366		2021/365		2022/365		2023/365	
			Karnataka	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days
1	76.75	11.75	Chamarajanagar	280.28	94	174.61	156	541.92	143	555.74	158	895.35	140	839.39	204	1442.39	184	729.6803	165
2	76.75	12	Chamarajanagar	228.21	87	119.94	121	680.40	130	605.52	132	1102.79	127	865.37	164	1668.94	151	543.9764	101
3	77	12	Chamarajanagar	329.66	77	109.20	108	529.71	103	608.66	124	1227.87	117	994.10	162	1248.30	128	619.6565	103
4	77.25	12	Chamarajanagar	317.45	72	116.17	107	475.27	106	594.27	82	1189.87	89	1027.66	102	1230.24	99	668.3321	105
5	76	12	Srimangala	445.67	146	200.21	173	1634.21	193	895.55	183	1317.80	177	1632.12	203	1505.93	172	1395.813	147
6	76	12.25	Kodagu	466.41	136	191.19	152	1575.92	191	1142.01	174	1294.06	163	1152.45	199	1220.53	157	1038.991	151
7	76.5	12	Mysore	331.03	116	195.48	157	1032.89	160	900.02	172	1179.98	157	1200.51	180	1424.74	162	807.2031	131
8	76.25	12.25	Mysore	465.95	111	183.55	137	1210.71	167	1103.21	169	1316.80	146	1271.72	164	1500.99	170	913.286	139
9	76.5	12.25	Mysore	340.49	95	143.06	133	590.27	135	778.27	133	946.13	144	1153.79	161	1570.01	144	613.2245	107
10	76.75	12.25	Mysore	277.92	85	126.56	119	706.28	115	356.89	118	751.19	127	593.59	157	1548.95	141	717.1367	106
11	76	12.5	Ambalare	444.64	122	178.14	149	1661.26	193	795.85	174	1186.90	153	1141.23	198	1538.50	173	887.8608	134
12	76.25	12.5	Diddahaali	432.98	101	140.59	145	1006.08	165	741.27	144	1035.75	151	1143.39	173	1443.43	173	716.0515	117
13	76.5	12.5	Mavinikare	246.33	77	118.77	116	847.26	143	753.23	133	1107.58	138	1100.16	156	1455.72	143	553.5953	110
14	77	12.25	Hullambali	373.14	88	140.07	137	632.27	125	637.00	125	996.79	131	776.54	163	1357.19	145	619.6329	122
15	76.75	12.5	Pandavapura	413.21	101	165.47	164	868.25	149	752.87	157	1182.37	147	1152.60	180	1723.79	170	471.6462	160
16	77	12.5	Mandya	483.60	99	148.95	143	774.12	136	711.39	126	1145.98	122	1144.09	155	1681.09	153	684.6941	124
17	76.75	12.75	Nagamangala (Mandya)	999.46	156	160.02	178	1489.49	162	1509.63	169	2129.64	162	1737.16	183	2447.83	195	1332.499	159
18	77	12.75	Maddur	496.16	99	125.43	119	827.93	143	645.25	127	1333.43	121	1296.81	166	1744.05	148	771.1624	136
19	76.75	13	Ambigarahalli (Mandya)	563.28	109	143.51	147	1215.71	166	875.64	151	1438.86	148	1463.74	175	1549.83	150	743.0271	120
20	77.25	12.5	Ramanagaram	419.16	74	102.30	116	564.19	107	682.30	104	1189.12	103	888.27	144	1385.60	125	492.6124	106
21	77.25	12.75	Ramanagaram	491.39	98	143.81	130	758.36	139	676.32	129	1362.90	119	1205.69	175	1716.55	143	682.5864	117
22	77.25	13	Magadi	519.00	101	112.37	120	683.19	125	726.73	132	1262.30	128	1147.38	190	1542.14	150	641.6	126
23	75	12.75	Sendragaya	2625.48	157	184.15	157	3766.38	168	3976.83	180	5423.36	180	3276.03	225	4050.46	188	3336.639	158

Table 2 (continued)

Table 2.1. Study regions of Karnataka

St. No.	Long⁰ deg.	Lat⁰ deg.	Location	2016/366		2017/365		2018/365		2019/365		2020/366		2021/365		2022/365		2023/365	
			Karnataka	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days
24	75	13	Moodabedri	2807.40	151	170.86	158	4288.49	176	3819.62	160	6410.81	180	4320.40	217	4060.85	185	3263.672	154
25	75.25	13	Belthangady	2829.57	162	189.62	176	4564.48	175	4233.27	177	6287.90	186	4808.92	228	4573.69	190	3404.999	173
26	74.75	13.75	Beltangadi	3726.18	156	194.08	166	5243.29	164	4991.03	151	8601.45	162	5359.04	230	4632.15	174	3553.308	153
27	75.25	12.75	Puttur	2329.50	158	213.54	177	3879.90	188	3612.74	180	5080.27	196	4378.34	219	3590.13	189	2992.051	163
28	75.5	12.75	Bantra	1551.69	163	233.68	184	4126.74	194	2776.74	195	4286.37	201	3275.96	227	3009.34	191	2415.034	159
29	74.75	13.25	Pangala	3331.80	151	187.53	150	4663.60	166	3963.47	165	6947.81	168	4465.22	221	4253.38	184	3320.632	162
30	74.75	13.5	Yadtadi	4088.30	158	193.28	175	5257.83	171	4540.06	168	7732.52	178	5416.10	233	3994.15	186	3355.595	165
31	76.5	12.75	koratikere	816.41	147	166.42	173	1739.35	166	1433.48	175	1642.61	167	1507.18	183	1943.38	189	1348.316	153
32	76.5	14.25	Hale Kallahalli	210.01	90	99.11	107	448.91	103	400.94	104	935.03	103	737.96	133	785.18	119	462.9783	95
33	77.5	12.75	Bangalore Urban	558.26	92	116.02	107	536.34	98	681.60	112	1386.80	113	1094.73	169	1397.95	144	481.1283	124
34	77.75	12.75	Bangalore Urban	495.96	67	147.80	106	358.03	89	582.08	105	1199.40	103	1005.21	156	1549.99	130	718.4188	123
35	76	12.75	Arkalgud	354.57	101	150.87	143	1242.43	177	747.56	157	1157.41	148	1243.91	181	1636.82	164	733.4456	115
36	76.25	12.75	Holenarasipura	394.62	109	146.19	149	1200.55	159	787.36	137	1041.01	150	1162.70	177	1495.75	177	607.4489	118
37	76	13	Hassan	518.89	59	75.96	74	1650.08	98	1723.65	98	2267.32	105	2066.50	99	2991.19	116	993.4262	54
38	76.25	13	Chakkanahalli	414.66	109	128.06	130	1132.31	156	955.62	155	1248.70	151	1291.63	171	1661.13	160	649.3788	113
39	76.5	13	Channarayapatna	529.91	125	152.09	153	1480.44	162	1011.83	162	1262.42	148	1694.83	176	1719.63	159	877.171	150
40	76	13.25	Belur	483.43	115	144.48	146	1116.98	143	1140.26	165	1440.37	161	1310.51	169	1824.33	157	720.3117	123
41	76.25	13.25	Arasikere	492.94	99	123.54	124	987.09	140	927.96	148	1315.34	138	1216.08	163	1345.35	140	448.1199	110
42	76.25	13.5	Battihalli	294.26	79	94.94	96	782.15	128	965.31	122	1093.55	116	1192.41	149	1106.19	129	538.1862	107
43	76.25	14.25	Konanur	324.48	89	97.28	105	568.36	95	682.87	121	1186.97	123	925.06	140	981.69	119	482.0585	92
44	77	13	Kunigal	544.22	108	122.93	125	848.25	128	607.98	117	1277.07	124	1317.38	174	1454.57	136	714.896	122
45	76.5	13.25	Tiptur	443.36	103	131.77	135	907.66	145	815.65	144	1391.95	136	1315.28	173	1557.93	142	587.1757	116
46	76.75	13.25	Tumkur	503.85	109	137.96	142	710.17	142	824.32	140	1599.68	127	1529.10	180	1588.88	142	666.4539	110
47	76.5	13.5	Tumkur	368.72	78	114.29	104	647.62	105	749.99	129	1133.04	118	1254.49	154	1253.73	139	583.8904	108
48	76	13.75	Hebbur	401.78	98	101.29	111	645.28	115	1067.93	122	1277.37	101	1194.85	139	1148.11	120	585.1517	97

Table 2 (continued)

Table 2.1. Study regions of Karnataka

St. No.	Long⁰ deg.	Lat⁰ deg.	Location	2016/366		2017/365		2018/365		2019/365		2020/366		2021/365		2022/365		2023/365	
			Karnataka	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days
49	75	13.25	Murur	2853.25	168	183.23	167	5089.01	168	3988.68	171	6273.68	191	4452.76	235	4140.84	194	2596.105	168
50	74.25	14.75	Karwar	3030.75	147	191.84	149	2526.73	150	3960.05	152	7370.18	160	4012.20	206	3461.00	154	3132.029	142
51	74.5	14.75	Ankola	1659.49	147	154.29	149	2102.51	155	3257.58	155	4423.72	166	2891.38	210	2688.55	165	2367.826	147
52	74.75	14.75	Mogadde	992.65	127	137.92	142	1694.75	159	2669.47	156	2966.85	159	2313.95	201	2016.05	165	1650.052	137
53	75.75	13.25	Chikkamagaluru	438.87	128	131.35	148	862.16	144	1141.31	170	1475.33	151	1057.28	184	1041.45	168	731.9596	149
54	76	13.5	Pattanagere	231.73	86	99.66	112	749.05	133	856.15	122	944.10	113	1121.08	137	782.20	119	578.532	97
55	75.75	13.75	Hurulihalli	577.38	129	117.33	129	824.02	143	1216.32	147	1226.30	140	1380.22	167	920.56	154	736.3261	111
56	75	13.75	Savehaklu	2624.05	155	155.73	159	4027.32	160	3860.77	162	4952.62	170	3818.34	234	3667.76	188	2422.557	153
57	75.25	14	Mugute Koppa	942.57	132	138.23	137	1453.62	147	2055.04	157	2576.40	155	1960.10	180	1967.74	162	1229.923	141
58	75.5	14	Shimoga	414.84	104	110.97	117	820.46	130	1146.27	142	1367.07	132	1322.24	175	1411.97	143	675.7865	128
59	75.75	14	Hole Hatti	534.32	102	109.58	117	755.03	126	925.22	132	1350.99	128	1452.62	175	1313.60	126	675.3209	121
60	75.25	14.25	Sagara	614.39	121	120.10	121	1039.13	136	1246.35	152	1617.62	143	1548.96	171	1620.84	152	768.5044	116
61	75.5	14.25	Baluru	454.24	114	87.22	90	634.89	126	728.05	107	1065.51	100	1220.83	168	1530.14	137	511.1345	115
62	75	14.75	Siddapura	541.39	81	92.56	92	1116.80	146	1488.96	151	1586.84	142	1406.62	183	1110.58	128	625.1396	99
63	76	14	Bannihatti	378.03	81	93.19	103	624.76	104	950.07	117	1017.50	118	1159.63	143	1206.22	132	498.2879	97
64	76	14.25	Channagiri	406.87	106	92.44	98	657.97	121	859.22	131	1235.14	137	1217.55	159	1285.55	136	492.9382	106
65	75.75	14.25	Neralagundi	327.50	85	111.28	119	598.14	107	727.46	124	1172.03	125	1129.46	140	1259.09	131	488.83	93
66	76	14.75	Harapanahalli	315.54	98	109.98	120	655.22	133	800.51	140	1213.24	120	982.71	149	1253.98	139	508.1696	94
67	75.25	14.75	Tumarikoppa	463.02	106	98.30	105	791.01	129	1269.12	136	1175.88	128	1044.45	162	998.01	148	426.7407	93
68	75.5	14.75	Arabagonda	381.73	111	107.10	118	580.40	135	1125.05	144	1072.57	152	1050.86	166	1194.12	155	500.7615	98
69	75.75	14.75	Haveri	363.72	133	134.28	148	606.26	145	793.66	144	1244.83	139	1020.85	173	1377.64	146	598.6176	98
70	76.25	14.75	Bellary	318.25	90	104.54	117	516.16	113	666.31	128	1031.96	113	812.27	129	1005.13	117	428.9126	84

Table 2 (continued)

Table 2.2. Study regions of Kerala

St. No.	Long⁰ deg.	Lat⁰ deg.	Location	2016/366		2017/365		2018/365		2019/365		2020/366		2021/365		2022/365		2023/365	
			Kerala	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days
1	77	8.5	Trivandrum	770.19	140	375.52	177	1434.71	179	1359.41	165	1844.56	166	2427.16	184	1910.99	186	1971.501	162
2	76.75	8.75	Varkala	1132.57	189	299.86	197	1940.57	191	1574.65	202	2862.99	189	3352.33	249	1982.80	209	2200.511	210
3	77	9.5	Kumily	1315.90	183	362.42	216	2826.73	186	2498.63	193	4748.13	203	4006.92	250	3114.44	215	2053.284	218
4	77	8.75	Puthussery	910.38	168	407.45	189	1543.12	174	1499.16	189	2322.80	177	2740.69	235	1482.64	177	1471.688	128
5	76.5	10.5	Palakkad	1010.74	143	164.27	155	2305.89	157	2073.00	153	2599.21	162	2435.00	211	1964.22	183	1456.435	146
6	76.25	10.75	Shoranur	1726.95	133	196.98	146	4124.78	141	3820.93	146	4626.49	147	3172.49	210	2150.86	154	2166.73	156
7	76.5	10.75	Pakkanji	1305.65	131	182.00	152	3028.87	141	2607.83	151	3275.96	140	2423.36	209	2621.00	169	1792.169	141
8	76.75	10.75	Chittur	716.04	124	165.52	152	1382.25	149	1377.51	151	1642.31	151	1546.19	188	1650.94	168	1010.824	144
9	76.5	11	Mannarkkad	1215.02	143	229.06	179	2237.57	154	2403.95	171	3031.75	169	2909.77	216	2686.95	180	1899.495	197
10	76.75	9	Kollam	1893.30	163	308.10	178	2576.46	170	2193.10	169	3065.10	160	4323.40	209	2530.40	178	2547	155
11	77	9	Edamann	1570.69	146	730.57	165	1509.52	155	1950.59	156	2826.96	157	3579.10	210	2506.74	147	1668.3	162
12	76.5	9.25	Mavelikarra	1339.65	187	269.80	211	2358.26	197	2286.83	192	3736.60	194	3683.29	250	2513.41	211	3133.08	204
13	76.75	9.25	Pathanamthitta	1710.76	192	312.45	226	2560.26	206	2580.86	205	4128.88	202	5254.53	266	2901.16	209	3212.331	222
14	76.75	9.5	Manimala	1746.03	213	253.22	236	3315.93	215	3225.10	212	5752.97	224	5280.03	268	3379.31	223	3452.034	242
15	76.5	9.5	Kottayam	1681.11	198	256.79	227	2740.62	208	2507.36	208	4249.40	224	4533.57	260	3276.05	223	3264.806	228
16	76.5	9.75	Vaikom	1843.67	192	278.65	218	4089.15	212	2851.29	189	4661.33	213	4172.54	252	3365.12	215	3115.258	228
17	77.25	9.5	Idukki	249.70	82	333.63	112	380.66	101	833.55	112	1081.33	122	1085.98	142	1047.51	119	1278.036	130
18	77.25	9.75	Cumbummatu	525.10	144	381.90	192	1575.89	166	1159.81	161	2095.73	186	2020.95	223	1757.38	203	780.0088	165
19	77	10	Irunnoor	1511.76	181	247.84	218	3233.56	204	2015.45	201	3618.83	215	3050.81	264	3129.04	237	2434.874	231
20	76.25	10.25	Trissur	1495.82	151	183.55	174	2596.87	165	3481.35	176	4033.40	193	3867.25	238	3231.74	194	2606.627	180
21	76.25	10.5	Trissur	1573.92	156	169.53	172	2753.38	160	2782.96	163	3781.75	183	3555.05	228	2523.07	192	2302.738	170
22	76.25	10	Ernakulam	1922.51	169	198.32	193	2349.82	187	2920.52	186	4197.30	207	3940.58	242	3275.50	203	2799.214	183
23	76.5	10	Kolenchery	1916.56	189	233.45	203	4059.30	209	2871.32	192	4810.20	209	4334.25	250	3585.52	215	3006.563	207
24	76.75	10	Kadavoor	2087.53	202	235.27	218	4246.16	217	2661.46	217	4888.62	225	4181.56	263	4020.64	235	2994.963	241
25	76.75	10.25	Idamalayar	1327.66	193	223.02	225	2889.95	200	2729.64	207	5214.02	220	3992.88	262	4240.66	220	3140.239	222

Table 2 (continued)

Table 2.2. Study regions of Kerala

St. No.	Long^0 deg.	Lat^0 deg.	Location	2016/366		2017/365		2018/365		2019/365		2020/366		2021/365		2022/365		2023/365	
			Kerala	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days
26	76.75	9.75	Kayyoor	2129.41	204	246.21	229	4018.62	213	2746.97	211	5040.54	226	4723.12	267	3910.80	234	3236.731	232
27	75.5	11.75	Thalassery	2305.39	149	185.46	166	2720.82	162	3774.83	173	5896.90	171	3619.36	225	3176.01	175	2527.512	161
28	75.5	12	Pavannur	2005.30	150	227.24	172	2457.71	166	3415.03	170	5202.11	169	3636.56	232	3237.68	185	2593.241	164
29	75.75	12	Edoor	846.47	158	213.27	182	1962.69	191	2001.14	186	2771.82	186	2326.28	225	2315.36	178	1546.068	151
30	75.25	12.25	Cheemeni	2764.25	172	204.95	186	4152.37	186	4109.96	181	7015.98	196	4508.56	236	4744.07	207	3119.721	176
31	75.5	12.25	Udayagiri	2120.99	176	225.29	182	4456.62	194	3622.70	199	5974.49	194	3868.15	234	4526.35	200	2398.967	175
32	75	12.5	Kasargod	2519.16	161	196.46	171	3432.08	170	3936.58	180	5998.81	190	4188.31	231	4187.03	197	3123.641	167
33	75.25	12.5	Kasargod	2781.23	176	207.02	187	4615.06	188	3985.32	188	6693.68	200	4475.74	240	4852.03	201	3213.435	177
34	76	10.75	Ponnai	1224.46	143	178.68	165	2345.67	147	2530.63	151	3178.24	144	3159.81	211	2159.81	162	2207.873	148
35	76	11	Kottakal	1330.98	140	212.62	169	2789.79	153	2831.13	154	3471.97	147	3087.19	208	2281.82	155	2404.017	182
36	76.25	11	Ponnyakurshy	1440.12	140	249.59	168	2486.22	155	2831.15	158	3596.20	158	3761.09	214	3043.41	167	2414.55	193
37	76	11.25	Malappuram	1354.35	168	171.30	182	3352.67	182	2828.27	188	3159.41	192	2639.52	236	2471.93	201	1951.162	189
38	76.25	11.25	Malappuram	1017.68	150	195.43	191	2211.93	183	2717.38	194	4222.57	193	2736.44	224	2899.63	197	2099.603	228
39	76.5	11.25	Mukurthi	803.83	161	426.59	207	1141.59	171	1717.67	192	1765.77	177	1787.12	225	1945.81	212	1187.593	191
40	76.25	11.5	Nilambu Hills	370.92	147	186.50	188	774.40	176	3129.72	198	8071.25	188	3530.47	230	4160.88	196	2403.558	187
41	75.75	11.5	Arikkulam	1401.55	154	185.34	181	3232.85	184	3310.48	196	5249.96	184	3808.18	228	3495.95	197	2612.565	187
42	76	11.5	Vanaparvam	1108.00	160	197.22	192	3239.58	191	3135.09	205	4453.53	190	3018.53	236	3208.82	192	2192.564	173
43	76	11.75	Peechamcode	907.51	167	188.57	190	2608.97	195	2225.00	202	2923.08	192	2277.12	233	2621.91	188	1613.691	172
44	76.25	11.75	Wayanad	768.43	159	228.32	202	2095.70	195	1878.15	202	2475.13	187	1855.43	227	2173.71	192	1293.69	154

Table 2.3. Study regions of Tamil Nadu

St. No.	Long^0 deg.	Lat^0 deg.	Location	2016/366		2017/365		2018/365		2019/365		2020/366		2021/365		2022/365		2023/365	
			Tamil Nadu	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days
1	77.25	8.25	Karungal	445.44	60	339.11	96	879.11	126	1054.16	115	1210.93	115	1941.49	166	1056.18	126	1347.221	122
2	77.5	8.25	Aralvaimozhi	182.58	40	200.40	49	467.55	65	933.91	68	620.99	54	1212.28	144	572.61	60	1089.845	149
3	77.75	8.25	Parameshwarapuram	265.46	60	272.41	72	460.43	82	986.55	87	530.97	73	1125.59	109	572.80	91	1329.884	125
4	77.5	8.5	Nanguneri	330.00	42	153.35	57	306.81	59	580.18	71	509.97	63	1101.80	124	644.77	75	951.0714	159
5	77.75	8.5	Tirunelveli	303.37	47	296.90	74	464.65	65	985.26	69	476.43	50	1126.38	102	607.68	75	1385.786	133
6	77.5	8.75	Ambasamudram	260.43	54	245.17	98	457.78	84	792.45	93	702.02	89	1185.96	134	740.14	102	1292.63	103
7	77.75	8.75	Palayamkotai	162.76	52	245.25	90	316.54	69	748.71	78	627.49	70	1037.28	98	519.44	85	1222.983	85
8	77.5	9	Uthumalai	150.14	56	187.41	76	209.05	76	501.42	93	617.59	97	1031.75	121	708.61	107	983.5522	87
9	77.5	9.25	Sankarankovil	184.37	57	252.23	97	365.17	97	656.11	104	895.77	110	1074.56	129	721.74	121	835.5836	106
10	77.75	9.25	Kuruvikulam	251.89	53	217.01	79	229.25	79	594.76	73	929.11	88	1060.69	115	851.46	99	1187.121	87
11	77.5	9.75	Andipatti	329.06	47	228.85	109	516.26	83	639.29	86	1202.40	100	1123.65	128	1184.34	113	1370.068	128
12	77.5	10	Theni	337.20	31	108.94	63	345.10	66	619.94	58	1183.63	65	1155.27	139	1394.27	89	1363.91	123
13	77.75	9.75	Peraiyur	464.08	66	223.06	109	592.96	91	556.90	76	1190.72	96	1078.87	138	1000.43	117	1109.024	131
14	78	9.75	Tirumangalam	535.89	69	231.92	92	809.44	87	735.17	88	1223.30	104	1214.03	151	1399.68	107	1118.359	117
15	78.25	9.75	Avarangulam	554.55	70	204.98	101	748.38	90	743.44	94	1355.27	97	1157.01	124	985.82	93	1064.091	110
16	77.75	10	Pochi Patti hill	483.82	51	226.11	90	684.39	68	695.38	82	1287.22	73	1349.60	113	1126.31	97	725.9902	106
17	78	10	Vadipatti	452.68	63	170.27	96	628.00	86	640.12	95	1102.28	105	1129.74	147	1018.42	106	891.7997	114
18	78.25	10	Melur	481.67	77	216.49	111	780.20	103	734.06	110	1092.20	110	1088.94	142	1001.10	117	776.8895	121
19	77.5	10.25	Kodaikanal	477.88	106	278.00	159	855.64	149	1010.63	151	1339.07	155	1330.52	209	1628.71	174	679.368	183
20	77.75	10.25	Athoor	405.55	63	175.93	112	610.64	96	535.41	85	926.89	91	1029.08	139	1248.47	119	951.842	116
21	78	10.25	Chinapatti	653.80	73	207.19	119	552.43	100	576.53	91	1438.67	101	1272.50	147	1444.27	120	1208.93	130
22	78.25	10.25	Natham	373.14	79	205.84	117	593.23	88	750.52	100	1301.50	111	1141.54	145	1107.97	122	747.114	126
23	77.5	10.5	Palani	277.18	40	159.91	93	442.73	81	427.46	61	1201.81	84	1153.69	103	988.26	98	622.3063	99
24	77.75	10.5	Oddanchatram	264.70	49	155.99	95	526.68	86	641.93	73	1594.48	89	1164.62	120	1276.39	103	996.2366	101

Table 2 (continued)

Table 2.3. Study regions of Tamil Nadu

St. No.	Long⁰ deg.	Lat⁰ deg.	Location	2016/366		2017/365		2018/365		2019/365		2020/366		2021/365		2022/365		2023/365	
			Tamil Nadu	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days	RF in mm	No of days
25	78	10.5	Dindigul	212.10	52	165.07	87	430.93	78	593.11	70	944.18	84	1087.34	128	810.15	101	540.9296	94
26	77.25	10.5	Udumalaipetai	263.03	50	149.93	99	421.64	95	341.13	70	777.47	111	881.37	112	761.27	101	450.8977	88
27	77.25	10.75	Madathukulam	240.59	49	120.68	96	397.55	109	395.46	93	873.10	93	852.20	151	722.32	114	412.0211	82
28	77.5	10.75	Dharapuram	244.93	45	155.39	104	308.52	101	373.82	88	945.57	93	572.00	158	547.70	114	676.389	108
29	77.75	10.75	Dharapuram	177.31	29	108.39	71	462.26	54	807.65	55	1000.05	63	1106.37	114	905.16	67	552.991	98
30	77.25	11	Palladam	316.21	65	168.57	103	632.63	109	454.92	100	1043.55	98	868.16	160	928.79	126	589.2252	76
31	77.5	11	Kangayam	288.79	64	205.24	118	530.08	124	497.62	108	1101.92	113	877.33	152	831.94	142	645.41	108
32	77.75	11	Velakovil	213.56	57	174.84	97	352.37	90	507.56	89	1062.42	98	947.45	129	1074.46	107	639.5325	109
33	77.25	11.25	Avinashi	314.39	61	171.70	101	632.66	84	546.10	98	924.26	95	1014.38	132	1011.39	119	791.9729	94
34	77	10.75	Soolakal	394.35	55	106.89	93	622.83	124	715.47	100	862.57	110	979.56	140	599.84	122	537.1212	100
35	76.75	11	Coimbatore	201.51	45	107.07	86	427.18	103	603.50	89	803.07	96	782.43	124	507.72	101	674.9071	93
36	77	11	Coimbatore	149.74	28	91.77	71	515.69	86	681.10	76	765.58	86	672.38	113	885.99	128	512.2721	95
37	77	11.25	Karamadai	820.70	68	109.45	99	680.58	96	2264.07	116	5448.77	171	4966.05	226	5173.89	189	766.1071	162
38	77.5	11.25	Perundurai	301.11	62	166.80	102	476.11	87	587.64	100	671.40	92	944.02	137	1176.43	130	928.221	117
39	77.75	11.25	Madakkurichi	238.40	56	164.68	107	354.23	77	589.15	90	887.66	93	1013.03	142	1006.23	112	690.6723	97
40	77.25	11.5	Sathyamangalam	258.99	56	198.71	90	581.41	65	657.78	89	1026.17	70	1177.94	132	1217.87	108	934.8086	98
41	77.5	11.5	Gobichettipalayam	280.17	62	120.94	96	566.89	83	618.66	99	647.91	87	944.14	137	1133.27	128	868.7806	110

The wind speed data for this study are taken from NASA's POWER CERES/MERRA-2 (NASA GMAO, 2015) and provided at a spatial resolution of 0.625° longitude by 0.5° latitude (which is approximately 50km by 50km), at 50-meters above the surface of the earth, in m/s (WS50M_RANGE). The wind speed dataset is plotted, analyzed and categorized within a simplified classification as breeze (1-16 m/s), depression/gale (17-33 m/s) and cyclone (34 m/s) for the period of 2016-2023. National Oceanic and Atmospheric Administration (NOAA) uses Oceanic Niño Index (ONI) for classifying El Niño (warm) and La Niña (cool) events in the eastern tropical Pacific. The Oceanic Niño Index (ONI) is a three-month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region, spanning latitudes 5°N to 5°S and longitudes 120°W to 170°W (Trenberth, 1997; Tinmaker *et al.*, 2017). El Niño Southern-Oscillation (ENSO) events are identified based on the occurrence of SST anomalies that meet or exceed ±0.5°C for a minimum of five consecutive overlapping three-month seasons. Anomalies ≥ +0.5°C are classified as El Niño (warm phase) events, while anomalies ≤ −0.5°C are identified as La Niña (cool phase) events. These events are further categorized by intensity: Weak (0.5 to 0.9°C), Moderate (1.0 to 1.4°C), Strong (1.5 to 1.9°C), and Very Strong (≥ 2.0°C), based on the magnitude of the SST anomaly (Wahiduzzaman *et al*, 2022). Table 3 and Figure 2 present the periods during which SST anomalies met or exceeded the ±0.5°C threshold for at least five consecutive overlapping seasons.

Table 3. Oceanic Niño Index (ONI) Measures - NOAA / National weather service.

Months/ Years	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2016	2.5	2.1	1.6	0.9	0.4	-0.1	-0.4	-0.5	-0.6	-0.7	-0.7	-0.6
2017	-0.3	-0.2	0.1	0.2	0.3	0.3	0.1	-0.1	-0.4	-0.7	-0.8	-1.0
2018	-0.9	-0.9	-0.7	-0.5	-0.2	0.0	0.1	0.2	05	0.8	0.9	0.8
2019	0.7	0.7	0.7	0.7	0.5	0.5	0.3	0.1	0.2	0.3	0.5	0.5
2020	0.5	0.5	0.4	0.2	-0.1	-0.3	-0.4	-0.6	-0.9	-1.2	-1.3	-1.2
2021	-1.0	-0.9	-0.8	-0.7	-0.5	-0.4	-0.4	-0.5	-0.7	-0.8	-1.0	-1.0
2022	-1.0	-0.9	-1.0	-1.1	-1.0	-0.9	-0.8	-0.9	-1.0	-1.0	-0.9	-0.8
2023	-0.7	-0.4	-0.1	0.2	0.5	0.8	1.1	1.3	1.6	1.8	1.9	2.0

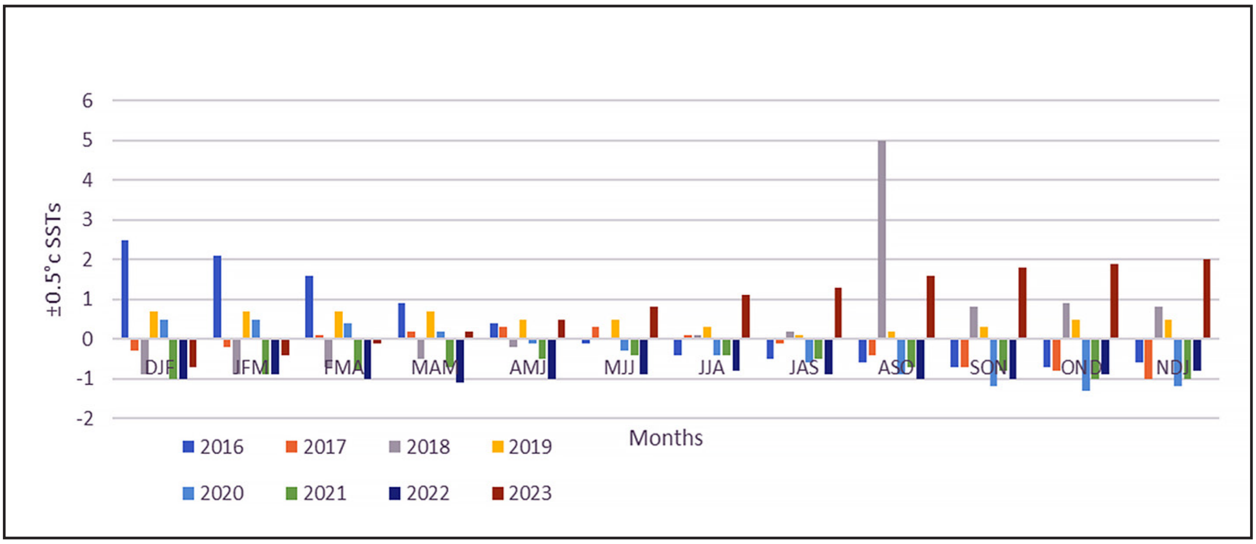

Fig. 2. Oceanic Niño Index (2016-2023).

3. RESULTS AND DISCUSSION

The monthly rainfall trends of the selected study regions were analyzed from 2016 to 2023 (Figs. 3a, 3b, 3c). It can be observed that January, February, and March did not exhibit any appreciable trend in major cities of Karnataka (Fig. 3a). The rainfall in the months of April (partially) and May shows an increasing trend for all the study areas and is considered in this study as pre-monsoon rainfall, except for a few negative trends in the months of April and May for Kerala (Fig. 3b). Rainfall in the month of June, generally considered as the beginning of the monsoon season, is showing a normal trend in general for all regions considered in this study, except for a positive trend of ghats and river basins in few study areas. The month of July also exhibited similar trend as of June. The increasing trend in the month of July was predominant as compared to June in cities and decreasing trends in few ghats and river basins where shown. In contrast to the behavior of rainfall in monsoon season of June, July, August and September, the rainfall in the month of August showed an increasing trend for all cases (Fig. 3 a, b, c). The month of September showed a declining trend comparatively to the rainfall in the month of August. The post monsoon months like October and November also are showing an inclining trend of rainfall except few lowlands of the Western Ghats (W.G).

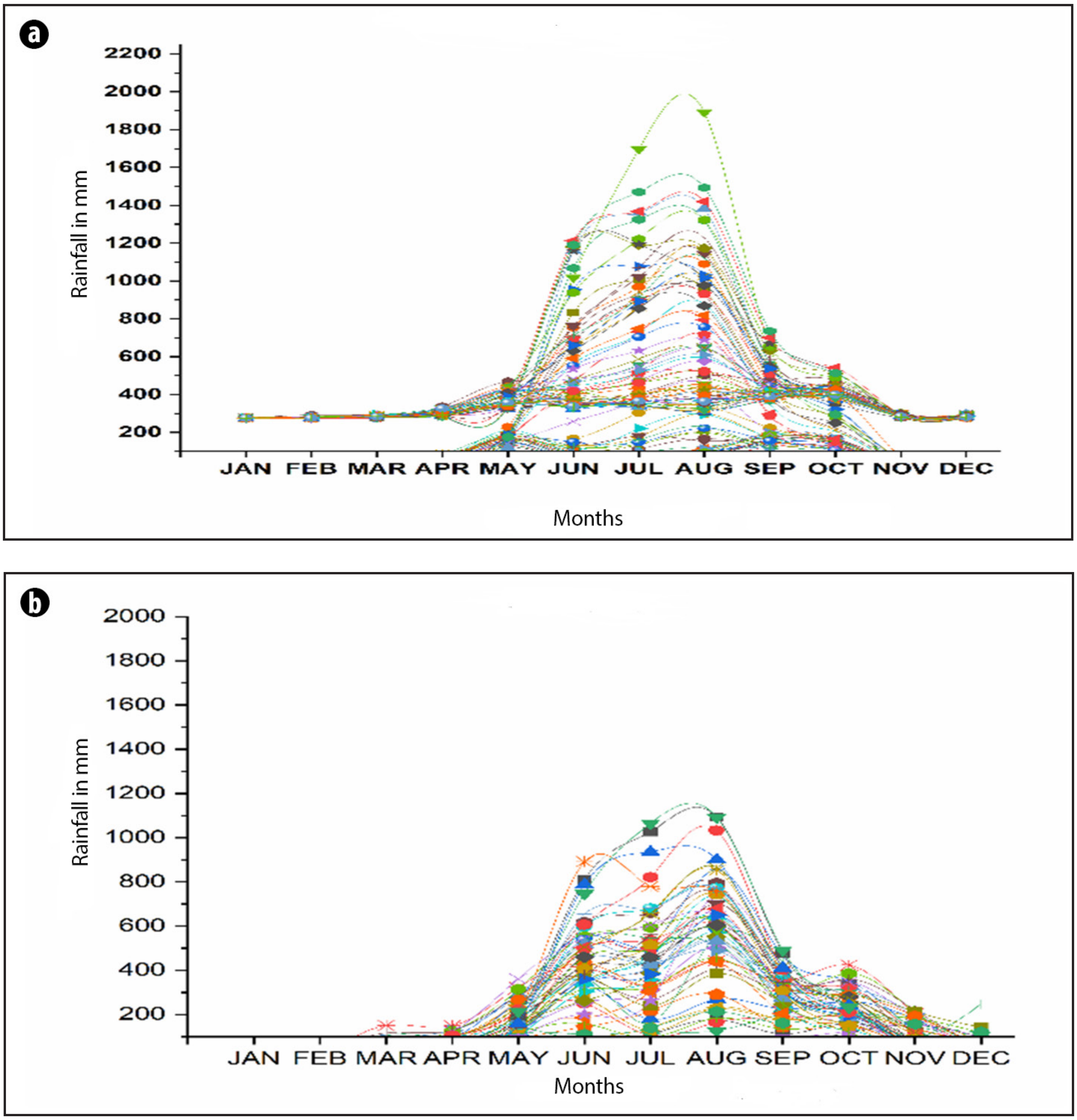

Fig. 3. Annual Average Rainfall plots: (**a**) Karnataka; (**b**) Kerala.

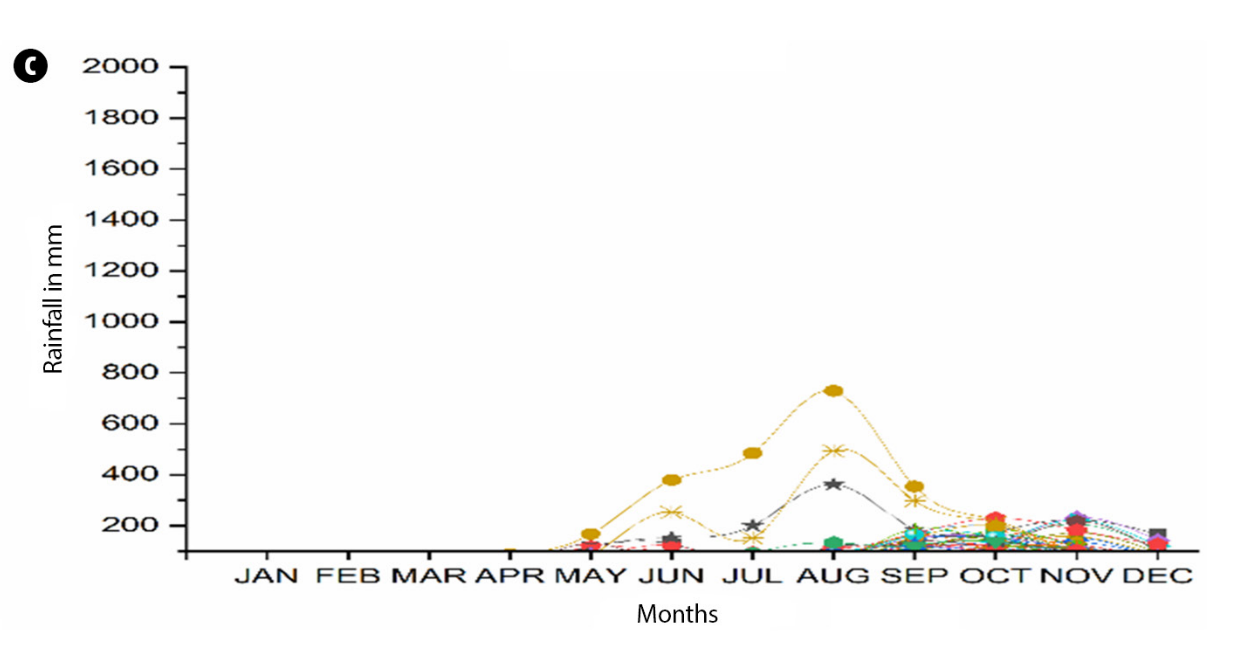

Fig. 3. Annual Average Rainfall plots: (**c**) Tamil Nadu.

4. CONCLUSIONS

After a thorough analysis of the rainfall pattern trends and the annual rainfall rate in mm presented in the Figures 4a, b, c, it can be seen that Udupi in Karnataka has the extremely heavy rainfall and Parameshwarpuram of Nagercoil receives the minimal amount of rainfall in all the selected eight years (2016-2023). Though Parameshwarpuram is nearer to southern Western Ghats, it can be considered as a shadow region. Therefore Table 4 shows the classifications of low rainfall, moderate rainfall, and heavy and/or very heavy rainfall region with reference of Western Ghats.

Table 4. Classification of locations in the Western Ghats by annual rainfall rate.

Low Rainfall Regions	Moderate Rainfall Regions	Heavy/Very heavy rainfall Regions	Extremely Heavy Rainfall Regions
Parameshwarapuram	Theni	Karungal	Udupi
Palayamkottai	Madurai	Nanguneri	Shimoga
Salem	Tirupur	Madurai	Kannur
Hulllambali	Coimbatore	Trivandrum	Malappuram
Pandavapura	Erode	Wayanad	Idukki
Ramanagaram	Trissur	Palakkad	Dindigul
Chitra Durga	Chamarajanagar	Kollam	Theni
Bangalore Urban	Mysuru	Kodagu	
Tumkur	Chikamangaluru	Dakshina Kannada	
Bijapur	Davenegere		
Bellary	Haveri		

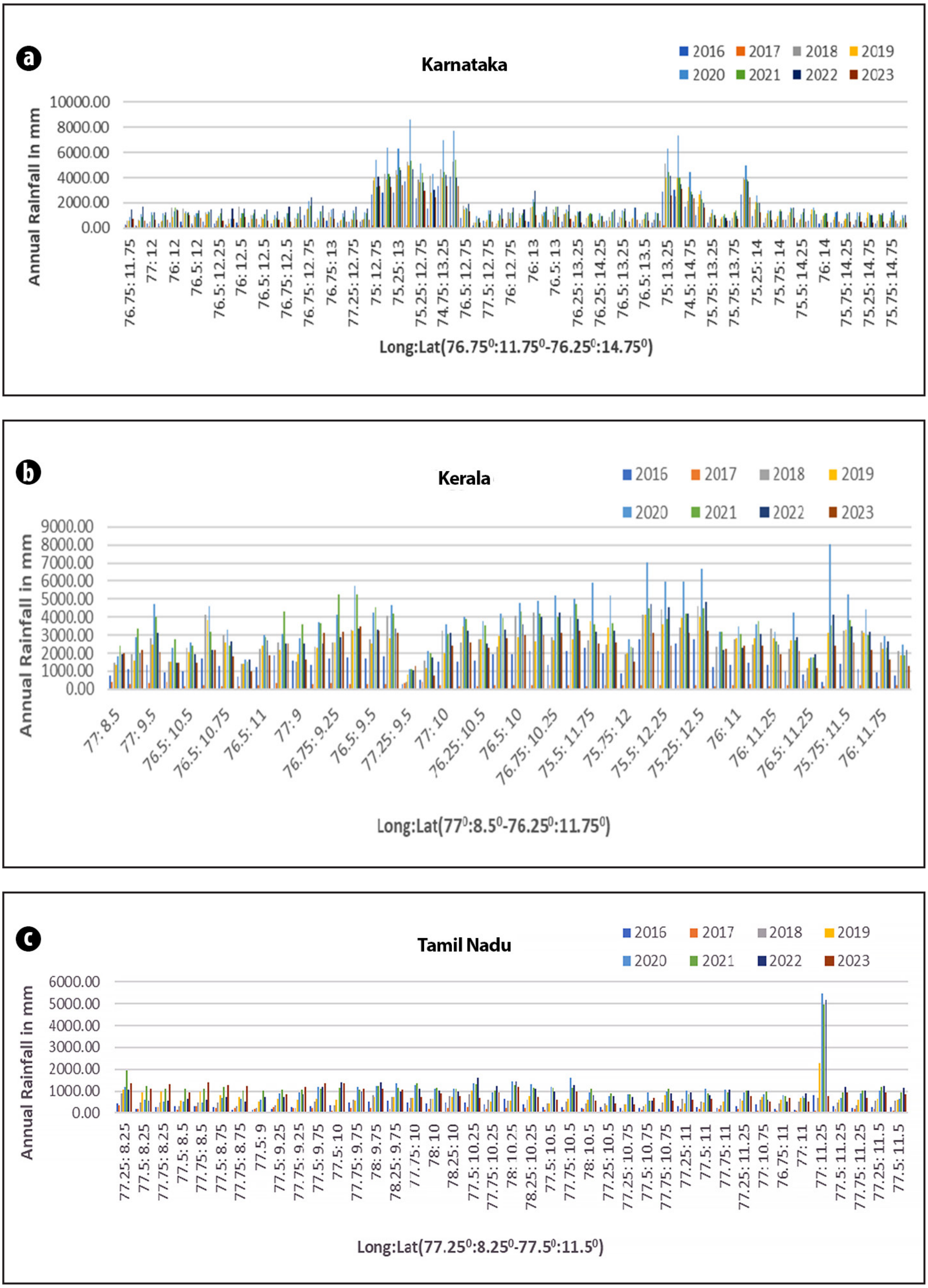

Fig. 4. Locations and the annual rainfall rate for years 2016-2023: (**a**) Karnataka; (**b**) Kerala; (**c**) Tamil Nadu.

Together, the extreme rainfall events and Land Use / Land Cover (LULC) changes have an adverse impact on the mountain environments over India. The extreme rainfall events during the 2018 and 2019 monsoon seasons caused flash floods and thousands of landslides in several places in Western Ghats region, southern India, killing numerous people and damaging their properties (Mishra and Shah, 2018; Ramasamy *et al.*, 2019; Sankar, 2018; Vishnu *et al.*, 2019). The W.G. region is known for wide spread deforestation, changing the forest cover to plantation, mining and quarrying, and unplanned infrastructure development. The year 2017 has minimal rainfall intensity rate, year 2020 and year 2021 have recorded the extremely heavy rainfall intensity rate.

Figure 5 shows the wind speed pattern for the years 2016-2023 which does not exceed the range above 34 m/s as the maximum is 19.8m/s, so it clearly exhibits there is no cyclonic effect in the wind speed which could impact the trend in rainfall. The years 2018-19 and 2015-16 were considered as weak and very strong El Niño events, similarly, 2016-18, 2022-23 and 2020-22 were considered as week and moderate La Niña events. These events can be one of the reasons for variation of rainfall trends in the selected eight years of study (2016-2023).

5. DECLARATIONS

The authors did not receive support from any organization for the submitted work.

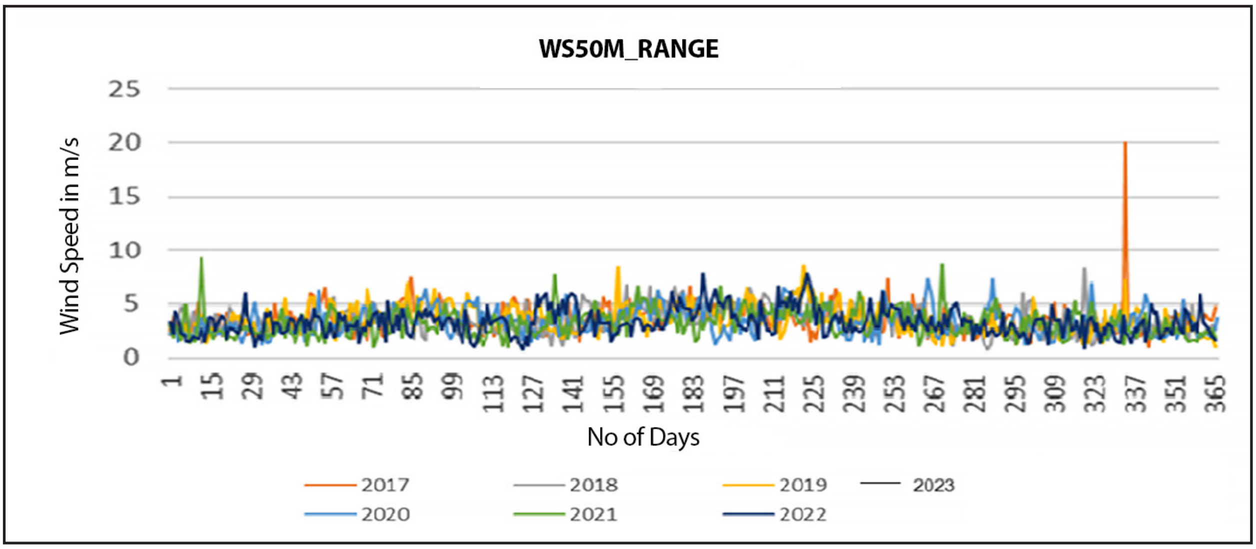

Fig. 5. Average day wind speed for years 2016-2023.

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