National River Conservation Directorate
Ministry of Jal Shakti, Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Climate Change Assessment Report of Periyar River Basin

September 2025

cPeriyar
IIT PALAKKAD
cGanga

Climate Change Assessment Report
of
Periyar River Basin

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Acknowledgment

This report is a comprehensive outcome of the project jointly executed by IIT Palakkad (Lead Institute) and NIT Calicut (Fellow Institute) under the supervision of cGanga at IIT Kanpur. It was submitted to the National River Conservation Directorate (NRCD) in 2024. We gratefully acknowledge the individuals who provided information and photographs for this report.

Disclaimer

This report is a preliminary version prepared as part of the ongoing Condition Assessment and Management Plan (CAMP) project. The analyses, interpretations and data presented in the report are subject to further validation and revision. Certain datasets or assessments may contain provisional or incomplete information, which will be updated and refined in the final version of the report after comprehensive review and verification.

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Preface

The Periyar River Basin, situated on the windward slopes of the Western Ghats in Kerala, represents one of the most climatically sensitive and socio-economically important river systems in southern India. Strongly influenced by the Southwest and Northeast monsoons, the basin exhibits pronounced spatial and seasonal variability in rainfall and temperature, making it highly vulnerable to climate change induced hydro-climatic alterations. Recent extreme rainfall events, floods, and rising temperatures in Kerala have further underscored the need for basin-scale climate assessments to support sustainable water resources planning and risk management.

This report presents a comprehensive analysis of historical and projected climate variability over the Periyar River Basin using long-term observed datasets from the India Meteorological Department (IMD) and bias-corrected climate projections from multiple CMIP6 Global Climate Models. By integrating observational evidence with future climate scenarios, the study aims to quantify changes in rainfall and temperature characteristics, identify statistically significant trends and shifts, and assess potential future climatic conditions under different emission pathways. The findings are intended to provide a scientific basis for understanding climate change impacts on the basin and to inform adaptation strategies for water management, flood mitigation, and ecosystem sustainability.

Centres for Periyar River Basin Management Studies (cPeriyar)
IIT Palakkad & NIT Calicut

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1. Introduction

The Periyar River Basin, situated in central Kerala along the Western Ghats, is a hydrologically important river system that supports agriculture, hydropower projects and urban water supply while sustaining ecologically sensitive regions. Due to its complex topography, strong orographic control by the Western Ghats, and dependence on the Southwest and Northeast monsoons, the Periyar River Basin exhibits pronounced spatial and seasonal hydro-climatic variability (Saranya et al., 2020). Recent studies across humid tropical regions indicate that climate change is significantly altering precipitation regimes and temperature patterns, thereby influencing runoff generation, evapotranspiration, and groundwater recharge processes in river basins similar to the Periyar (Sadhwani et al., 2023). Observational and modelling evidence further suggests that extreme rainfall events are intensifying across peninsular India and the Western Ghats, increasing the vulnerability of monsoon-dominated basins to floods and hydro-climatic extremes under a warming climate (Roxy et al., 2017; Krishnan et al., 2020).

Climate change impact assessments at the river basin scale increasingly rely on the integration of hydrological models with climate projections derived from global climate models. In the Periyar River Basin, hydrological simulations using the Soil and Water Assessment Tool (SWAT) have demonstrated that future climate scenarios are likely to induce notable changes in streamflow magnitude and variability, with projected increases in precipitation and runoff under higher emission pathways (Barman et al., 2026). Such hydro-climatic alterations are expected to intensify flood hazards during monsoon seasons while simultaneously affecting dry-season water availability and baseflow conditions. Recent hydrologic and hydraulic modelling studies further highlight that climate-driven increases in rainfall intensity and extremes can substantially elevate flood risk, particularly in downstream reaches of the basin that experience high levels of urbanization and anthropogenic pressure (Renu et al., 2025). Similar CMIP6-based regional assessments across the southern Western Ghats indicate that rising temperatures, especially minimum temperatures, are likely to enhance evapotranspiration demand and modify basin-scale water balances in coming decades (Kashyap et al., 2025).

Beyond surface hydrology, climate variability and change also influence internal water cycle dynamics and water quality conditions within the Periyar River Basin. Isotopic investigations have shown that prolonged drought episodes and reservoir operations, often exacerbated by climate variability, significantly alter basin-scale water circulation, storage, and residence times (Saranya et al., 2020). In addition, recent water quality assessments emphasize that climate-induced changes in flow regimes can influence pollutant transport, dilution capacity, and ecological health across the basin (Aditya et al., 2024). Collectively, these findings underscore the necessity of a comprehensive climate change assessment that integrates observed climatic trends with future climate projections to better understand potential impacts on hydrology, water quality, flood risk, and long-term basin sustainability in the Periyar River system.

2. Data and Methodology

The climatological assessment of the Periyar River Basin uses observed gridded rainfall and temperature data from the India Meteorological Department (IMD) to analyze historical climate variability over the Basin. Future climate changes are assessed using bias-corrected projections from multiple CMIP6 Global Climate Models developed for South Asia (Mishra et al., 2020). These datasets improve the representation of regional climate processes, particularly monsoon dynamics. Multiple Shared Socioeconomic Pathway (SSP) scenarios are considered to capture model uncertainty and emission pathway dependence. Details of the datasets employed in this study are presented in Table 1.

Table 1. Data used and sources

Sl No.	Type of Data	Source of Data	Period
1	Historical Climate Data	India Meteorological Department (IMD)	1970-2024
2	GCM Data	Bias-corrected climate projections for South Asia from Coupled Model Intercomparison Project-6 (CMIP6) Reference: Mishra, V., Bhatia, U., & Tiwari, A. D. (2020). Bias-corrected climate projections for South Asia from Coupled Model Intercomparison Project-6. Scientific Data, 7, 338. https://doi.org/10.1038/s41597 020-00681-1	1950-2014 (Historical) 2015-2100 (Projected)

2.1 Historical Climate Data

Gridded daily rainfall and temperature data obtained from the India Meteorological Department (IMD) were used to analyze historical climate variability over the Periyar River Basin for the period 1970–2024. The rainfall data are available at a spatial resolution of 0.25°, while temperature data are provided at a resolution of 1°. For rainfall analysis, all grid cells falling within the Periyar

River Basin and an additional 5 km buffer zone were considered to adequately represent basin-scale precipitation variability; the corresponding grid details are given in Table 2 and Figure 1. In the case of temperature, only two IMD grid cells fall within Kerala and lie outside the Periyar Basin which are given on Table 3 and Figure 1. These grids were therefore included and averaged to assess general temperature variability over the region. Given the relatively low spatial variability of temperature across Kerala, this approach is considered sufficient for capturing historical temperature trends relevant to the basin.

Table 2. Location details of IMD rainfall grids in the Periyar River Basin

Sl. No.	Label	Latitude	Longitude
1	R1	9.25° N	77.25° E
2	R2	9.50° N	77.00° E
3	R3	9.50° N	77.25° E
4	R4	9.75° N	77° E
5	R5	9.75° N	77.25° E
6	R6	10° N	76.25° E
7	R7	10° N	76.75° E
8	R8	10° N	77° E
9	R9	10° N	77.25° E
10	R10	10.25° N	76.25° E
11	R11	10.25° N	76.50° E
12	R12	10.25° N	76.75° E
13	R13	10.25° N	77° E

Table 3. Location details of IMD temperature grids in Kerala

Sl. No.	Label	Latitude	Longitude
1	T1	10.50° N	76.50° E
2	T2	9.50° N	76.50° E

2.2 GCM Data

Future climate information used in this study was obtained from bias-corrected outputs of Global Climate Models (GCM) from the Coupled Model Intercomparison Project Phase 6 (CMIP6). The dataset was developed specifically for the South Asian region by Mishra et al. (2020) and incorporates statistical bias-correction techniques to adjust model-simulated climate variables against observed historical records. This bias correction enhances the reliability of GCM outputs for regional-scale climate impact assessments.

The dataset is based on simulations from 13 CMIP6 GCMs, as listed in Table 4. These models provide spatially consistent and high-resolution climate projections under multiple greenhouse gas emission pathways. Climate projections are available for one historical experiment and four Shared Socioeconomic Pathway (SSP) scenarios; SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, representing a range of future development trajectories from low-emission sustainable pathways to high-emission fossil-fuel intensive scenarios.

Daily precipitation, maximum temperature (T_{max}), and minimum temperature (T_{min}) were extracted as the primary climatic variables for this analysis. The historical simulations cover the period 1951-2014, while future projections span 2015-2100. All data are provided at a spatial resolution of 0.25° × 0.25° and cover 18 major river basins across the Indian subcontinent. The Periyar River Basin (PRB) falls within the South Coast region. To adequately capture basin-scale climate variability, all grid points located within the PRB and an additional 5 km buffer zone surrounding the basin boundary were selected for analysis. The geographic coordinates of the extracted grid points are presented in Table 5 and their locations are shown in Figure 1.

Table 4. CMIP6 climate models evaluated in this study

Sl. No	Model Name	Spatial Resolution
1	ACCESS-CM2	0.25° × 0.25°
2	ACCESS-ESM1-5	
3	BCC-CM2-MR	
4	CanESM5	
5	EC-Earth3	
6	EC-Earth3-Veg	
7	INM-CM4-8	
8	INM-CM5-0	
9	MPI-ESM-1-2 HR	
10	MPI-ESM-1-2 LR	
11	MRI-ESM2-0	
12	NorESM2-LM	
13	NorESM2-MM	

Table 5. Location of climate model grid points in PRB

Sl. No.	Label	Latitude	Longitude
1	G1	9.375⁰ N	77.375⁰ E
2	G2	9.625⁰ N	76.875⁰ E
3	G3	9.625⁰ N	77.125⁰ E
4	G4	9.625⁰ N	77.375⁰ E
5	G5	9.875⁰ N	76.875⁰ E
6	G6	9.875⁰ N	77.125⁰ E
7	G7	10.125⁰ N	76.375⁰ E
8	G8	10.125⁰ N	76.625⁰ E
9	G9	10.125⁰ N	76.875⁰ E
10	G10	10.125⁰ N	77.125⁰ E
11	G11	10.375⁰ N	76.125⁰ E

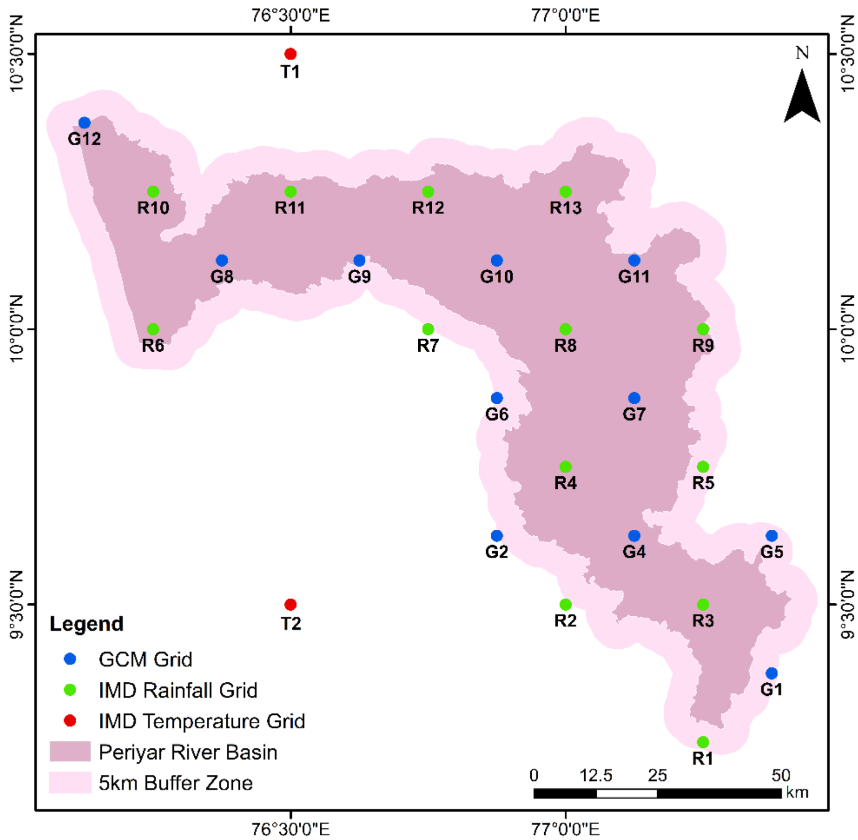


Figure 1. Locations of IMD and CMIP6 grids considered in the study.

3. Analysis of IMD Data

3.1 Rainfall Data

The mean annual rainfall over the Periyar River Basin exhibits substantial spatial variability, with basin-wide values ranging from approximately 841 mm to 3379 mm. The spatial distribution of mean annual rainfall shown in Figure 2 reveals a distinct gradient from the southern upstream regions toward the northeastern downstream reaches.

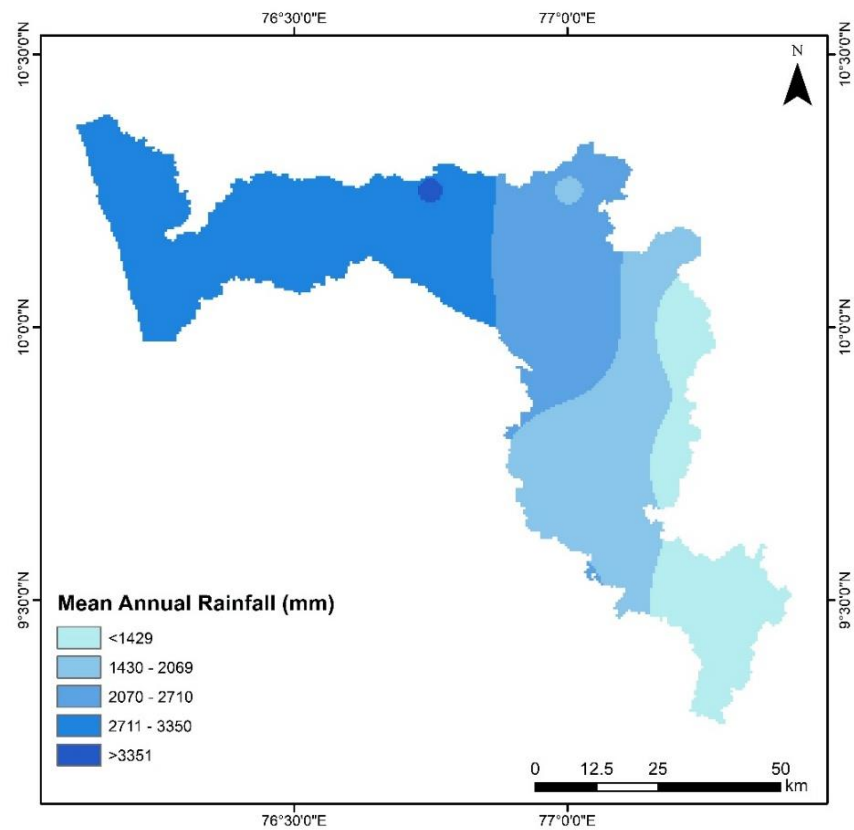


Figure 2. Spatial distribution of mean annual rainfall over the Periyar River Basin

3.2 Temperature Data

The observed annual average maximum and minimum temperature patterns over the Periyar River Basin, derived from IMD gridded data shown in Figure 3, indicate a clear warming trend over the study period. Both T_{max} and T_{min} exhibit interannual variability; however, a consistent increase is evident, particularly from the late 1990s onward. The basin-averaged maximum temperature shows a gradual rise with more pronounced fluctuations, reflecting increasing daytime heat intensity in recent decades. In contrast, minimum temperature displays a more persistent and steady upward trend, especially after 2010, indicating warmer nights and a reduction in nocturnal cooling. The concurrent rise in both T_{max} and T_{min} highlights an overall warming of the regional climate, with the stronger increase in T_{min} suggesting a narrowing of the diurnal temperature range.

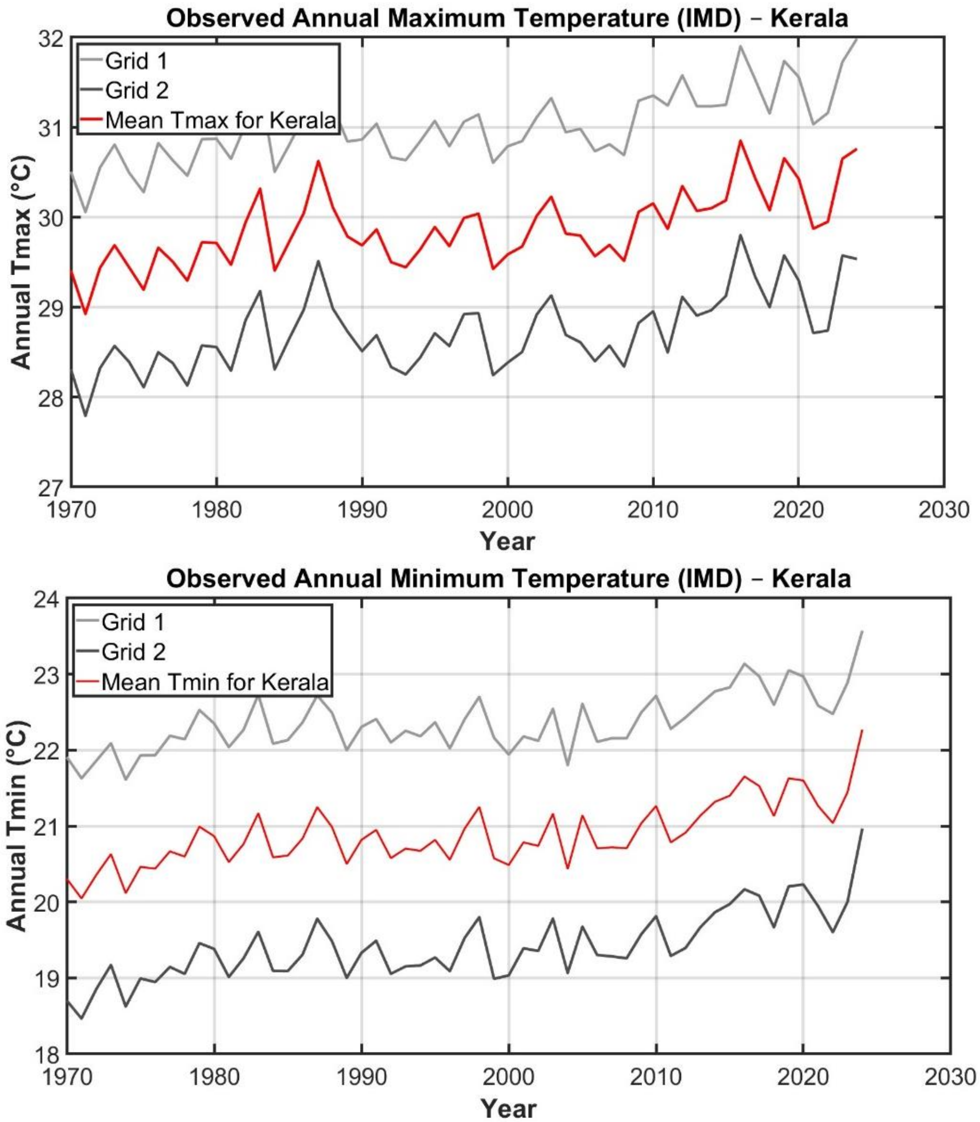


Figure 3. a) Observed annual average maximum temperature (T_{max}) for two IMD grid points in Kerala and their basin-averaged mean. b) Observed annual average minimum temperature (T_{min}) for two IMD grid points in Kerala and their basin-averaged mean.

Monthly analysis of temperature data was carried out to examine seasonal variability in detail. The monthly distribution of maximum and minimum temperatures over the Periyar River Basin for the period 1970-2024 is presented in Figure 4 shows a clear seasonal progression. Maximum temperature (T_{max}) shows a steady increase from the winter months (December-February) and attains peak values during the summer season (March-May), with March and April exhibiting the highest median temperatures and April-May displaying greater variability. During the southwest monsoon period (June-September), T_{max} decreases and exhibits a narrower spread, reflecting relatively uniform conditions, followed by a marginal increase during the northeast monsoon months (October-November). Minimum temperature (T_{min}) similarly increases from winter toward the pre-monsoon season, reaching maximum values during April-May. T_{min} subsequently declines during the southwest monsoon and remains relatively stable through the northeast monsoon, before decreasing toward the end of the year. Overall, both T_{max} and T_{min} display a consistent seasonal pattern, characterized by higher temperatures during the pre-monsoon months and comparatively lower values during the monsoon and winter seasons across the basin.

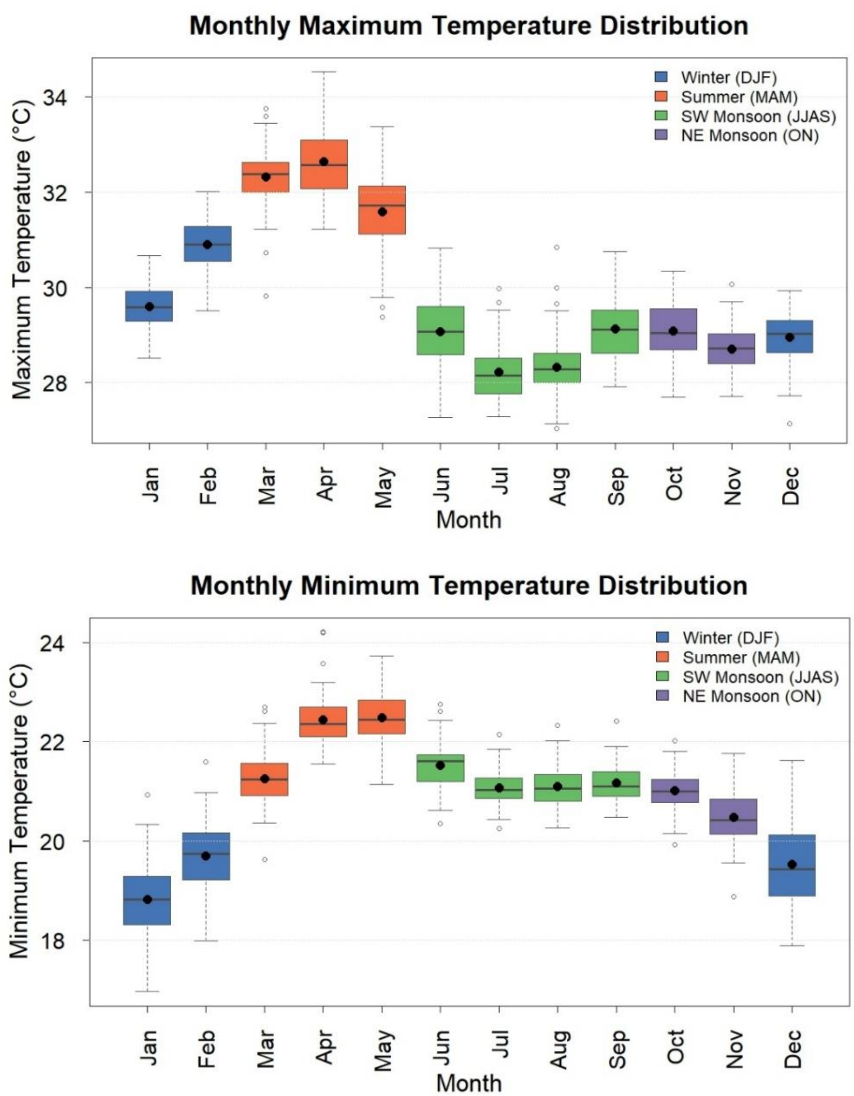


Figure 4. Monthly distribution of T_{max} and T_{min} over the period 1970-2024 in the Periyar River Basin.

The change-point analysis of monthly and annual average maximum and minimum temperature series was conducted to identify statistically significant shifts in the temperature data over the basin and presented in Table 6 and Table 7 respectively.

For T_{max}, most months indicate distinct change points between the late 1990s and early 2000s, with strong agreement among the Pettitt, Buishand Range, Buishand U, and Standard Normal Homogeneity Test, particularly for January, July, August, October, and the annual series. The annual T_{max} shows a highly significant and consistent change point around 2008 across all tests ($p < 0.001$), indicating a basin-wide shift toward higher maximum temperatures. In contrast, some months such as March, April, May, and December show weaker or inconsistent signals, suggesting relatively stable T_{max} conditions during these periods.

Table 6. Change point analysis for monthly and annual T_{max} data

	Pettit Test		**Buishand Range Test**		**Buishand U Test**		**SNH Test**		
Variable	Change Point	P-Value	Change Point	P-Value	Change Point	P-Value	Change Point	P-Value	**Change Point**
Jan	1995	**0.0010**	1995	**0.0043**	1995	**0.0000**	1995	**0.0015**	1995
Feb	2002	**0.0091**	2002	**0.0410**	2002	**0.0004**	2008	**0.0096**	2002
Mar	1981	0.1512	2008	0.3157	2008	**0.0258**	2015	0.0940	No change point
Apr	2012	0.0758	2012	0.1148	2012	**0.0351**	2015	**0.0062**	No change point
May	1978	0.2110	1978	0.3736	1978	0.3183	1978	0.1256	No change point
Jun	2001	**0.0423**	2001	0.1673	2001	**0.0021**	2018	**0.0164**	2001
Jul	1999	**0.0005**	1999	**0.0070**	1999	**0.0000**	2009	**0.0004**	1999
Aug	2002	**0.0005**	2002	**0.0016**	2002	**0.0000**	2008	**0.0003**	2002
Sep	2007	**0.0288**	2007	0.0928	2007	**0.0013**	2010	**0.0160**	2007
Oct	2008	**0.0007**	2008	**0.0026**	2008	**0.0000**	2008	**0.0001**	2008
Nov	2006	**0.0261**	2011	**0.0532**	2011	**0.0013**	2011	**0.0034**	2011
Dec	2001	**0.0203**	1999	0.0624	1999	**0.0014**	1973	**0.0113**	No change point
Annual	2008	**0.0001**	2008	**0.0002**	2008	**0.0000**	2008	**0.0000**	2008

P-values shown in bold indicate statistical significance at the 5% level ($p < 0.05$).

For T_{min}, the results exhibit even stronger and more consistent change-point detection, with most months identifying significant shifts clustered around 2008. Nearly all statistical tests converge on this period for monthly T_{min}, especially from June to December, as well as for the annual series, highlighting a pronounced and persistent transition in minimum temperature behavior. Earlier change points during the 1990s are evident in winter and pre-monsoon months (January-March), indicating the onset of warming trends prior to the basin-wide shift in the late 2000s. Overall, the combined analysis of T_{max} and T_{min} suggests a robust and statistically significant regime shift in basin temperature characteristics around 2008, with T_{min} exhibiting stronger and more widespread change-point signals than T_{max}, underscoring an intensification of warming across the basin during recent decades.

Table 7. Change point analysis for monthly and yearly T_{min} data

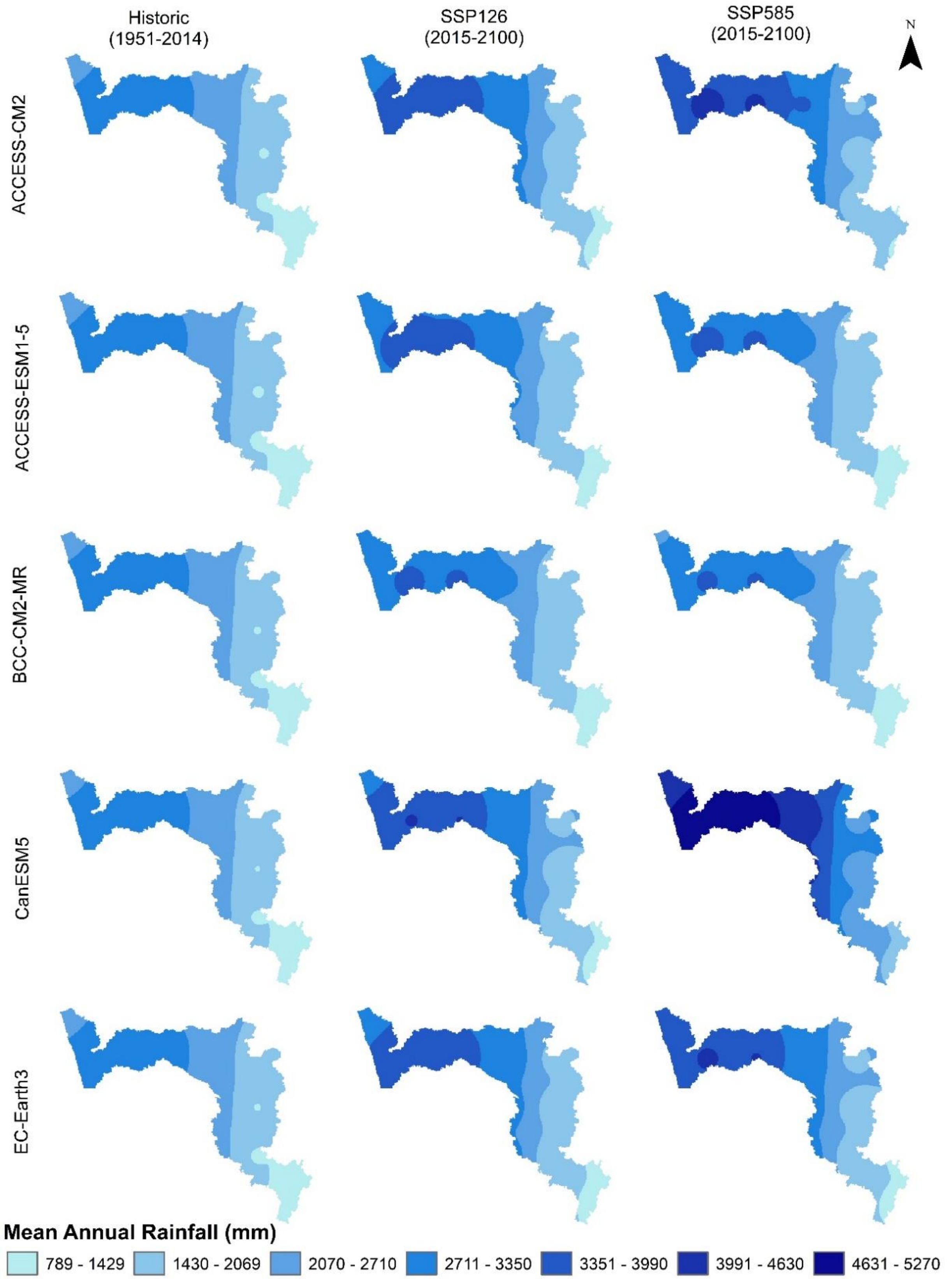
	Pettit Test		**Buishand Range Test**		**Buishand U Test**		**SNH Test**		**Change Point**
Variable	Change Point	P-Value	Change Point	P-Value	Change Point	P-Value	Change Point	P-Value	
Jan	1993,1994	**0.0016**	1994	**0.0022**	1994	**0**	1993	**0.0012**	1994
Feb	1993	**0.0261**	1993	0.0524	1993	6 x10^{-4}	1976	0.0106	1993
Mar	1997	**5x10^{-4}**	1997	**0.0066**	1997	**0**	2014	**4 x10^{-4}**	1997
Apr	2012	**0.0288**	2012	**0.0226**	2012	**0.0024**	2015	**3x10^{-4}**	2012
May	1978,1979	0.1455	2009	0.4411	2009	**0.0244**	1978	0.0598	2009
Jun	2008	**0.0082**	2008	**0.0386**	2008	**6 x10^{-4}**	2013	**8 x10^{-4}**	2008
Jul	2001	**1 x10^{-4}**	2008	**5 x10^{-4}**	2008	**0**	2013	**0**	2008
Aug	2008	**4 x10^{-4}**	2008	**3 x10^{-4}**	2008	**0**	2008	**0**	2008
Sep	2008	**1 x10^{-4}**	2008	**1 x10^{-4}**	2008	**0**	2008	**0**	2008
Oct	2008	**0**	2008	**2 x10^{-4}**	2008	**0**	2008	**0**	2008
Nov	2008	**9 x10^{-4}**	2008	**0.0017**	2008	**0**	2012	**0**	2008
Dec	2007,2008	**2 x10^{-4}**	2008	**2 x10^{-4}**	2008	**0**	2013	**0**	2008
Annual	2008	**1 x10^{-4}**	2008	**0**	2008	**0**	2012	**0**	2008

P-values shown in bold indicate statistical significance at the 5% level ($p < 0.05$).

4. Analysis of GCM Data

4.1 Rainfall Data

Figure 5 illustrate the spatial distribution of mean annual rainfall over the Periyar River Basin as simulated by multiple CMIP6 GCMs for the historical period (1951–2014) and future scenarios (SSP1–2.6 and SSP5–8.5). Across all models and scenarios, a consistent spatial pattern is evident, with higher rainfall concentrated in the western and north-western parts of the basin, corresponding to the windward side of the Western Ghats, and comparatively lower rainfall toward the eastern and south-eastern regions.


Historic
(1951-2014)
SSP126
(2015-2100)
SSP585
(2015-2100)
N
ACCESS-CM2
ACCESS-ESM1-5
BCC-CM2-MR
CanESM5
EC-Earth3
Mean Annual Rainfall (mm)
789 - 1429
1430 - 2069
2070 - 2710
2711 - 3350
3351 - 3990
3991 - 4630
4631 - 5270

(Coninued)


Historic
(1951-2014)
SSP126
(2015-2100)
SSP585
(2015-2100)
N
EC Earth3-Veg
INM-CM4-8
INM-CM5-0
MPI ESM1-2 HR
MPI ESM1-2 LR
Mean Annual Rainfall (mm)
789 - 1429
1430 - 2069
2070 - 2710
2711 - 3350
3351 - 3990
3991 - 4630
4631 - 5270

(Coninued)

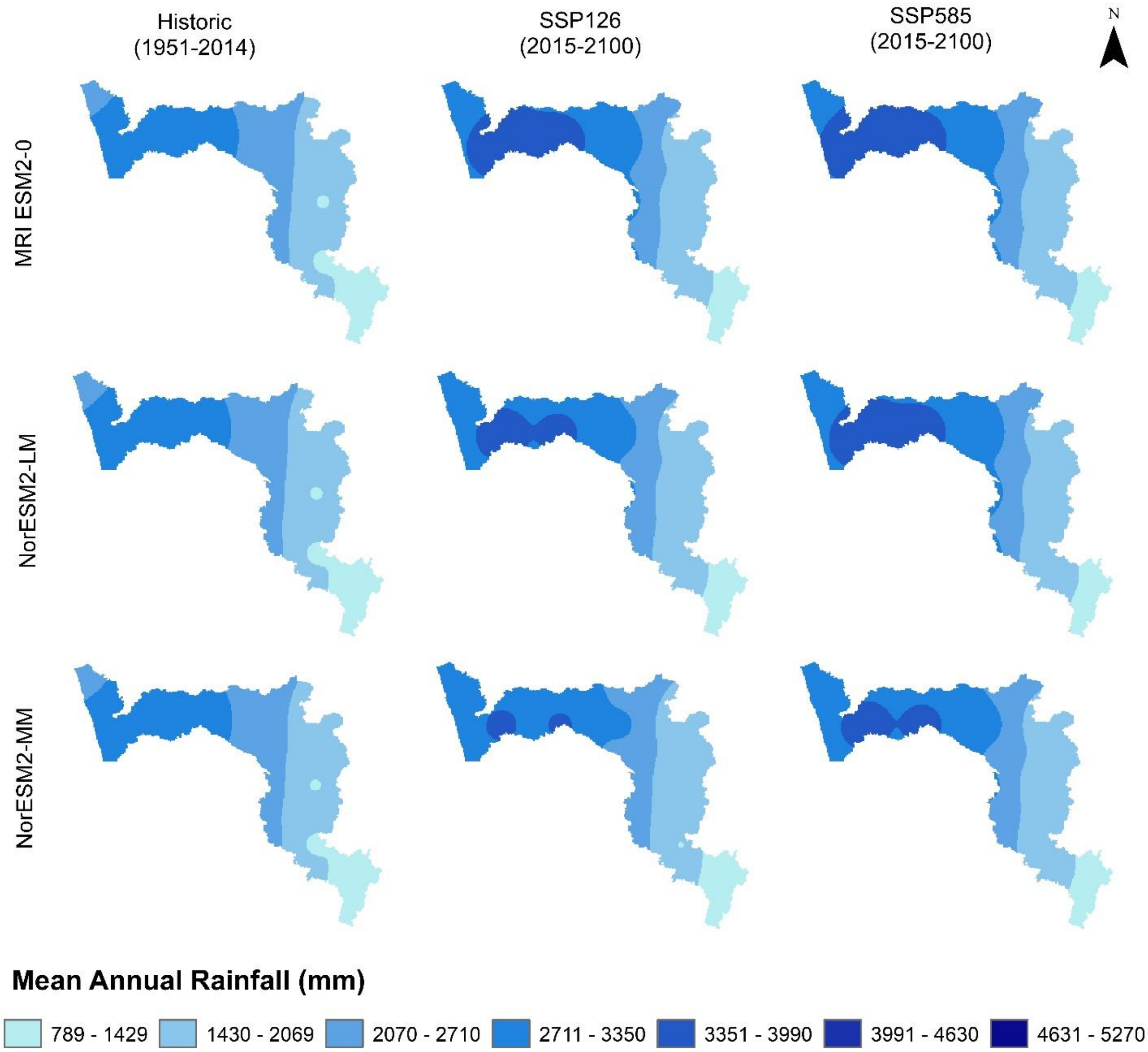
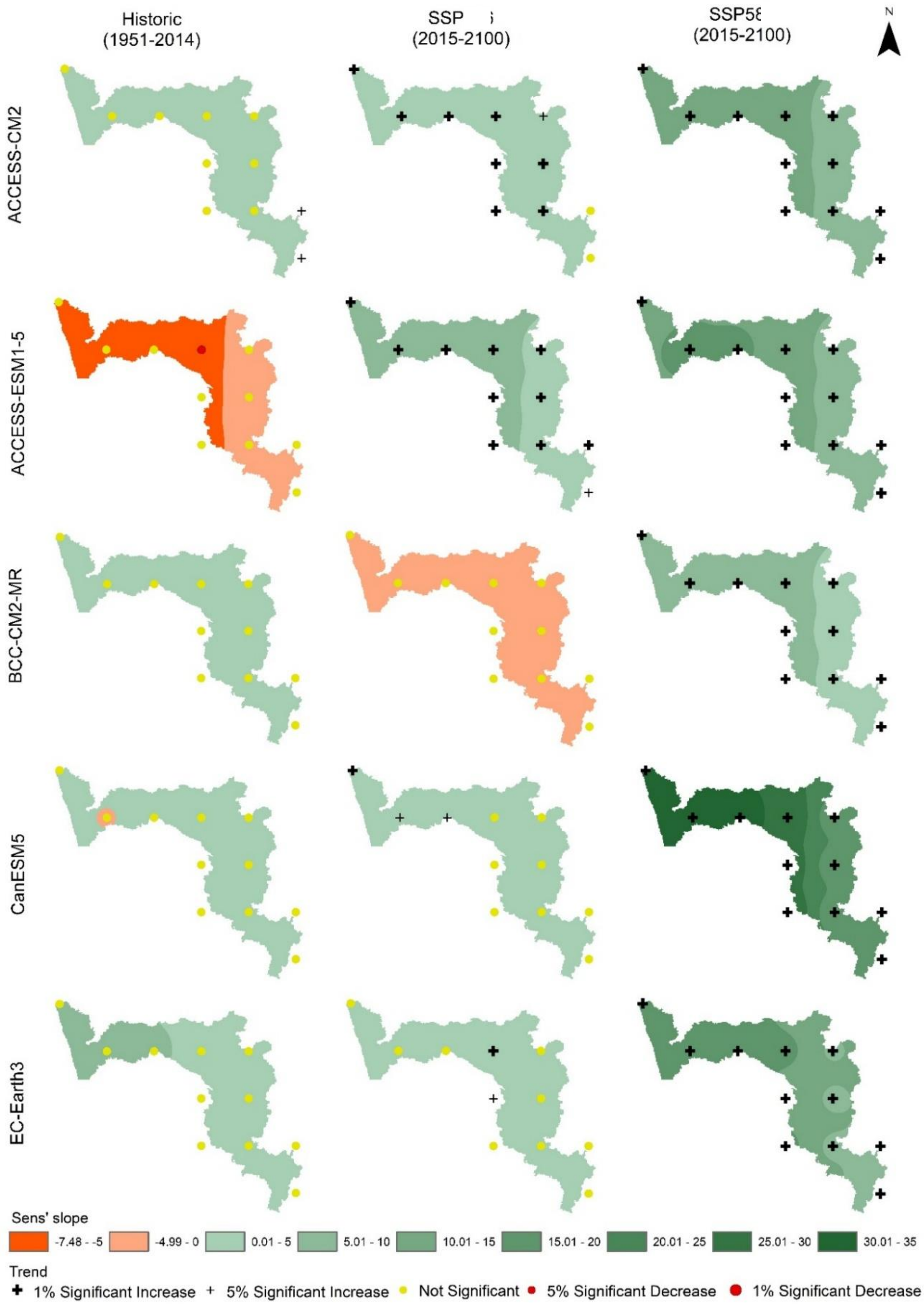


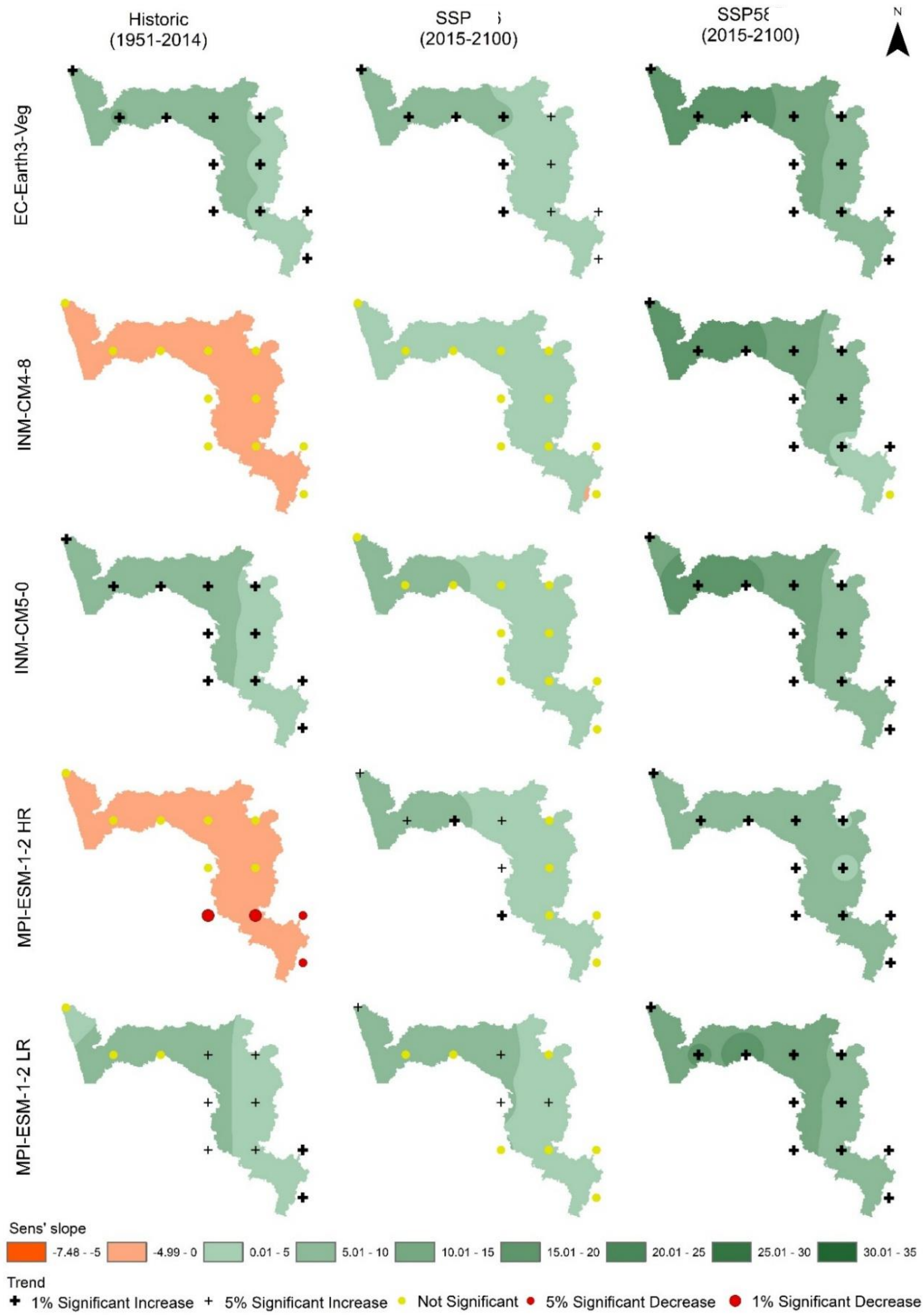
Figure 5. Mean annual rainfall over the Periyar River Basin from CMIP6 GCMs for the historical period and SSP1-2.6 and SSP5-8.5 scenarios.

Under historical conditions, most GCMs capture this orographic rainfall gradient with moderate inter-model variability in magnitude. Future projections indicate an overall intensification of mean annual rainfall across the basin, with a more pronounced increase under the high-emission SSP5–8.5 scenario compared to SSP1–2.6. Several models project an expansion of high-rainfall zones (>3350 mm) in the western and central parts of the basin under SSP5–8.5, suggesting enhanced monsoonal precipitation. While the spatial rainfall pattern remains broadly consistent across GCMs, noticeable differences in rainfall magnitude highlight inter-model uncertainty, particularly under future scenarios.



Historic
(1951-2014)
SSP
(2015-2100)
SSP5
(2015-2100)
N
ACCESS-CM2
ACCESS-ESM1-5
BCC-CM2-MR
CanESM5
EC-Earth3
Sens' slope
-7.48 - -5
-4.99 - 0
0.01 - 5
5.01 - 10
10.01 - 15
15.01 - 20
20.01 - 25
25.01 - 30
30.01 - 35
Trend
1% Significant Increase
5% Significant Increase
Not Significant
5% Significant Decrease
1% Significant Decrease

(Coninued)


Historic
(1951-2014)
SSP
(2015-2100)
SSP5
(2015-2100)
N
EC-Earth3-Veg
INM-CM4-8
INM-CM5-0
MPI-ESM-1-2 HR
MPI-ESM-1-2 LR
Sens' slope
-7.48 - -5
-4.99 - 0
0.01 - 5
5.01 - 10
10.01 - 15
15.01 - 20
20.01 - 25
25.01 - 30
30.01 - 35
Trend
1% Significant Increase
5% Significant Increase
Not Significant
5% Significant Decrease
1% Significant Decrease

(Coninued)

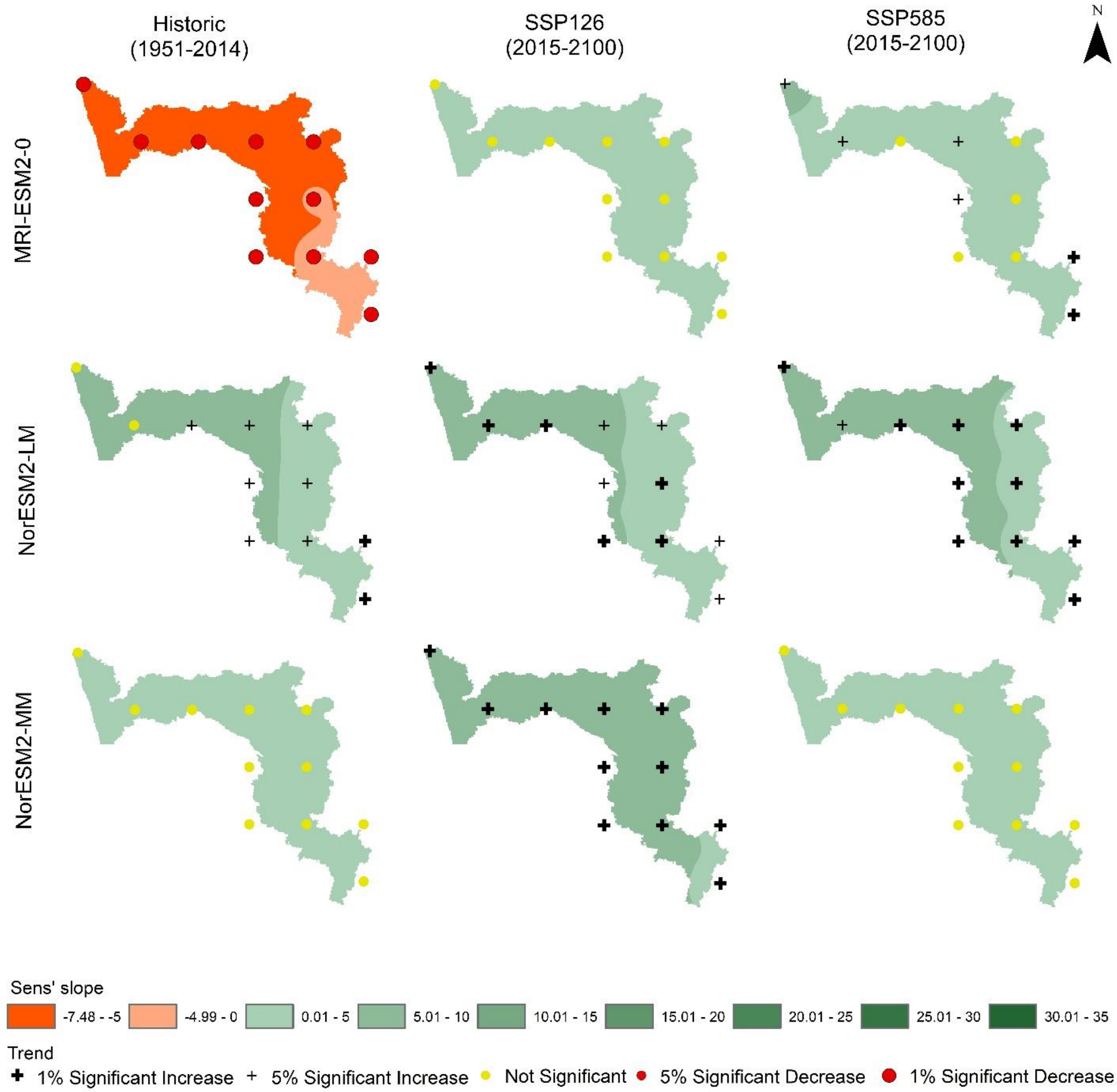


Figure 6. Spatial distribution of Sen's slope and Modified Mann–Kendall (MMK) trend in rainfall over the Periyar River Basin for different GCMs under historical, SSP1-2.6, and SSP5-8.5 scenarios.

The Modified Mann–Kendall (MMK) test was applied to the GCM-derived rainfall time series to detect the presence and direction of monotonic trends while accounting for serial correlation. The spatial distribution of Sen's slope estimates for each grid point was interpolated using the Inverse Distance Weighting (IDW) method to generate basin-wide trend maps for the historical period and future scenarios, as presented in Figure 6. The interpolated maps indicate distinct spatial variability in trend magnitude and direction across the Periyar River Basin for different GCMs and scenarios. Shades of green represent positive trends, while shades of orange indicate negative trends, with the magnitude of Sen's slope values illustrated in the legend. The significance of trends at individual grid points is explicitly marked, distinguishing statistically significant increases and decreases at the 1% and 5% levels from non-significant trends. Overall, the results reveal model-dependent spatial patterns, with future projections-particularly under SSP5-8.5, showing a stronger prevalence of positive trends and higher Sen's slope values compared to the historical period, indicating an intensification of rainfall trends over the basin in higher-emission scenarios.

Analysis of rainfall data revealed that the highest magnitude of rainfall is projected by CanESM5 model under the SSP5-8.5 scenario, suggesting a pronounced intensification of rainfall and a stronger positive trend over the Periyar River Basin under this high-emission scenario.

4.2 Temperature Data

4.2.1 Maximum Temperature (T_{max})

The historical record of annual average T_{max} anomalies over the Periyar River Basin as shown in Figure 7, reveals a distinct shift from largely neutral conditions to predominantly positive anomalies during the latter half of the 20th century. The multi-model ensemble mean shows a statistically robust upward trend relative to the 1971–1990 baseline, despite considerable inter-annual fluctuations and inter-model differences. The persistence of positive anomalies since the 1990s indicates the emergence of a warming signal that clearly exceeds natural background variability.

Future projections demonstrate a strong dependence of T_{max} anomalies on emission scenarios. Under SSP1-2.6, T_{max} increases are moderate and tend to stabilize over time, whereas SSP5-8.5 exhibits a pronounced and accelerating warming trajectory, with ensemble-mean anomalies surpassing approximately 3°C by the late 21st century and a substantial broadening of uncertainty ranges. The increasing spread under SSP5-8.5 reflects heightened model sensitivity under strong radiative forcing. Nonetheless, the sustained positive anomalies across both scenarios provide strong evidence of basin-scale warming.

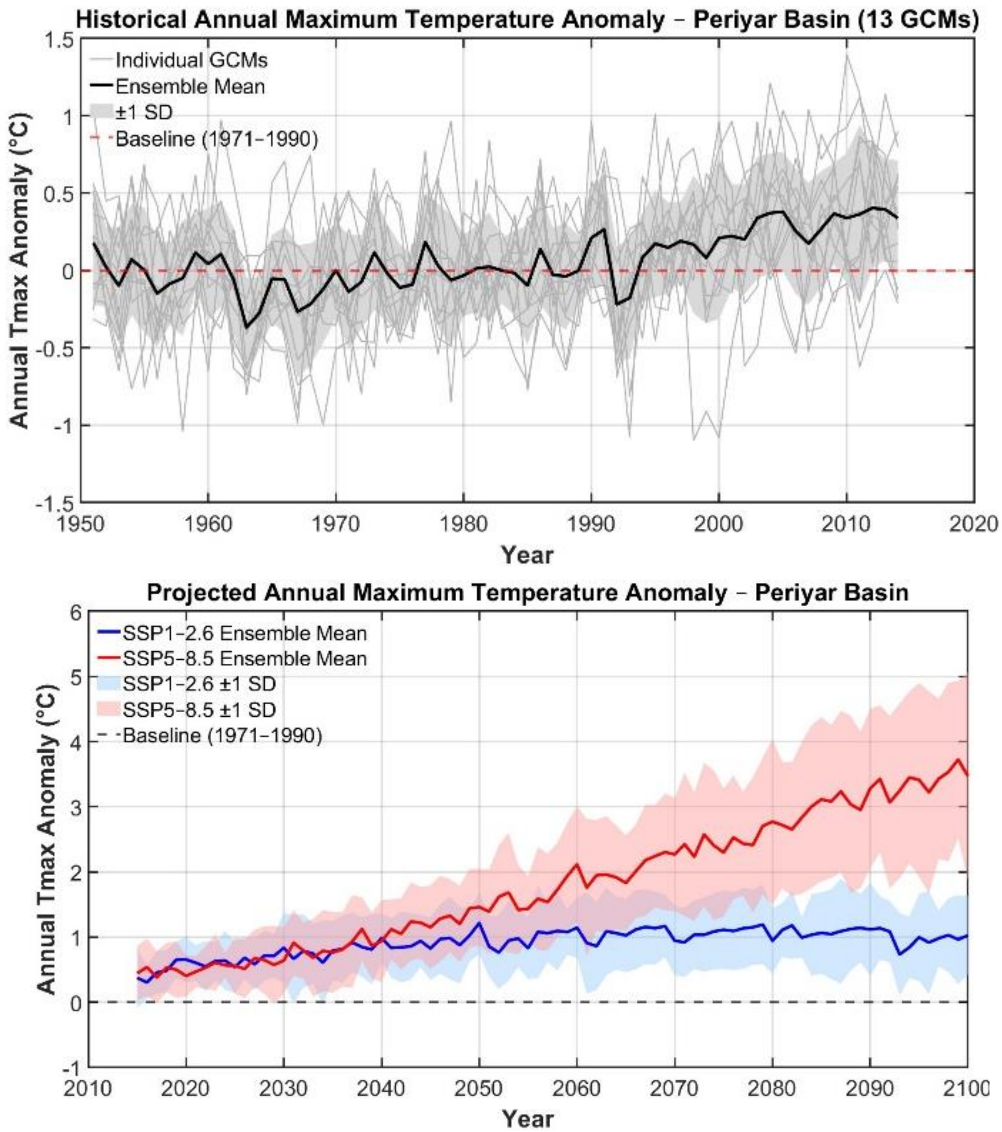


Figure 7. Annual average T_{max} anomalies over the Periyar River Basin a) Historical b) Future projection

Figure 8 illustrates the basin-averaged monthly distribution of T_{max} across multiple GCMs for the Periyar River Basin under historical conditions and future climate scenarios (SSP1-2.6 and SSP5-8.5), highlighting clear seasonal and scenario-dependent variability. Under the historical period (Figure 8a), T_{max} exhibits a pronounced seasonal cycle, with lowest values during the winter months (DJF), a steady rise through summer (MAM) reaching peak temperatures in April–May, followed by a marked reduction during the southwest monsoon (JJAS) and relatively moderate temperatures during the northeast monsoon (ON). Future projections indicate a consistent warming across all months and seasons. Under the SSP1-2.6 scenario (Figure 8b), T_{max} increases moderately compared to the historical baseline, with the largest warming observed during the summer months, while monsoon-season temperatures also show a noticeable upward shift. The SSP5-8.5 scenario (Figure 8c) shows a substantially stronger warming signal, characterized by higher median T_{max} values, increased upper extremes, and a wider inter-model spread, particularly during the summer and early monsoon months. This amplification of T_{max} under high-emission pathways suggests enhanced heat stress conditions, increased evapotranspiration demand, and potential implications for water resources, agriculture, and ecosystem health in the Periyar Basin.

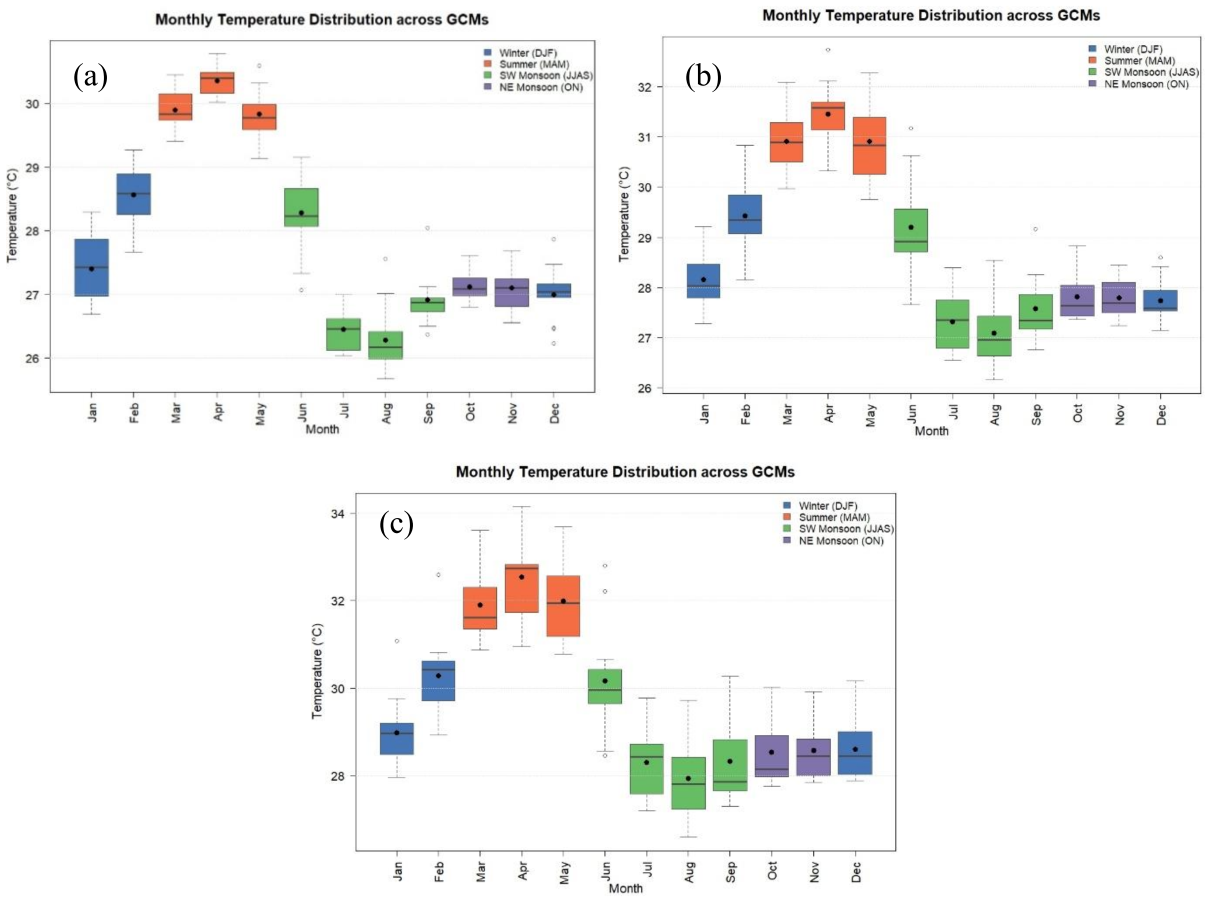


Figure 8. Basin averaged monthly distribution of T_{max} across GCMs showing seasonal variability (Winter, Summer, SW Monsoon and NE Monsoon). a) Historical b) SSP1 c) SSP5

4.2.2. Minimum Temperature (T_{min})

The T_{min} anomaly time series presented in Figure 9 illustrates the evolution of annual minimum temperature anomalies over the Periyar River Basin for both the historical period and future climate scenarios.

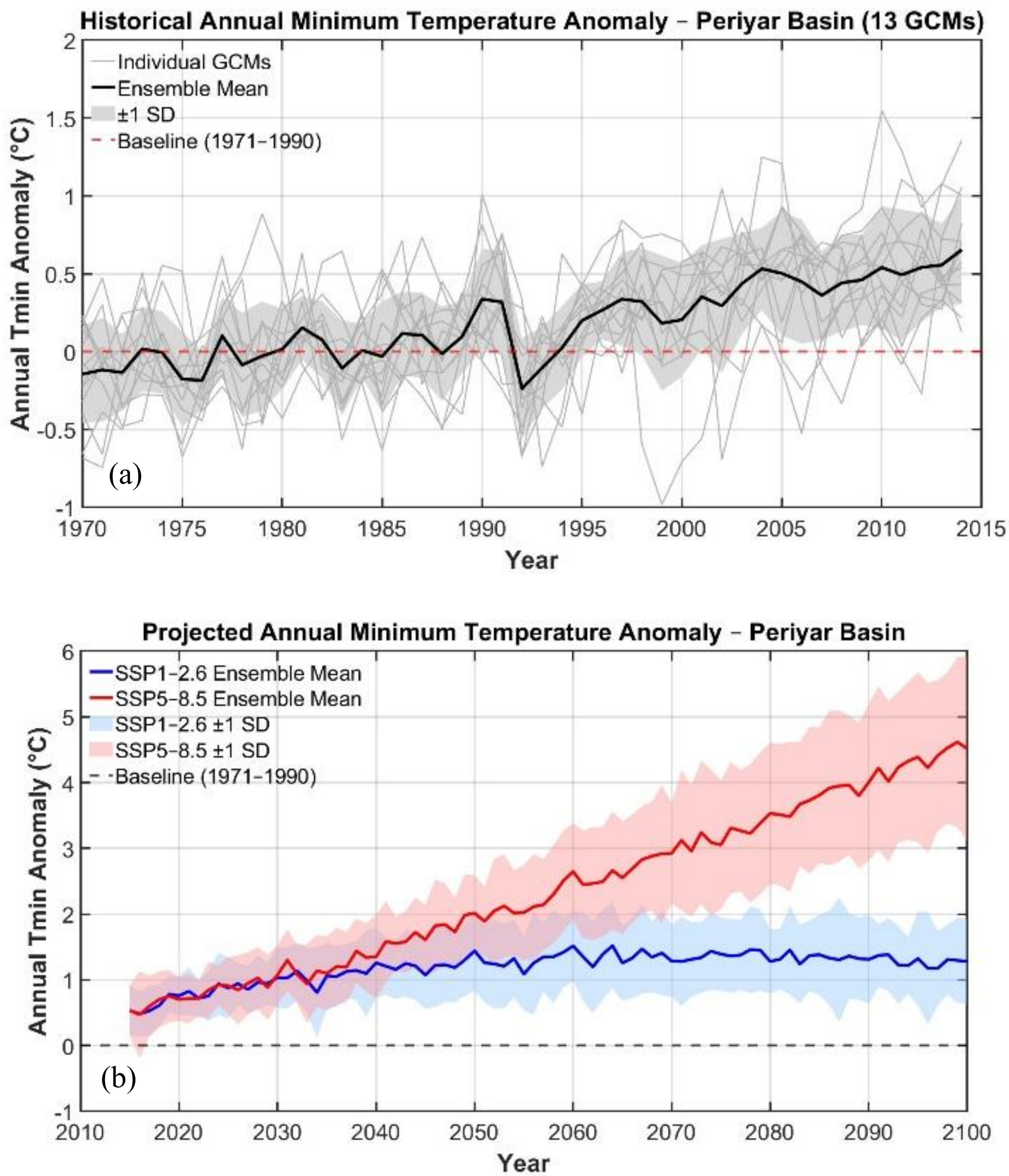


Figure 9. Annual average T_{min} anomalies over the Periyar River Basin a) Historical b) Future projection

During the historical period (1971-2014), T_{min} anomalies fluctuate around the baseline with a gradual transition toward predominantly positive values after the mid-1990s, indicating a consistent warming signal across most GCMs despite inter-model variability. The ensemble mean shows a modest but persistent upward trend, with the spread among models captured by the ±1 standard deviation envelope. In the future projections, T_{min} anomalies increase under both SSP1-2.6 and SSP5-8.5 scenarios, with a clear divergence between the two pathways after mid-century. Under SSP1-2.6, anomalies rise gradually and tend to stabilize toward the latter part of the century, whereas SSP5-8.5 exhibits a strong and continuous increase, reaching substantially higher anomaly magnitudes by the end of the 21st century. The widening uncertainty band under SSP5-8.5 reflects increasing inter-model spread, highlighting enhanced warming and greater uncertainty in minimum temperature projections under high-emission scenarios.

Figure 10 illustrates the basin-averaged monthly distribution of across GCMs for the historical period and future SSP1-2.6 and SSP5-8.5 scenarios, highlighting clear and consistent seasonal variability.

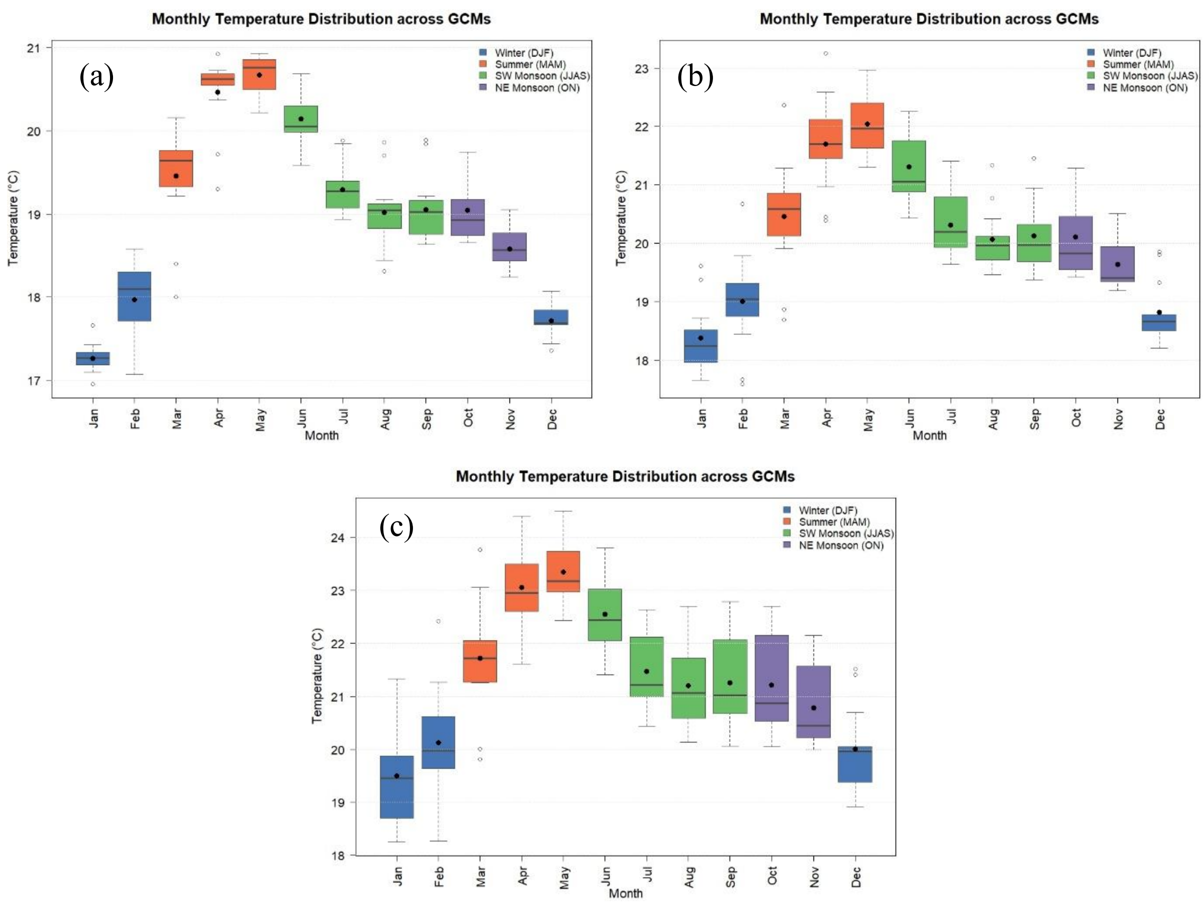


Figure 10. Basin averaged monthly distribution of T_{min} across GCMs showing seasonal variability (Winter, Summer, SW Monsoon and NE Monsoon). a) Historical b) SSP1 c) SSP5

In the historical period, T_{min} increases from the winter months (December-February) to the pre-monsoon season, with the highest median values occurring during March-May, followed by a decline during the southwest monsoon (June-September) and relatively moderate values during the northeast monsoon (October-November). The inter-model spread is relatively limited during the monsoon months, indicating greater agreement among GCMs, while slightly higher variability is observed during the pre-monsoon period. Under SSP1-2.6, the overall seasonal pattern is preserved, but monthly T_{min} values shift upward across all seasons, with modest increases in both median values and inter-model spread. In contrast, SSP5-8.5 shows a pronounced upward shift in T_{min} for all months, with substantially higher median values during the pre-monsoon and monsoon periods and a marked increase in variability across GCMs. The enhanced spread under SSP5-8.5 reflects growing inter-model uncertainty under stronger warming conditions, while the persistence of the seasonal cycle indicates that future warming primarily manifests as an amplification of existing temperature regimes rather than a fundamental change in seasonal structure.

5. Summary

This study provides an integrated assessment of historical and projected climatic variability over the Periyar River Basin, a monsoon-dominated catchment on the windward side of the Western Ghats in Kerala. By combining long-term gridded observations from the India Meteorological Department (IMD) with bias-corrected CMIP6 climate projections, the analysis captures spatial patterns, seasonal behavior, long-term trends, and future changes in rainfall and temperature that are critical for basin-scale hydro-climatic understanding.

Observed IMD data for the period 1970-2024 indicate substantial spatial variability in rainfall across the basin, with mean annual values ranging from approximately 841 mm to 3379 mm and a clear orographic gradient influenced by the Western Ghats. Seasonal analysis indicates that annual rainfall over most grid points is predominantly contributed by the Southwest Monsoon (SWM), accounting for more than 60% of the total annual rainfall. In contrast, grids located on the leeward side of the Western Ghats, particularly toward the Tamil Nadu region, receive a substantially lower contribution from the SWM (<30%). At these locations, the Northeast Monsoon (NEM) contribution is comparatively higher. Temperature analysis reveals a consistent warming signal in both maximum and minimum temperatures, with T_{min} exhibiting a stronger and more persistent increase. Basin -averaged T_{max} increased from 29.4 °C in 1970 to 30.6 °C in 2024, while T_{min} rose from 20.3°C to 22.3°C, over the same period. Monthly temperature distributions show a well-defined seasonal cycle, characterized by higher temperatures during the pre-monsoon months and lower values during the monsoon and winter seasons. Change-point analysis further identifies statistically significant shifts in temperature regimes, with a basin-wide transition toward warmer conditions occurring around 2008.

Analysis on future climate projections from 13 CMIP6 GCMs reveal an overall intensification of rainfall and a robust warming trend over the Periyar River Basin. While the spatial pattern of rainfall remains broadly consistent with historical conditions, projected magnitudes increase under future scenarios, especially under the high-emission SSP5-8.5 pathway. Trend analysis using the Modified Mann–Kendall test and Sen's slope indicates predominantly positive rainfall trends in future periods, with the strongest increase projected by the CanESM5 model under SSP5-8.5. Temperature projections exhibit strong scenario dependence: warming under SSP1-2.6 is relatively moderate and tends to stabilize, whereas SSP5-8.5 shows pronounced and accelerating increases in both T_{max} and T_{min} throughout the 21st century. Seasonal temperature patterns persist in future scenarios, indicating an amplification of existing climatic regimes rather than a fundamental shift in seasonality.

Overall, the results highlight the increasing influence of climate change on the hydro-climatic regime of the Periyar River Basin. The combined evidence of rising temperatures, intensifying rainfall, and strengthening trends under higher-emission scenarios underscores growing risks related to water availability, flood hazards, and ecosystem stress. These findings emphasize the need for climate-informed water resources management and adaptation strategies in the basin, particularly in the context of monsoon variability and projected future warming.

6. References

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