

Projected Compound Hydroclimatic Extremes in Khulna, Bangladesh Using C mip6 Based Climate Projections

Sudipto Kumar Paul

sudiptopaul473@gmail.com

Ahsanullah University of Science and Technology

Md. Tanbhir Rahman

Ahsanullah University of Science and Technology

Research Article

Keywords: CMIP6, Khulna, climate change, trend analysis, compound hydroclimatic extremes, copula based joint probability

Posted Date: September 8th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10705219/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

PROJECTED COMPOUND HYDROCLIMATIC EXTREMES IN KHULNA, BANGLADESH USING CMIP6 BASED CLIMATE PROJECTIONS

Sudipto Kumar Paul^{1*} and Md. Tanbir Rahman¹

¹Graduate Student, Department of Civil Engineering, Ahsanullah University of Science and Technology,
Dhaka, Bangladesh

*Corresponding Author. Email: sudiptopaul473@gmail.com

Acknowledgement: We are grateful to Bangladesh Meteorological Department (BMD) for providing us with the observed data.

ABSTRACT:

Khulna is a coastal district in southwestern Bangladesh, confronts a dual hydroclimatic challenge. That is waterlogging during the monsoon and acute water scarcity in the dry and pre-monsoon seasons. Climate change is likely to intensify these threats, amplifying the frequency and severity of compound extremes. This study explores how temperatures, rainfall patterns, extreme indices and seasonal variability might shift in Khulna over the near (2021-2060) and late (2061-2100) centuries. Drawing on observations from 1951-1990, we evaluate projections from three high-performing Coupled Model Intercomparison Project Phase 6 (CMIP6) models - MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR - under both the moderate Shared Socioeconomic Pathways (SSP)2-4.5 and the high-emission SSP5-8.5 pathways. Our findings indicate robust warming, especially in the late century and under SSP5-8.5, driving more frequent warm days, warm nights and prolonged heatwaves, while cold extremes wane. Rainfall is projected to become more erratic. The monsoon intensifies with wetter spells yet the dry and pre-monsoon are plagued by extended dry spells. Through copula-based joint probability we uncover a persistent negative link between temperature and rainfall anomalies. Which significantly raises the odds of warm-dry events, worsening water scarcity. Meanwhile, fiercer monsoon downpours increase waterlogging hazards. These projections reveal a future caught between drought and flood stresses, offering actionable scientific insights to inform climate-resilient water management and adaptation strategies for this vulnerable coastal population.

Keywords: CMIP6, Khulna, climate change, trend analysis, compound hydroclimatic extremes, copula based joint probability

Introduction:

Climate change has become one of the defining challenges of the twenty-first century, inducing discernible alterations in temperature, precipitation patterns and the frequency of weather extremes to nearly every corner of the globe (IPCC 2021, 2023). As global warming accelerates, heat extremes are becoming more intense, rainfall patterns are changing and the balance of the water cycle is being disrupted in many regions (Trenberth et al., 2014; Tabari, 2020). However, these climatic changes do not unfold uniformly. From a practical and socioeconomic standpoint, what matters most to vulnerable communities is how climate change manifests locally. Consequently, region-specific assessments are imperative for designing effective localized planning and adaptation strategies. (Giorgi and Gutowski, 2015).

In recent years, researchers have begun paying closer attention not only to single extremes like heatwaves or heavy rainfall, but also to compound extremes, where two or more hazards occur together or in quick succession and produce impacts that are greater than the sum of their parts (Z Schenscher et al., 2018; Z Schenscher et al., 2020). For example, a period of high temperatures combined with very little rain can turn water scarcity into a serious drought, while intense rainfall on top of already hot conditions can cover drainage systems and worsen flooding (Hao et al., 2018; Brunner et al., 2021). Studies have shown that these compound events often cause more severe damage to infrastructure, livelihoods and ecosystems than isolated extremes, making them especially important to understand as the climate continues to warm (Kopp et al., 2017; Raymond et al., 2020).

Bangladesh is among the countries most at risk from climate change due to its low-lying geography, high population density and heavy reliance on agriculture and water resources that are directly sensitive to weather and climate (Shahid et al., 2016). Bangladesh's coastal regions face a particularly complex set of hazards, including rising temperatures, uncertain rainfall, cyclones, storm surges and the slow but steady intrusion of saltwater into freshwater areas (Dasgupta et al., 2015; Nicholls et al., 2021). Recent research warns that climate change may make these hazards more frequent and more severe, increasing the chances of compound extremes that threaten water supplies, food production and people's ability to maintain their livelihoods (Tabari and Willems, 2023).

Khulna, in the south-western coastal belt, is at the sharp end of this vulnerability. People here are already familiar with the seasonal pattern of hot, dry pre-monsoon months, heavy monsoon rains and the ongoing challenge of saltwater creeping inland from the Bay of Bengal. When high temperatures and low rainfall coincide before the monsoon, evaporation increases, freshwater becomes scarce and soils grow saltier—all at once (Chamberlin et al., 2020). Then, when the monsoon arrives, intense downpours—sometimes driven

by cyclones—can quickly lead to flooding and waterlogging those damages homes, fields and roads (Borrego et al., 2017). Despite the real and present nature of these risks, there has been relatively little systematic analysis of how compound temperature and rainfall extremes might evolve in Khulna over the coming decades.

Most climate studies for Bangladesh have looked at temperature or rainfall extremes separately, or have worked at the national scale where local details can be missed (Kamaruzzaman et al., 2021). While these studies provide important context, they often do not capture how different climate variables interact at the local level, or what happens when extremes combine. CMIP6 generation offers better physics, finer resolution and more realistic socio-economic scenarios (Eyring et al., 2016; IPCC 2021). Using CMIP6-based regional projections therefore allows for a sharper, more credible picture of what future climate extremes might look like in vulnerable places like Khulna.

This study investigates future compound climate extremes over the Khulna region using high-resolution, bias-corrected climate projections from the CMIP6 models. We evaluate the changing dynamics of individual temperature and rainfall extremes using standardized climate, detect historical and future trends through statistical techniques and model the joint probability of concurrent hazards using copula-based approach. By analyzing these hydro-climatic variables in combination rather than in isolation, the study aims to provide a nuanced understanding of future compound risks under different future scenarios, ultimately offering valuable insights to guide resilient water management and adaptation planning in this highly vulnerable coastal region.

2. Materials and Methods

2.1 Study Area

Khulna district is located in the south-western coastal part of Bangladesh (22°12' N to 23°01' N latitude and 89°06' E to 89°48' E longitude) in the deltaic region of the Ganges, Brahmaputra and Meghna rivers with an area of ~4,389 km². It is surrounded by Jessore and Narail to the north, Satkhira to the west, Bagerhat to the east and the Bay of Bengal and the Sundarbans mangrove forest to the south (Morshed et al. 2026). The economic and administrative hub of the region is Khulna city. The district is flat and low lying (<10 m above mean sea level) (Rahman and Rahman 2015). The northern part consists of deltaic silt, while the central and southern parts are tidal plains that are likely to be flooded. The Sundarbans, the world's largest contiguous mangrove forest is located on the southern edge.

According to (Mazhar et al. 2024), the climate of Khulna is a tropical monsoon type where the temperature ranges from 14°C to 35°C. Long term annual maximum and minimum temperatures have increased at rates of 0.022°C/year and 0.034°C/year, respectively. The mean annual rainfall range is 1600-1900 mm, where more than 70% of rain falls in monsoon (June to October) and pre-monsoon (March to May) and winter (December to February) seasons are comparatively dry (Huq H. et al., 2013).

Dry season freshwater scarcity exacerbates the salinity intrusion in the soil and groundwater, which in turn has a significant effect on agriculture. On the other hand, during the heavy rains of the monsoon season, poor drainage results in prolonged waterlogging. High population density, coupled with heavy dependence on climate sensitive livelihoods (agriculture, fishing, shrimp farming), renders Khulna highly vulnerable to climate change (Murshed et al. 2022). The study area is shown in Fig. 1.

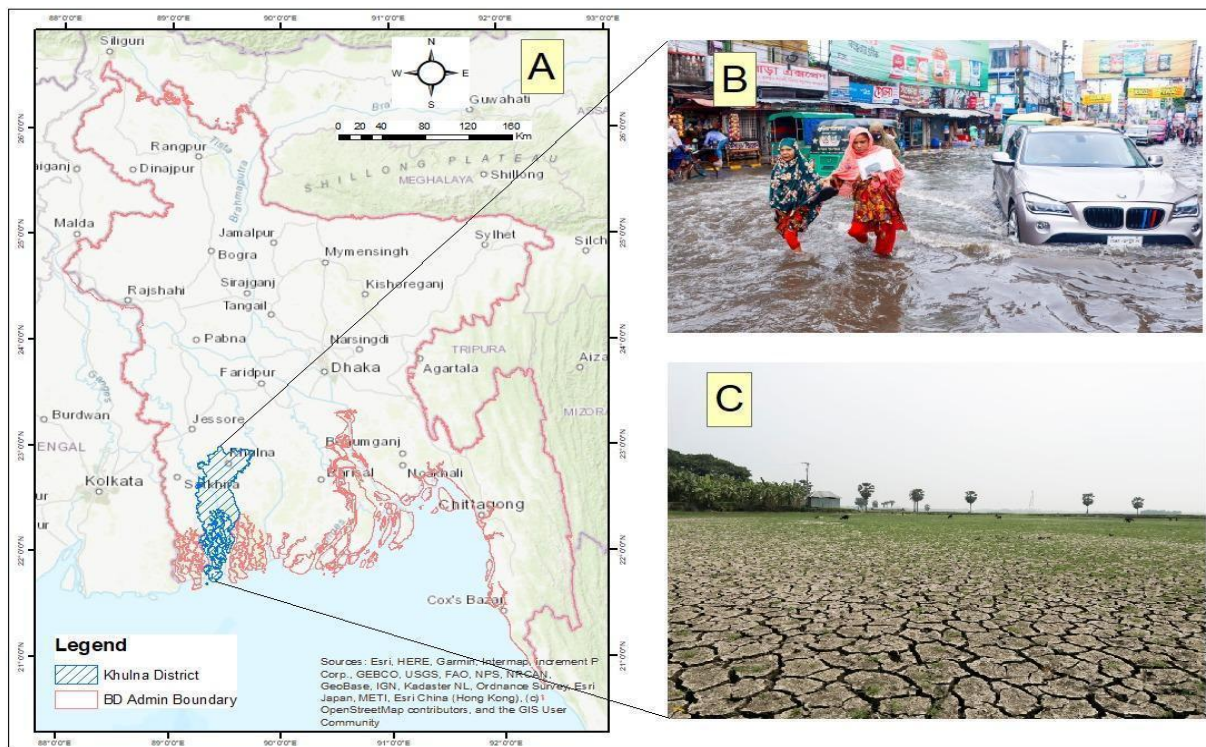


Fig. 1 | (a) Khulna region's location map (b) Khulna City's waterlogging during the monsoon (Source: <https://www.thedailystar.net/environment/news/khulna-city-waterlogging-issues>) (c) Khulna's water crisis during the post-monsoon season (Source: <https://www.dhakatribune.com/bangladesh/environment/climate-change-impact-khulna-water-crisis>)

2.2 Data

2.2.1 Climate Model Data

High-resolution regional climate prediction and impact assessment require advanced climate models and data analysis techniques. Shared Socio-economic Pathways (SSPs) are used in the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) to provide a broad foundation for climate impact and adaptation analyses, linking radiative forcing with varying socio-economic scenarios (O'Neill et al., 2016). Although there are a few studies based on the output of the CMIP6 models for Bangladesh (Kamaruzzaman et al., 2023), no comprehensive study has yet focused specifically on the Khulna region.

GCMs are available at coarse resolutions and do not necessarily resolve important local phenomena such as orographic rainfall and temperature differences between land and sea, which are important for deltaic and coastal areas such as Khulna (Giorgi et al., 2009). To address this, downscaled and bias corrected regional projections are needed. In a recent study, (Mishra et al., 2020) demonstrated that high-resolution, bias-corrected CMIP6 model projections could successfully capture the regional climate characteristics and trends across South Asia. Following the similar framework, in this study we utilized the daily maximum temperature ($T_{\max}$), minimum temperature ($T_{\min}$) and precipitation datasets from (Mishra et al., 2020). It provides finely downscaled and bias-corrected CMIP6 projections at a $0.25^\circ \times 0.25^\circ$ (approximately 25 km $\times$ 25 km) spatial resolution. 13 Global Climate Models (GCMs) were considered for historical daily time series over the period of 1951-2005. Table 1 shows the details of these 13 GCM models.

For this study, two representative scenarios were used for future climate projections: SSP2-4.5, which is a moderate mitigation pathway (with 4.5 W/m² by 2100) and SSP5-8.5, a high-end, fossil-fuel-intensive emissions pathway (with 8.5 W/m² by 2100). The projections were analyzed over 2021-2060 and 2061-2100 periods relative to the 1951-1990 baseline. Model performance was validated with the statistical metrics and then well performing models were chosen for the future extreme climate analysis.

2.2.2 Observed Data

The daily rainfall, maximum and minimum temperature data for the Khulna region were collected from the Bangladesh Meteorological Department (BMD) for the period 1951 to 2005. These long-term meteorological data from the stations are highly useful in the context of climate analysis as the records are scarce and unevenly distributed in coastal Bangladesh. Minor data gaps and inconsistencies, especially in the earlier years, were filled using data from nearby stations by applying standard procedures (Shahid, 2010) without causing significant distortion to the dataset.

Before analysis, thorough data screening was done to remove unrealistic data such as negative rainfall, anomalous rainfall during dry-season and irregular wet or dry sequences (Shahid, 2010). Minor inconsistencies can also affect long-term trend analysis hence basic statistical homogeneity checks were also performed. We combined the real station records with the Rainfall Estimates on a Gridded Network (REGEN) 1°×1° daily precipitation dataset to strengthen our model evaluation across land (Bador et al., 2020). This REGEN dataset helps more accurately assess the performance of the chosen models by incorporating long-term data from the Global Precipitation Climatology Center (GPCC) platform ([Index of /climate environment/GPCC/](#)).

2.3 | Analysis Techniques

2.3.1 Climate Extremes Indices

The Expert Team on Climate Change Detection and Indices (ETCCDI) indices highlight specific features of extreme climate events, such as their frequency, intensity and duration. For this study, we have selected 10 climate change indicators that are effective in identifying the key aspects of future climate patterns. A concise description of these selected indices is provided in Table 2.

2.3.2 | Trend Analysis

Trend analysis is a fundamental statistical approach used to evaluate the behavior of time-series data over a specific period. To detect statistically significant trends within time-series datasets, the Mann-Kendall (MK) non-parametric test is widely employed. Recognized for its robustness, the MK test has been extensively utilized by researchers globally to identify existing climate trends (Mann 1945, Econometrica ; Kendall 1975, Rank Correlation Methods, Charles Griffin & Company). Many researchers around the globe have found the MK test to be a reliable tool for detecting existing statistically significant trends (Ilori ; Ajayi 2020).

For a time, series data X_i (where $i = 1, 2, \dots, n-1$) and X_j (where $j = i+1, 2, \dots, n$), the Kendall test statistic S is calculated to determine the presence of a trend:

$$S = \text{Summation of } [\text{sgn}(X_j - X_i)]$$

Here, the signum function, $\text{sgn}(X_j - X_i)$, is defined as:

$$1 \text{ if } (X_j - X_i) > 0$$

$$0 \text{ if } (X_j - X_i) = 0$$

$$-1 \text{ if } (X_j - X_i) < 0$$

165 The statistic S follows an approximately normal distribution when the sample size is sufficiently large. The
 166 mean and variance of S are given by $E(S) = 0$ and:

$$167 \quad V(S) = [n(n-1)(2n+5) - \text{Summation of } \{t(t-1)(2t+5)\}] / 18$$

168 where ' t ' represents the number of data points in the tied group. The standardized Mann-Kendall test
 169 statistic, Z_{mk} , is then computed to test the significance of the trend:

$$170 \quad Z_{mk} = (S - 1) / \sqrt{V(S)} \text{ [if } S > 0]$$

$$171 \quad Z_{mk} = 0 \text{ [if } S = 0]$$

$$172 \quad Z_{mk} = (S + 1) / \sqrt{V(S)} \text{ [if } S < 0]$$

173 The calculated Z_{mk} value follows a standard normal distribution. In a two-sided test with a significance level
 174 of $\alpha = 0.05$, the null hypothesis (which assumes no trend) is rejected if $|Z_{mk}| \geq Z(\alpha/2)$. A positive Z_{mk}
 175 value indicates an upward or increasing trend, whereas a negative value signifies a downward or decreasing
 176 trend.

177 Once a linear trend is detected, its magnitude or rate of change is quantified using Sen's slope estimator
 178 (Sen, 1968). This non-parametric method estimates the slope Q_i between any two data points as:

$$179 \quad Q_i = (X_j - X_k) / (j - k)$$

180 for all $j > k$. The true slope of the overall time series is represented by the median (Q_{med}) of all calculated N
 181 values of Q_i :

$$182 \quad \text{If } N \text{ is an odd number: } Q_{med} = Q_{((N+1)/2)}$$

$$183 \quad \text{If } N \text{ is an even number: } Q_{med} = [Q_{(N/2)} + Q_{((N+2)/2)}] / 2$$

184 2.3.3 Copula-based Joint Probability Analysis

185 The relationship between variations in temperature and precipitation is widely recognized (Tabari, 2020).
 186 When these two climate factors interact, their combined effect on human society and the environment is
 187 often much more severe than if they occurred in isolation. Consequently, evaluating the combined
 188 hydroclimatic risks requires a thorough understanding of how these variables depend on one another.

189 To model multiple interacting variables and analyze their dependence structures, researchers in recent
 190 decades have increasingly turned to copula functions (Tootoonchi et al., 2020). Essentially, a copula is a
 191 mathematical tool that links individual variables to form a joint probability distribution. This makes it
 192 highly effective for simulating the combined probabilities of future extreme rainfall and temperature shifts.

In this analysis, Parametric Copulas were selected due to their strong capability in assessing the specific dependence structures within the datasets. A variety of Parametric Bivariate Copulas were tested, including the Gumbel, Clayton, Frank, Gaussian and Shih-Louis models, among others.

Mathematically, if temperature and rainfall are defined as random variables X and Y , their individual (marginal) cumulative distribution functions can be written as:

$$M(x) = P[X \leq x]$$

$$N(y) = P[Y \leq y]$$

Using these individual probabilities, the bivariate copula function (C) that calculates their joint probability is defined as:

$$P[X \leq x, Y \leq y] = C(M(x), N(y))$$

3 | Results and Discussion

3.1 Evaluation and Selection of CMIP6 General Circulation Models (GCMs)

The Coupled Model Intercomparison Project Phase 6 (CMIP6) consists of the most advanced climate models used globally to predict future climate conditions (Eyring et al., 2016). These models play a vital role in understanding the potential impacts of climate change under different emission scenarios (O'Neill et al., 2016). However, to ensure the reliability of the projections, it is essential to evaluate these models based on their ability to replicate historical climate data (Taylor, 2001).

Prior to future climate projections, we evaluated the historical performance of the CMIP6 GCMs against the observed data using Taylor diagrams. The numbering of the models (1-14) corresponds directly to the serial numbers in Table 1. For the rainfall evaluation, the reference baseline denoted by number 15 on the Taylor diagram. It was taken as the station data along with REGEN data (GPCC data). The rainfall performance of the selected CMIP6 models was evaluated with respect to both station records and the GPCC data. It is observed that the GPCC backed REGEN rainfall provided an almost perfect match with the actual station data and achieved a spatial correlation coefficient greater than 0.99.

Based on a multi-criteria statistical assessment across all three variables, BCC-CSM2-MR (Model 4), EC-Earth3 (Model 6) and MPI-ESM1-2-LR (Model 11) emerged as the top-performing models. For mean monthly rainfall (Fig. 2c), these three models plotted closest to the reference baseline, showing the lowest

RMSE and highest spatial correlation among the individual GCMs. For temperature simulations, Models 4,6 and 11 displayed remarkable consistency and they maintained high spatial correlations ($COR > 0.85$) with an RMSE close to or below $1.0^{\circ}C$ for T_{max} (Fig. 2a) and clustered tightly within the high accuracy quadrant for T_{min} (Fig. 2b). This three-model ensemble consistently delivered the most balanced representation of both thermal and hydrological parameters. That's why we selected these three models for our future climate projections.

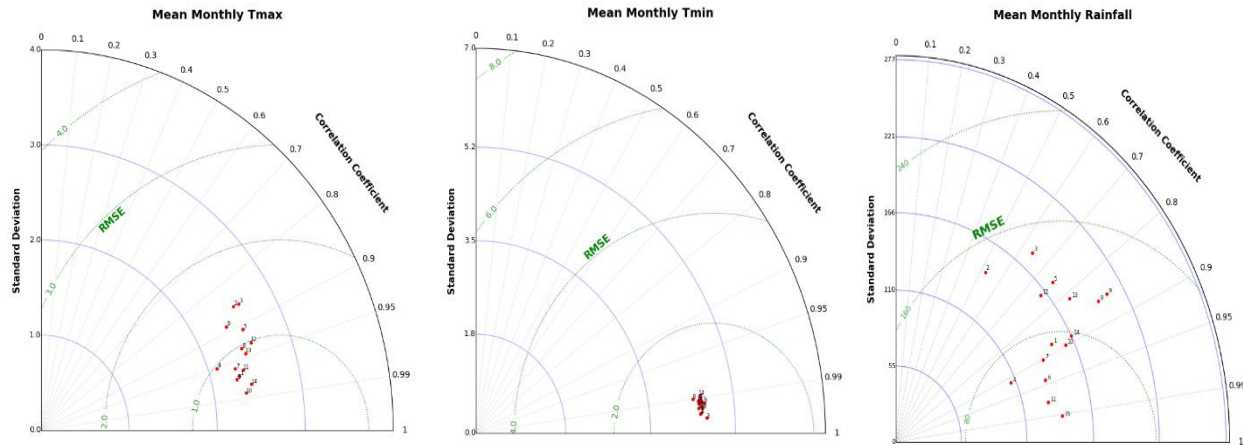


Fig. 2 | Taylor diagram for (a) mean monthly T_{max} (b) mean monthly T_{min} and (c) mean monthly rainfall (including GPCC rainfall), from the selected GCMs and the station over 1951–2005 period.

249 **Table 1** | Details of the selected dynamically downscaled and bias-corrected CMIP6 climate models.

Serial number	Model name (CMIP6)	Country of origin	Spatial resolution (km × km)	Temporal resolution
1	Multi model ensemble (CMIP6)	N/A	25	Daily
2	ACCESS-CM2	Australia	25	Daily
3	ACCESS-ESM1-5	Australia	25	Daily
4	BCC-CSM2-MR	China	25	Daily
5	CanESM5	Canada	25	Daily
6	EC-Earth3	Europe	25	Daily
7	EC-Earth3-Veg	Europe	25	Daily
8	INM-CM4-8	Russia	25	Daily
9	INM-CM5-0	Russia	25	Daily
10	MPI-ESM1-2-HR	Germany	25	Daily
11	MPI-ESM1-2-LR	Germany	25	Daily
12	MRI-ESM2-0	Japan	25	Daily
13	NorESM2-LM	Norway	25	Daily
14	NorESM2-MM	Norway	25	Daily

250
251
252
253
254
255
256
257
258
259
260
261
262
263

3.2 | Future Climate Variability

Table 2 | Definitions of 10 climate change indices used in this study.

Notation	Indices name	Units	Description
TX90P	Warm days	% Days	% Of days when TX > 90th percentile
TX10P	Cold days	% Days	% Of days when TX < 10th percentile
TN10P	Cold nights	% Days	% Of days when TN < 10th percentile
TN90P	Warm nights	% Days	% Of days when TN > 90th percentile
WSDI	Warm spell duration index	days	Annual count of days with at least 6 consecutive days when TX > 90th percentile
CSDI	Cold spell duration indicator	days	Annual count of days with at least 6 consecutive days when TN < 10th percentile
R95P	Very wet days	mm	Annual total PRCP when RR > 95th percentile
RX5DAY	Maximum 5-day precipitation	mm	Monthly maximum consecutive 5-day precipitation
CDD	Consecutive dry days	days	Maximum number of consecutive days with RR < 1 mm
CWD	Consecutive wet days	days	Maximum number of consecutive days with RR ≥ 1 mm

In this study, the future climate projections for the Khulna region were analyzed across two climate windows: the near century (2021–2060) and late century (2061–2100) periods, compared to the baseline period of 1951–1990. Selected models MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR were evaluated under both the SSP2-4.5 and SSP5-8.5 scenarios. According to Table 3, the $T_{\max}$ and $T_{\min}$ anomalies range from 0.45 °C to 2.51 °C and 0.39 °C to 3.55 °C, respectively. The mean increase in $T_{\max}$ is projected to be ~0.50 °C under SSP2-4.5 and ~0.73 °C under SSP5-8.5 during 2021–2060. This warming is significantly enhanced considerably during the late-century time period, with an average $T_{\max}$ increase of ~1.22 °C under SSP2-4.5 and ~2.29 °C under SSP5-8.5. Minimum temperatures also follow a similar trend of increase but $T_{\min}$ anomalies are larger than those of $T_{\max}$ anomalies, especially during the late century. This suggests more significant warming at night and a potential decrease in the diurnal temperature range.

On an annual scale, future projections indicate a consistent increase in precipitation over Khulna with positive precipitation anomalies across all the selected models and scenarios. Changes in rainfall are larger for the late century than for the near century, particularly under the high-emission SSP5-8.5 scenario.

Table 3 | Anomaly with respect to base period (1951–1990)

GCMs	Period	Rainfall anomaly (mm/year)	T _{max} anomaly (°C)	T _{min} anomaly (°C)
MPI-ESM1-2-LR	SSP2-4.5 2021–2060	653.29	0.45	0.39
	SSP2-4.5 2061–2100	670.53	1.08	1.15
	SSP5-8.5 2021–2060	642.16	0.76	0.79
	SSP5-8.5 2061–2100	682.25	2.02	2.50
EC-Earth3	SSP2-4.5 2021–2060	635.20	0.51	0.83
	SSP2-4.5 2061–2100	680.91	1.36	1.97
	SSP5-8.5 2021–2060	457.53	0.78	1.08
	SSP5-8.5 2061–2100	780.69	2.51	3.50
BCC-CSM2-MR	SSP2-4.5 2021–2060	369.08	0.55	1.03
	SSP2-4.5 2061–2100	387.85	1.23	1.93
	SSP5-8.5 2021–2060	249.73	0.65	1.27
	SSP5-8.5 2061–2100	497.67	2.34	3.55

The monthly box and whisker plots for $T_{\max}$ (Fig. 3) and $T_{\min}$ (Fig. 4) both reveal an overall upward shift in the medians, as well as the upper and lower quartiles throughout the year. This rising trend is well captured by all three models and is most prominent during 2061-2100 under the SSP5-8.5 scenario. The faster upward shift in the $T_{\min}$ baseline indicates that nights will warm more rapidly than days. Meanwhile, the daily rainfall box plots (Fig. 5) show both monthly increases and decreases. However, the data spread is quite large for the monsoon months (June to September) with high upper quartiles and extreme precipitation values. This is an indication of increased rainfall variability and a higher frequency of extreme events during the monsoon. In general, Khulna is expected to witness a continuous rise in temperature and increased rainfall, especially in the high emission scenario SSP5-8.5.

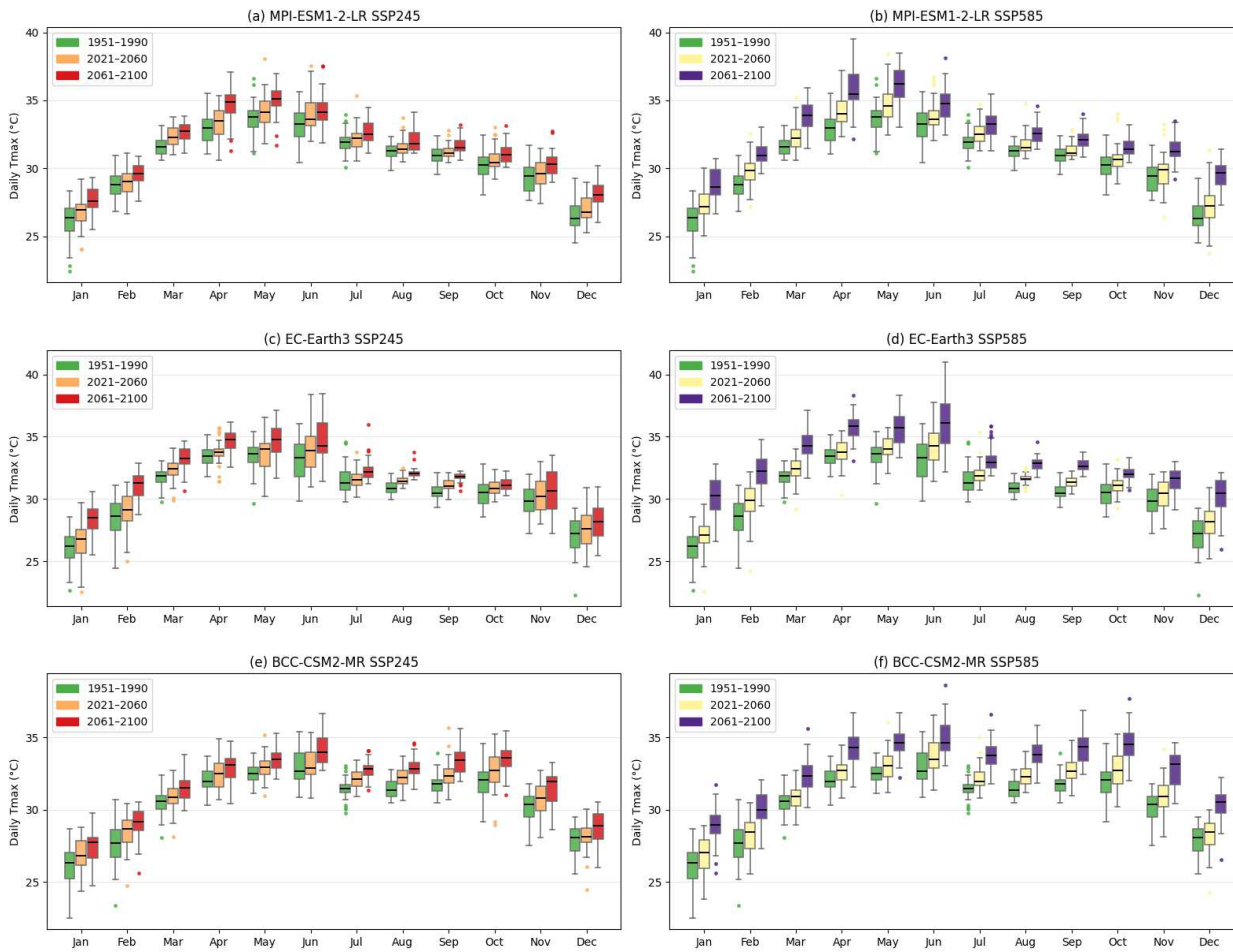


Fig. 3 | Box and whisker plot of daily $T_{\max}$ for 1951–1990, 2021–2060 and 2061–2100 from (a) MPI-ESM1-2-LR SSP2.4.5 (b) MPI-ESM1-2-LR SSP5-8.5 (c) EC-Earth3 SSP2.4.5 (d) EC-Earth3 SSP5-8.5 (e) BCC-CSM2-MR SSP2.4.5 (f) BCC-CSM2-MR SSP5-8.5

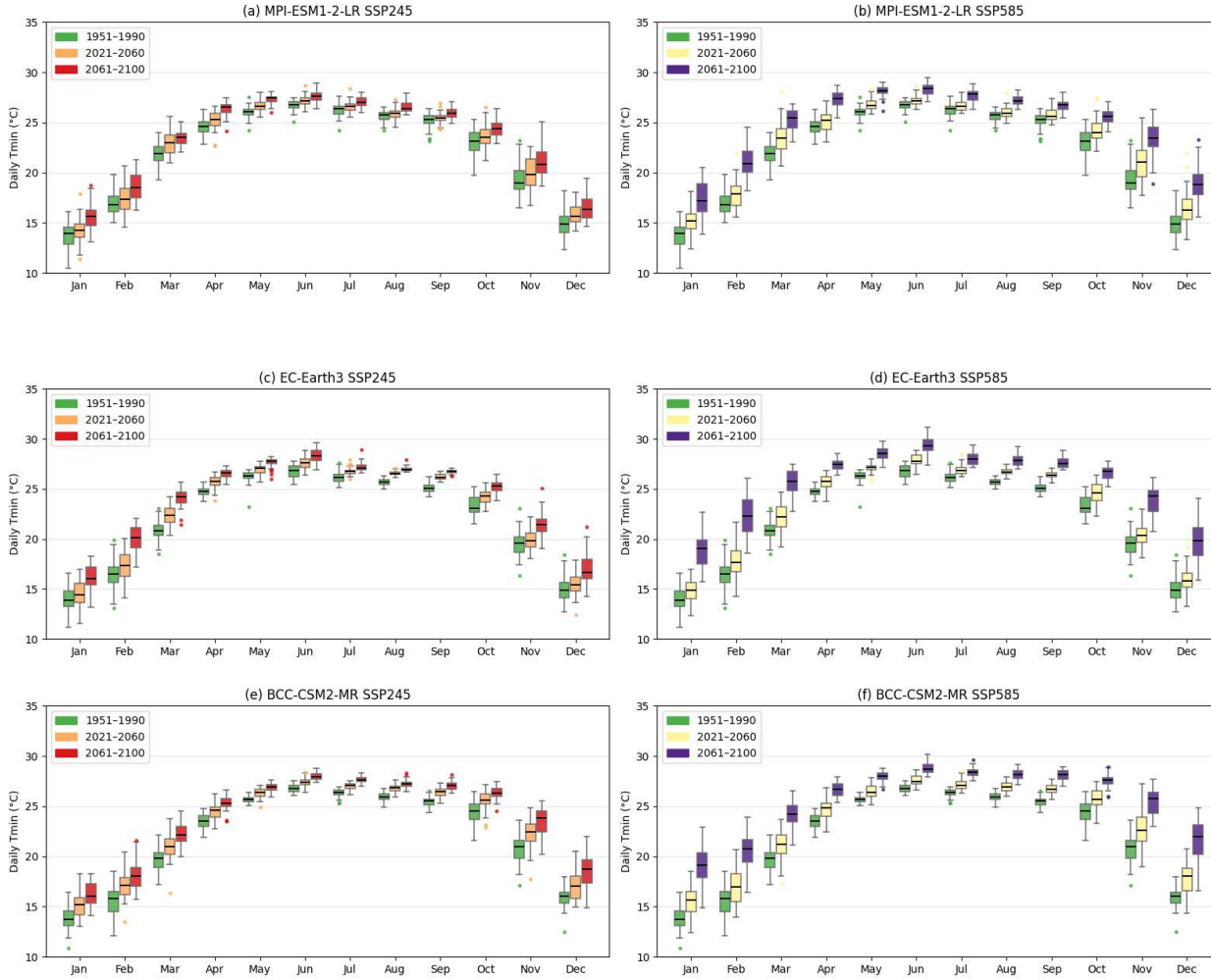


Fig. 4 | Box and whisker plot of daily T_{min} for 1951–1990, 2021–2060 and 2061–2100 from (a) MPI-ESM1-2-LR SSP2-4.5 (b) MPI-ESM1-2-LR SSP5-8.5 (c) EC-Earth3 SSP2-4.5 (d) EC-Earth3 SSP5-8.5 (e) BCC-CSM2-MR SSP2-4.5 (f) BCC-CSM2-MR SSP5-8.5

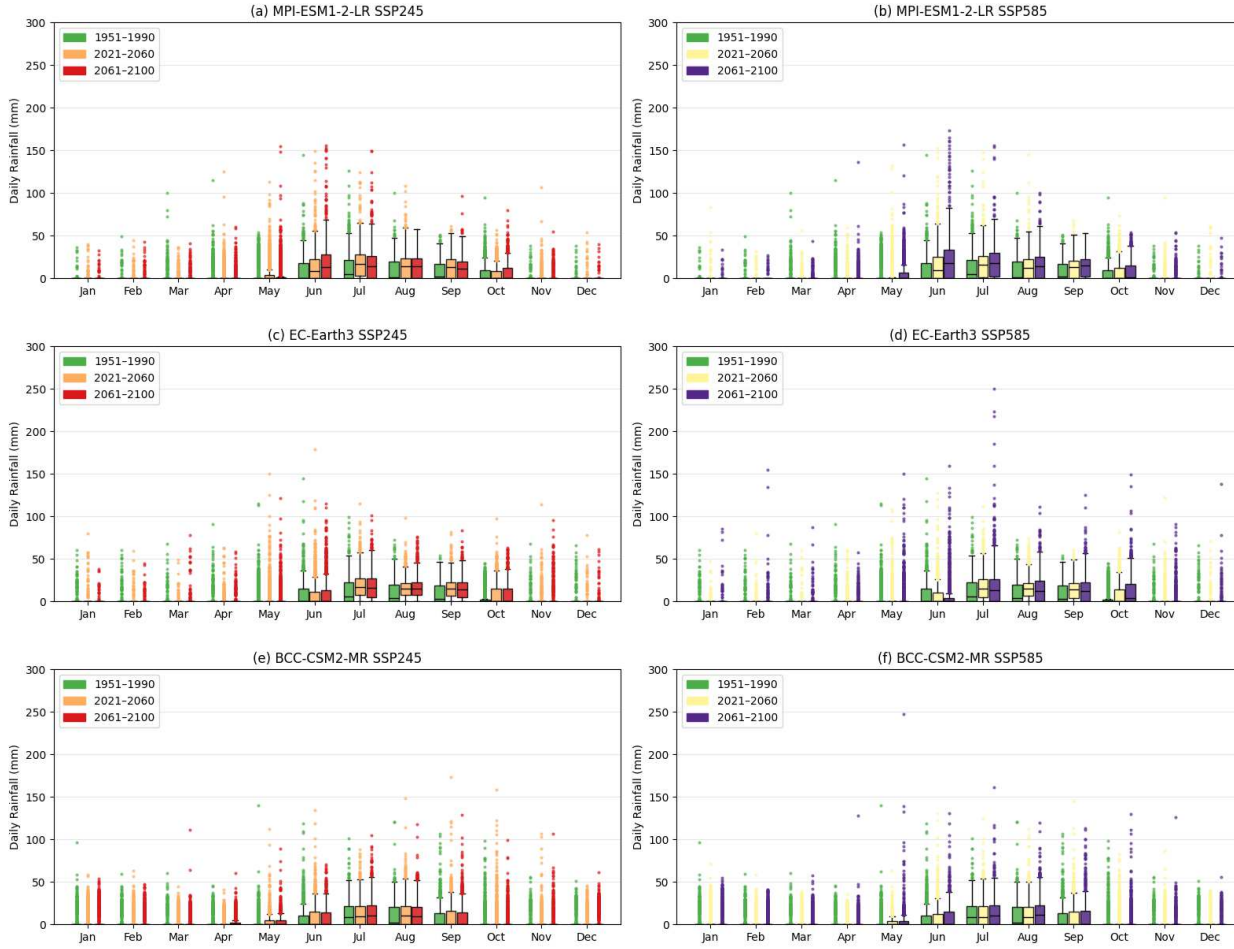


Fig. 5 | Box and whisker plot of daily rainfall for 1951–1990, 2021–2100 and 2061–2100 from (a) MPI-ESM1-2-LR SSP2-4.5 (b) MPI-ESM1-2-LR SSP5-8.5 (c) EC-Earth3 SSP2-4.5 (d) EC-Earth3 SSP5-8.5 (e) BCC-CSM2-MR SSP2-4.5 (f) BCC-CSM2-MR SSP5-8.5

3.3 | Warm Spell and Cold Spell Characteristics in the Future

The future projections of temperature over Khulna indicate an increase in temperature, driving distinct shifts in extreme climate indices under both the SSP2-4.5 and SSP5-8.5 scenarios. In Fig. 6, a clear rightward shift is visible in the Probability Density Function (PDF) curves of the mean maximum temperature (TMAXMEAN) across all three selected models (MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR). This demonstrates that future maximum temperature will exceed the base period (1951–1990). The shift is most pronounced during the late century period (2061–2100), particularly under SSP5-8.5. It reflects intense warming under the high emission scenario.

A similar response is also observed for mean minimum temperature (TMINMEAN) in Fig. 7. In the future, the PDF curves move significantly towards higher values, with a greater displacement under SSP5-8.5 than for SSP2-4.5. This implies a substantial rise in night time temperature over Khulna. In line with anomaly trends, this nighttime warming is more pronounced than daytime increases in certain models, indicating heightened nighttime thermal stress.

With the increase in both maximum and minimum temperature, the warm spell duration index (WSDI) also shows a clear rightward shift in the future in Fig. 8. Notably during the late century under SSP5-8.5, the PDF curves become wider and flatter. This indicates that under future climate scenarios longer and more frequent warm spells or heatwave like events can be expected in Khulna. While this upward trend in WSDI is robust across all models, the magnitude of change varies among them.

Conversely, PDF curves of cold spell duration index (CSDI) flatten, widen and shift rightward in several projections shown in Fig. 9. Concurrently, the probability density lowers relative to the base period. While rising minimum temperature signal overall warming, this widening CSDI distribution suggests increased variability in cold spell durations under future scenarios. The overall results confirm that Khulna is headed toward a significantly warmer climate, characterized by higher temperature thresholds, extended warm spells and altered cold extremes.

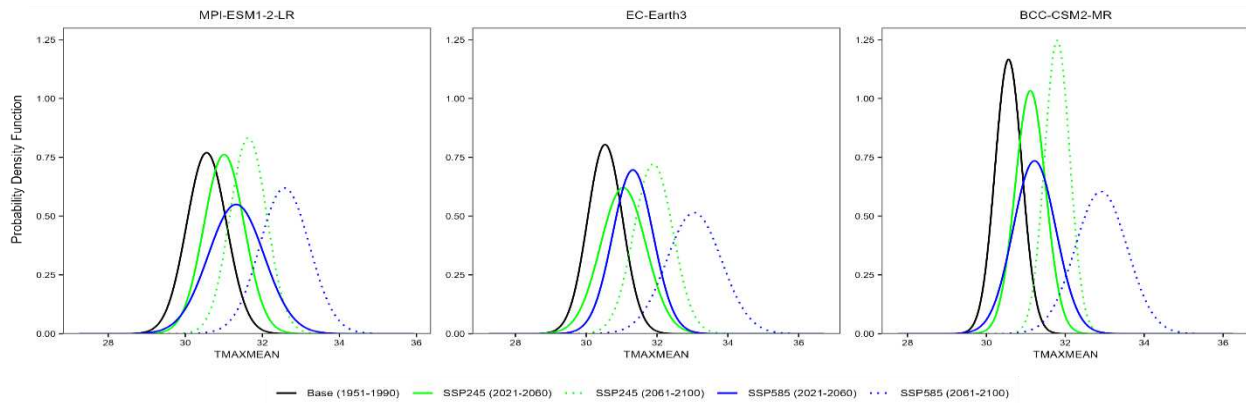


Fig. 6 | PDF plot for TMAXMEAN from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

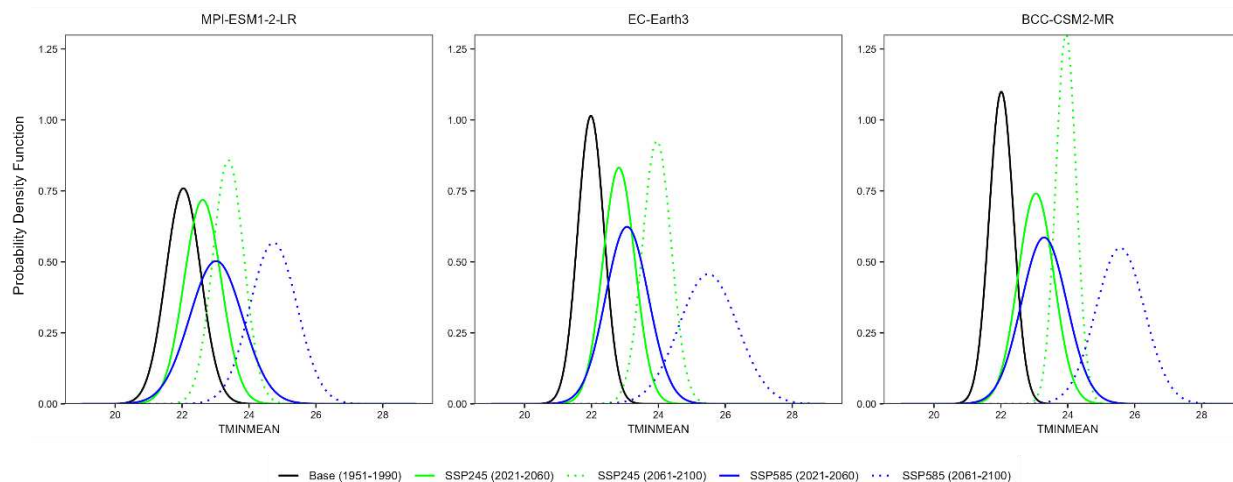


Fig. 7 | PDF plot for TMINMEAN from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

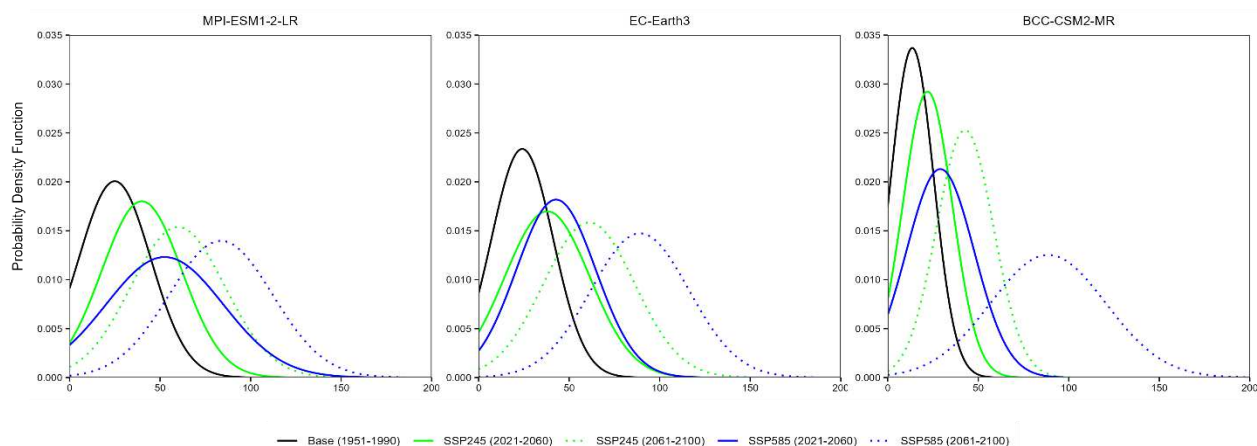


Fig. 8 | PDF plot for WSDI from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

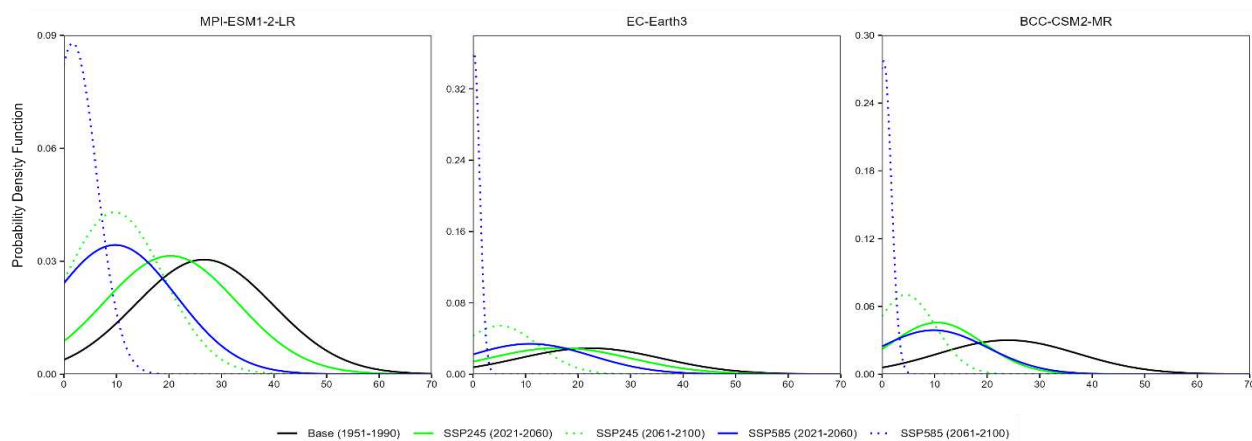


Fig. 9 | PDF plot for CSDI from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

3.4 | Dry and Wet Spell Characteristics in the Future

Long stretches of time without any rainfall are referred to as dry spells. A dry spell is defined by the ETCCDI as a period of consecutive days with daily rainfall of less than 1 mm. A wet spell is defined as a continuous period of days when daily rainfall is equal to or greater than 1 mm.

As shown in Fig. 10, the probability distribution function (PDF) curves of monthly maximum consecutive 5-day precipitation (RX5DAY) reveal noticeable future shifts over Khulna. Under both curves SSP2-4.5 and SSP5-8.5 scenarios, the curves for MPI-ESM1-2-LR and EC-Earth3 displace rightward, particularly during late century, signaling an intensification of short-duration heavy rainfall. This suggests that short-duration heavy rainfall events may become more intense in the future. Conversely, the displacement in BCC-CSM2-MR is subtle but the future curves still exhibit some widening, suggesting possible changes in the intensity of extreme 5-day rainfall.

A clear upward trend is visible for the precipitation of very wet days (R95P) in Fig. 11. Across all three selected models, the future distributions flatten, widen and shift towards higher thresholds relative to the baseline. The transition intensifies under the late century SSP5-8.5, especially in MPI-ESM1-2-LR and EC-Earth3, underscoring a higher probability of severe downpours.

For consecutive dry days (CDD), as shown in Fig. 12, the changes are not consistent across the models. While MPI-ESM1-2-LR and EC-Earth3 exhibit slight rightward shifts and broader distributions. It is hinting at prolonged dry spells. But BCC-CSM2-MR projects a shift towards lower CDD values. Consequently, future changes in dry spell durations remain highly model-dependent.

In contrast, most future PDF curves for consecutive wet days (CWD) shift rightward Fig. 13. The trend is prominent in MPI-ESM1-2-LR and EC-Earth3 and subtle yet discernible in BCC-CSM2-MR. The wider and flatter profile of these future curves suggests an increase in wet spell durations. Collectively, the findings point toward increased intensity of extreme rainfall events and longer wet spells over Khulna whereas dry spell projections remain uncertain and structurally sensitive.

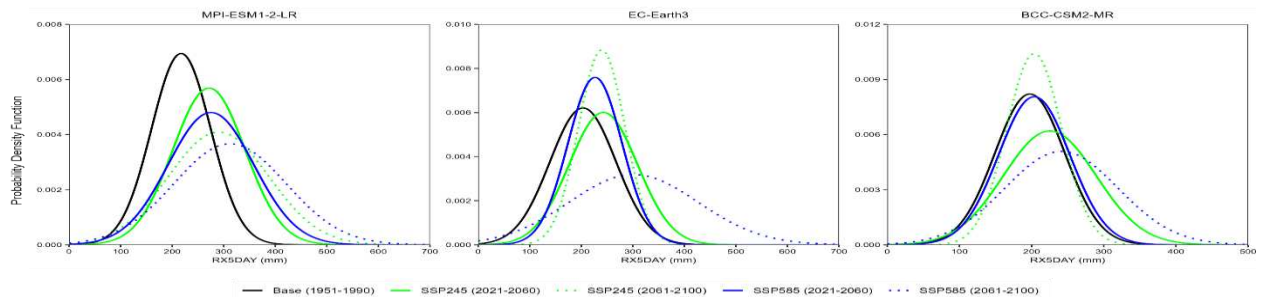


Fig. 10 | PDF plot for RX5 DAY from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

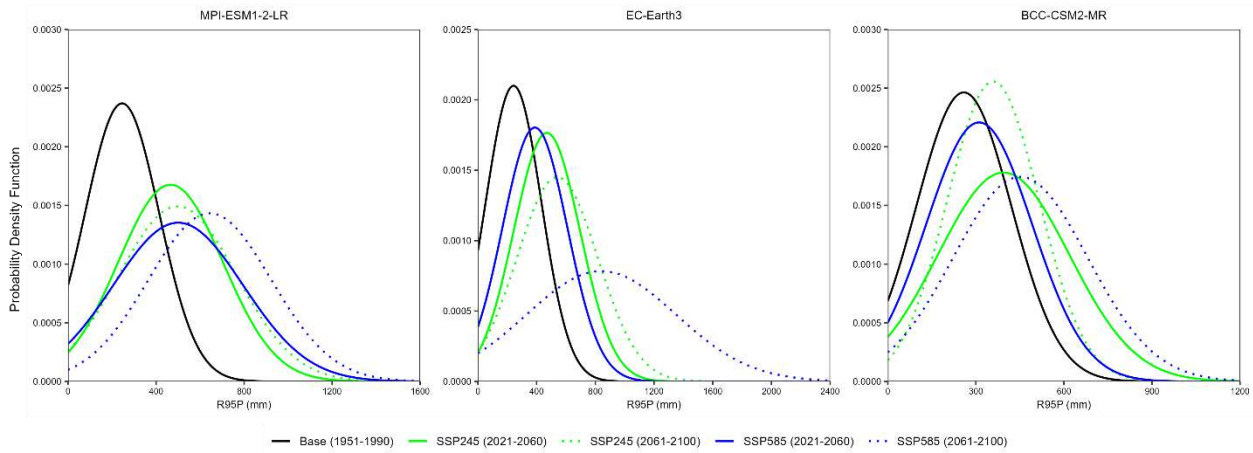


Fig. 11 | PDF plot for R95P from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

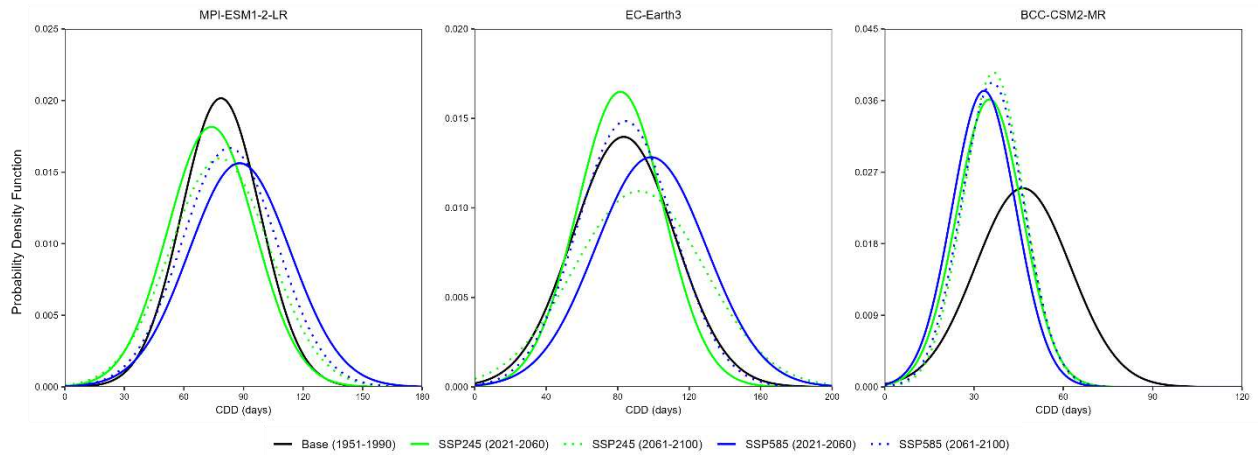


Fig. 12 | PDF plot for CDD from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

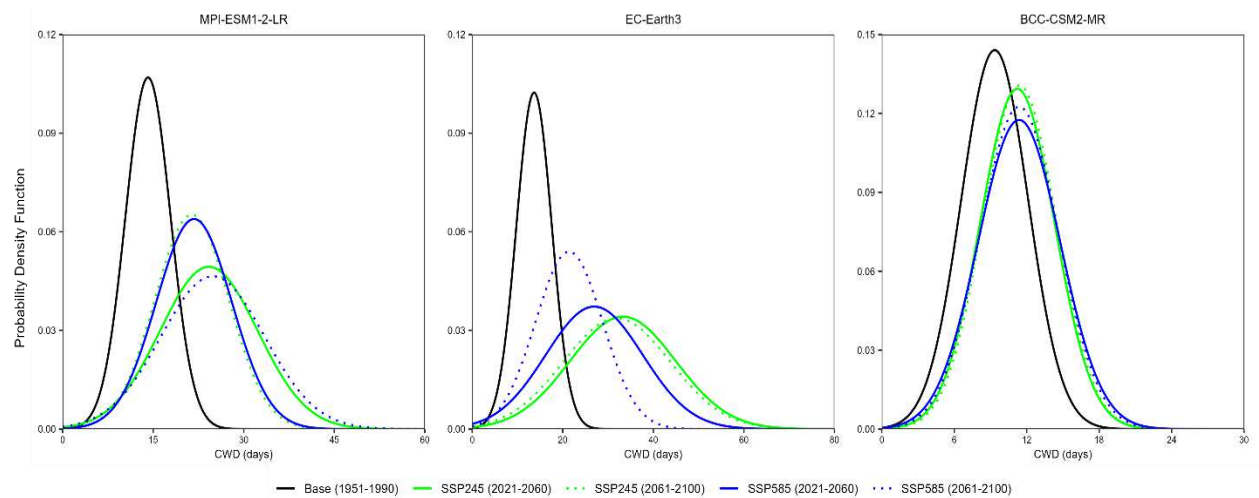


Fig. 13 | PDF plot for CWD from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR

3.5 Trend Analysis of Extreme Climate Indices:

Here, to identify the temporal trends and significant levels for the extreme climatic indices, Mann-Kendall (MK) non-parametric tests were used. The two-sided significance threshold in this study is 5% was employed to categorize the patterns as no significant, significant increasing and significance decreasing. To determine the current slope or rate of change, Sen's method has been used.

The temperature and rainfall indices from MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR for SSP2-4.5 throughout the 2021-2060 period are shown in Table 4 along with the results of Mann-Kendall trend test and Sen's slope at the 5% significance level. Although some indices show significance at the strict threshold of $p < 0.0005$, the trends are most pronounced and persistent under high-emission scenario. MPI-ESM1-2-LR did not exhibit any significant changes, model-specific significant reactions were found in EC-Earth3 for TX90P, TX10P, TN90P, TN10P, WSDI and CSDI and in BCC-CSM2-MR TN90P and TN10P. For EC-Earth3, percentage of warm days (TX90p) and percentage cold days (TX10P) are showing significant increasing and significant decreasing with Sen's slope 0.32% day/year and -0.18% day/year respectively. Between the two GCM EC-Earth3 and BCC-CSM2-MR, the percentage of warm nights (TN90P) is significantly increasing with the Sen's slope ranges from 0.42% to 0.47% day/year. Compare to that, the percentage of cold nights (TN10p) have significant decreasing trend and Sen's slope ranges from -0.13% to -0.24% day/year. While trends of the cold spell duration index (CSDI) are predicted to decline in the future and trends of the warm spell duration index (WSDI) suggest that the number of days with intense heatwaves will rise significantly in EC-Earth3. We have examined the maximum five-day precipitation (RX5DAY), very wet days (R95P), consecutive dry days (CDD) and consecutive wet days (CWD) for the severe rainfall indices. Since rainfall patterns are more difficult to identify the trends from extreme rainfall indices for all the chosen GCMs throughout the 2021-2060 timeframe under the SSP2-4.5 scenario indicate no significant changes for RX5DAY, R95P, CDD and CWD. These findings suggest that while the inter-seasonal variability may be considerable in the future, the overall trends of the extreme rainfall indices may not be very important.

The extreme climate indices trends for SSP2-4.5 for the 2061-2100 period from all of the chosen GCMs are shown in Table 5. In this instance, there is less consistency between indices from various GCMs and at $p < 0.0005$ none of the trends are deemed to be significant. Overall, there are no particularly noteworthy patterns in the rainfall or temperature indices throughout this time.

However, as Table 6 reveals that, several temperature indices show statically significant ($p < 0.0005$) trends under the SSP5-8.5 climate change scenario over the 2021-2060 decade. It suggests a warming tendency. Though, during this time, the extreme rainfall indices do not follow any statically significant trend.

Additionally, Table 7 presents the trends for the extreme climate indices under SSP5-8.5 during the 2061-2100 period ($p < 0.0005$). While rainfall indices do not show any significant changes, several temperature indices do.

Table 4 | Mann–Kendall and the Sen's slope test at 5% significant level from SSP2-4.5 for 2021–2060.

GCM	MPI-ESM1-2-LR			EC-Earth3			BCC-CSM2-MR		
Indices	Z	Sen's slope	p	Z	Sen's slope	p	Z	Sen's slope	p
TX90p	0.769	0.081	4.42E-01	3.602	0.322	3.16E-04	2.648	0.164	8.10E-03
TX10p	-1.504	-0.073	1.32E-01	-3.345	-0.183	4.22E-04	-1.737	-0.068	8.23E-02
TN90p	2.437	0.224	1.48E-02	4.207	0.467	2.59E-05	4.769	0.416	1.86E-06
TN10p	-2.203	-0.110	2.76E-02	-4.360	-0.235	1.30E-05	-3.634	-0.132	2.80E-04
WSDI	1.039	0.155	2.99E-01	3.515	0.500	4.40E-04	2.390	0.143	1.69E-02
CSDI	-0.397	-0.030	6.91E-01	-3.788	-0.282	1.52E-04	-2.994	-0.143	2.75E-03
RX5DAY	0.920	0.854	3.57E-01	-1.095	-0.896	2.73E-01	0.524	0.347	6.00E-01
R95p	1.480	5.338	1.39E-01	-1.270	-4.255	2.04E-01	1.480	3.510	1.39E-01
CDD	1.715	0.547	8.64E-02	-0.537	-0.179	5.92E-01	0.268	0.051	7.88E-01
CWD	1.284	0.167	1.99E-01	0.560	0.071	5.75E-01	-0.047	0.000	9.63E-01

Table 5 | Mann–Kendall and the Sen's slope test at 5% significant level from SSP2-4.5 for 2061–2100

GCM	MPI-ESM1-2-LR			EC-Earth3			BCC-CSM2-MR		
Indices	Z	Sen's slope	p	Z	Sen's slope	p	Z	Sen's slope	p
TX90p	0.944	0.126	3.45E-01	1.958	0.158	5.02E-02	0.338	0.025	7.35E-01
TX10p	-0.968	-0.032	3.33E-01	-0.397	-0.013	6.92E-01	0.537	0.021	5.91E-01
TN90p	1.818	0.212	6.91E-02	2.914	0.230	3.57E-03	0.863	0.052	3.88E-01
TN10p	-0.875	-0.037	3.82E-01	-2.533	-0.070	1.13E-02	0.105	0.000	9.16E-01
WSDI	-0.723	-0.133	4.69E-01	1.926	0.400	5.41E-02	1.745	0.087	8.10E-02
CSDI	-1.089	-0.083	2.76E-01	-2.438	-0.129	1.48E-02	-0.378	0.000	7.06E-01
RX5DAY	-0.082	-0.127	9.35E-01	-0.151	-0.078	8.80E-01	0.105	0.099	9.16E-01
R95p	0.338	1.402	7.35E-01	0.000	-0.100	1.00E+00	0.827	2.126	4.08E-01
CDD	0.117	0.042	9.07E-01	1.037	0.578	3.00E-01	1.122	0.128	2.62E-01
CWD	-0.654	-0.067	5.13E-01	1.365	0.225	1.72E-01	-0.532	0.000	5.95E-01

Table 6 | Mann–Kendall and the Sen's slope test at 5% significant level from SSP5-8.5 for 2021–2060

GCM	MPI-ESM1-2-LR			EC-Earth3			BCC-CSM2-MR		
Indices	Z	Sen's slope	p	Z	Sen's slope	p	Z	Sen's slope	p
TX90p	3.182	0.347	1.46E-03	1.212	0.110	2.26E-01	5.922	0.402	3.19E-09
TX10p	-2.460	-0.141	1.39E-02	-1.657	-0.067	9.76E-02	-2.122	-0.137	3.38E-02
TN90p	3.939	0.526	8.19E-05	5.676	0.741	1.38E-08	6.748	0.838	1.50E-11
TN10p	-3.862	-0.160	1.12E-04	-4.220	-0.189	2.45E-05	-2.196	-0.108	2.81E-02
WSDI	2.684	0.500	7.28E-03	1.481	0.279	1.39E-01	2.600	0.170	9.32E-03
CSDI	-3.491	-0.231	4.81E-04	-2.733	-0.222	6.28E-03	-1.419	-0.091	1.56E-01
RX5DAY	0.711	0.726	4.77E-01	0.396	0.280	6.92E-01	0.466	0.320	6.41E-01
R95p	0.501	0.913	6.16E-01	2.179	7.502	2.94E-02	1.456	3.698	1.45E-01
CDD	-0.455	-0.119	6.49E-01	-1.224	-0.575	2.21E-01	1.669	0.240	9.52E-02
CWD	0.877	0.083	3.81E-01	0.035	0.000	9.72E-01	-0.364	0.000	7.16E-01

Table 7 | Mann–Kendall and the Sen's slope test at 5% significant level from SSP5-8.5 for 2061–2100

GCM	MPI-ESM1-2-LR			EC-Earth3			BCC-CSM2-MR		
Indices	Z	Sen's slope	p	Z	Sen's slope	p	Z	Sen's slope	p
TX90p	4.558	0.471	5.17E-06	5.432	0.520	5.57E-08	5.129	0.558	2.91E-07
TX10p	-3.720	-0.033	1.99E-04	-1.386	-0.010	1.66E-01	-2.954	-0.068	3.14E-03
TN90p	4.604	0.629	4.14E-06	6.421	0.576	1.35E-10	5.457	0.434	4.84E-08
TN10p	-4.081	-0.037	4.49E-05	-3.953	0.000	7.71E-05	-2.818	0.000	4.84E-03
WSDI	1.657	0.440	9.76E-02	3.742	1.177	1.83E-04	2.185	0.192	2.89E-02
CSDI	-4.049	-0.100	5.14E-05	-3.958	0.000	7.57E-05	-2.974	0.000	2.94E-03
RX5DAY	0.408	0.548	6.83E-01	2.505	3.092	1.22E-02	0.478	0.492	6.33E-01
R95p	2.155	8.861	3.11E-02	2.668	18.807	7.63E-03	0.361	1.032	7.18E-01
CDD	-0.175	-0.063	8.61E-01	-0.256	-0.197	7.98E-01	-0.047	0.000	9.63E-01
CWD	1.788	0.167	7.38E-02	-1.378	-0.154	1.68E-01	-1.025	-0.031	3.05E-01

3.6 Joint Analysis of Future Seasonal Variations in Temperature and Rainfall

Researchers have acknowledged that climate variables act both jointly and concurrently rather than independently, in shaping of local climate. They may be misinterpreted and their true impact on the local climate may be underestimated if they are treated as distinct variables and calculated separately (Pandey et al. 2019). So, it is essential to comprehend their combined effect, for better understanding of regional climate change (Zhang et al. 2019).

In this study the projected anomalies in temperature and rainfall were jointly analyzed, as illustrated in Fig. 14. It is clear from the MPI-ESM1-2-LR model that temperature anomalies stay positive throughout the

year and showing continuous warming in every month for both the 2021-2060 and 2061-2100 periods under SSP2-4.5 and SSP5-8.5 scenarios. For March and April are predicted to have increased temperatures with an increase of rainfall under both scenarios. When there is a strong demand of water, the combined impact of rising temperatures and falling rainfall may be detrimental. However, June, July, August and September are likely to experience heavier rainfall along with moderate temperature increases. In Khulna, generally the heaviest rainfall occurs between June and August. Therefore, any additional increase in rainfall during this period may intensify the water logging and flood conditions in the study area. Fig. 15 and Fig. 16 present comparable analyses using EC-Earth3 and BCC-CSM2-MR, respectively. Using EC-Earth3 data sets for SSP2-4.5 and SSP5-8.5 across the 2021-2060 and 2061-2100 periods, a similar kind of results were found in Fig. 15. According to analysis, July to September is predicted to be wetter in the future, whereas March and April from EC-Earth3 are predicted to be warmer and drier. For the BCC-CSM2-MR, rainfall anomaly pattern for March, April and June to September is not consistent as seen in Fig. 16. Under both SSP2-4.5 and SSP5-8.5 it displays positive temperature anomalies all year long. However, rainfall anomalies differ significantly from month to month with increases in parts of the monsoon (June to September) and post-monsoon (March to May) seasons and decreases in some mid-year months. This suggests that future warming combined with uneven rainfall distribution may result in hotter and drier conditions in Khulna at specific times of the year.

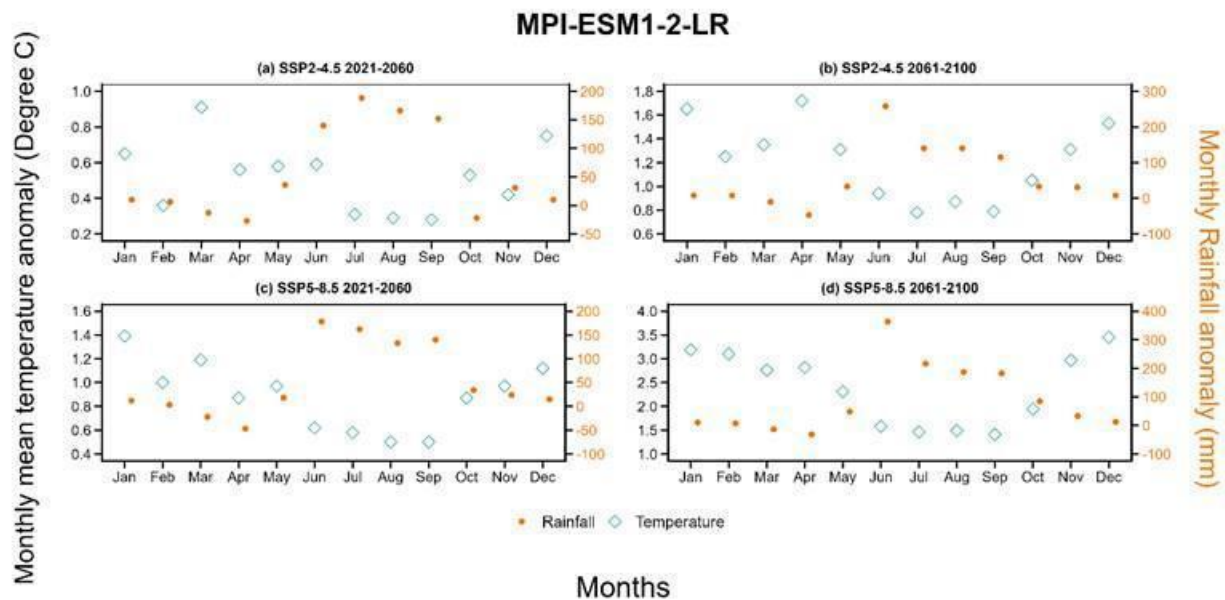


Fig. 14 | Combined temperature and rainfall anomaly for future periods from MPI-ESM1-2-LR

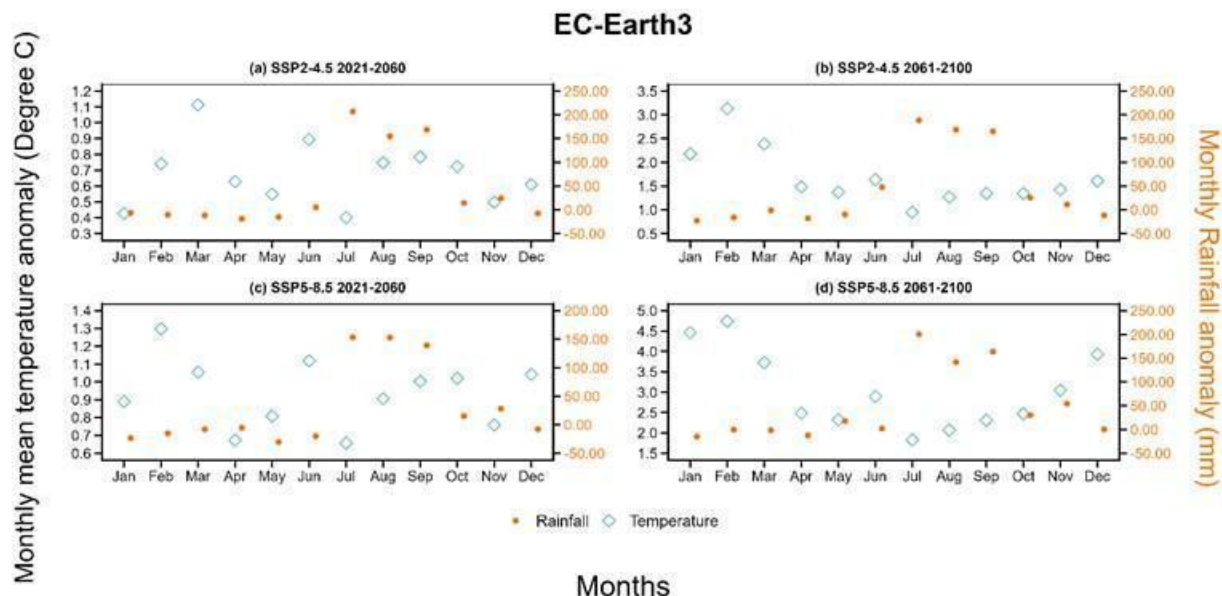


Fig. 15 | Combined temperature and rainfall anomaly for future periods from EC-Earth3

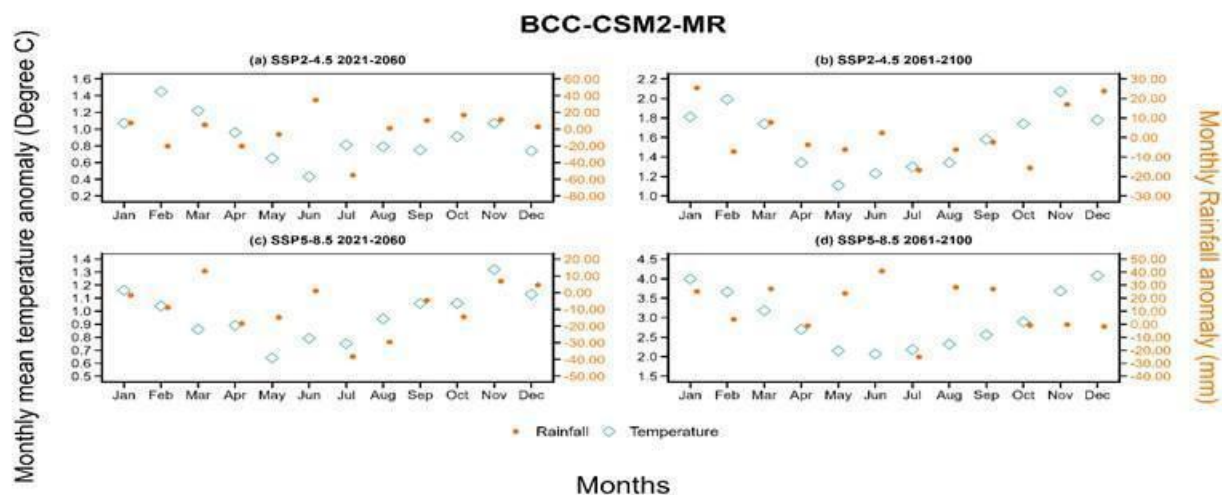


Fig. 16 | Combined temperature and rainfall anomaly for future periods from BCC-CSM2-MR

3.7 | Copula Analysis

Here, we have determined the temporal variabilities of likely wet-cold and dry-hot situations by the combined analysis of rainfall and temperature anomalies. In our study, the ensemble means monthly anomalies under the SSP2-4.5 and SSP5-8.5 scenarios for the periods 2021–2060 and 2061–2100 were used in a copula-based analysis to examine the dependence structure between variable 1 (mean monthly temperature anomaly) and variable 2 (mean monthly rainfall anomaly). At first, Pearson's correlation,

Spearman's rank order and Kendall's tau were used to evaluate the dependence between variables 1 and 2 and all scenario-period combinations revealed a significant negative link. For example, the comparable values under SSP2-4.5 during 2021–2060 were -0.2737 , -0.2953 and -0.1953 respectively, significant at 5% and the negative dependence increased under both SSP2-4.5 and SSP5-8.5 in 2061–2100.

The marginal distributions of the two variables were evaluated for each scenario and time slice before the joint distribution was estimated. Under SSP2-4.5 for 2021–2060, it was found that the Generalized Pareto Distribution (GPD) best represented variable 2, whereas the Normal distribution best suited variable 1. Variable 1 for SSP2-4.5 between 2061 and 2100 followed the GPD, while variable 2 followed the skew-normal distribution. The Generalized Extreme Value (GEV) distribution was used to fit variable 2 under SSP5-8.5 for 2021–2060, while the GPD was used to fit variable 1. In contrast, the Skew-normal distribution best represented variable 1 for SSP5-8.5 between 2061 and 2100, whereas the GPD suited variable 2 (Figs. 17-20). The parameters for both marginal and joint distributions were estimated using the maximum likelihood method and the goodness-of-fit was evaluated using the Chi-square test at a 5% significance level.

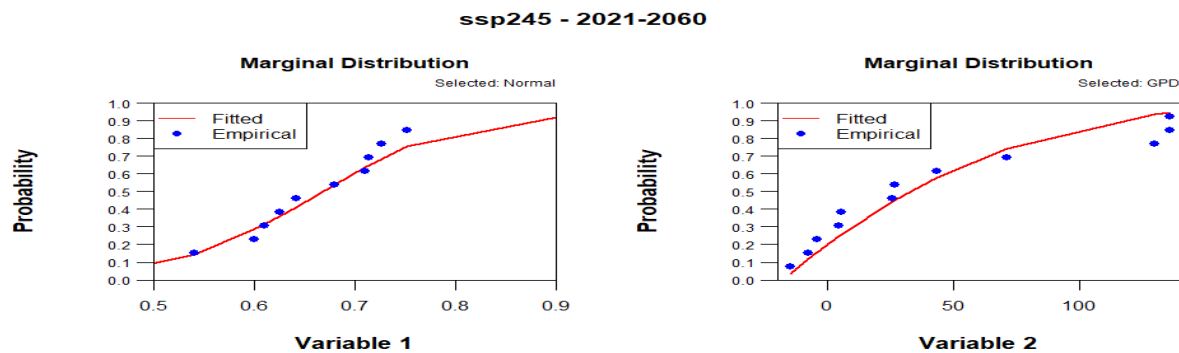


Fig. 17 | Marginal distributions of (a) variable 1 (mean monthly temperature anomaly), Normal distribution and (b) variable 2 (mean monthly rainfall anomaly), Generalized Pareto Distribution (GPD)

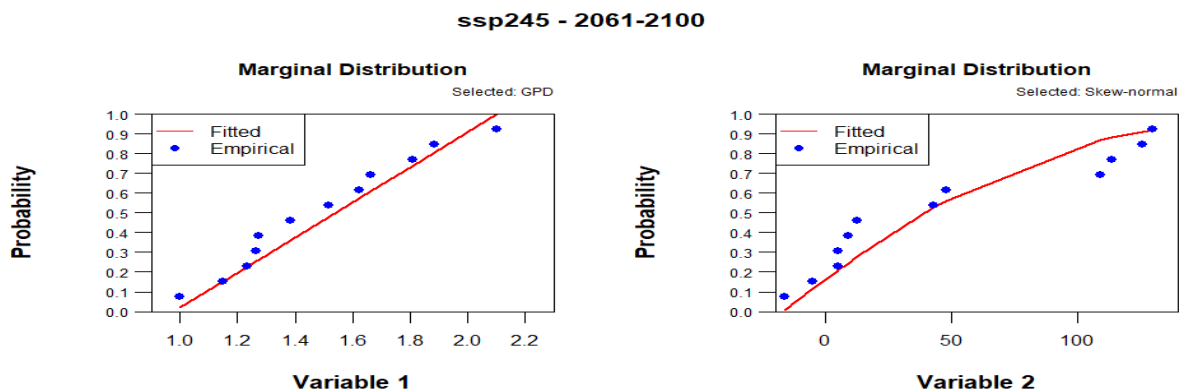


Fig. 18 | Marginal distributions of (a) variable 1 (mean monthly temperature anomaly), Generalized Pareto Distribution (GPD) and (b) variable 2 (mean monthly rainfall anomaly), Skew-normal distribution

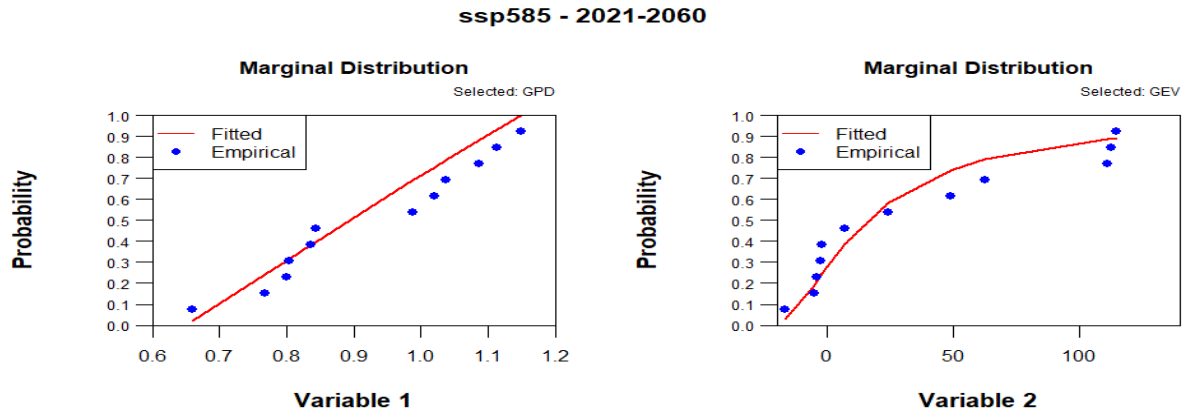


Fig. 19 | Marginal distributions of (a) variable 1 (mean monthly temperature anomaly), Generalized Pareto Distribution (GPD) and (b) variable 2 (mean monthly rainfall anomaly), Generalized Extreme Value (GEV) distribution

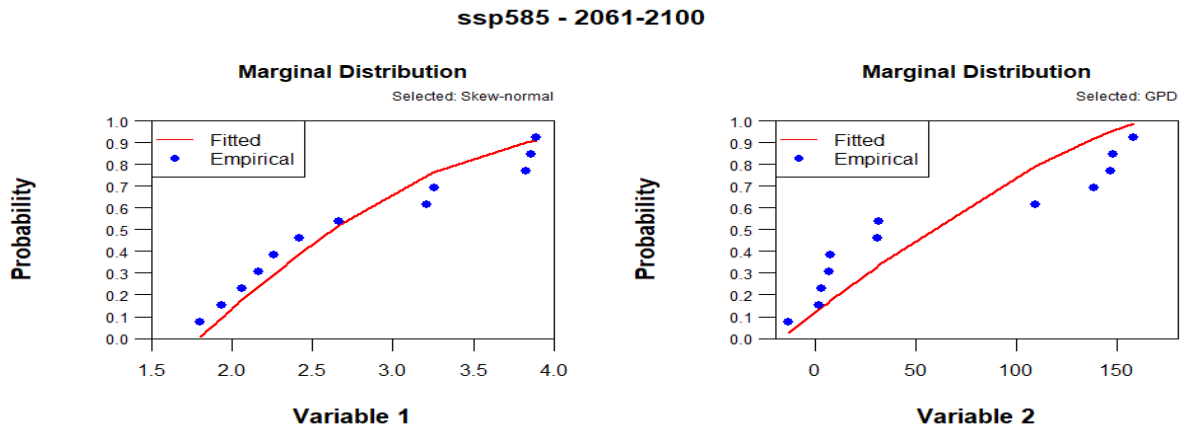


Fig. 20 | Marginal distributions of (a) variable 1 (mean monthly temperature anomaly), Skew-normal distribution and (b) variable 2 (mean monthly rainfall anomaly), Generalized Pareto Distribution (GPD)

The joint probability structure of temperature and rainfall anomalies was assessed using 20 copula families after the marginal distributions were fitted. The likelihood value, Akaike information criterion (AIC), Bayesian information criterion (BIC), root mean square error (RMSE) and Nash-Sutcliffe efficiency (NSE) were taken into consideration in order to rank the 20 copula families (Table 8). Notably, the best-fit copula family was found to be scenario-dependent. The findings show that, overall, the Cubic copula ranked first and was the chosen dependent structure for SSP2-4.5 during 2021–2060 (RMSE = 0.063668, NSE = 0.695454). The Marshall-Olkin copula ranked highest for SSP2-4.5 during 2061-2100, while the AMH (Ali-Mikhail-Haq) copula consistently ranked first under SSP5-8.5 for both periods.

Table 8 | The overall ranking of the 20-copula family parametric models for SSP2-4.5 under 2021-2060

Overall Rank	Copula Family	Rank logLik	Rank AIC	Rank BIC	Rank RMSE	Rank NSE	Total Score
1	Cubic	9	10	10	1	1	31
2	Frank	1	1	1	18	18	39
2	Gaussian	3	3	3	15	15	39
4	Plackett	2	2	2	17	17	40
5	Independence	13	7	7	7	7	41
6	FGM	6	5	5	13	13	42
7	AMH	7	6	6	12	12	43
8	t-Student	4	4	4	16	16	44
9	Clayton	8	9	8	11	11	47
10	Fischer-Kock	5	8	9	14	14	50
10	Raftery	16	14	14	3	3	50
10	Shih-Louis	14	12	12	6	6	50
13	Nelsen	15	13	13	5	5	51
14	Linear-Spearman	10	11	11	10	10	52
15	Gumbel	18	16	16	2	2	54
16	Cuadras-Auge	17	15	15	4	4	55
17	Fischer-Hinzmann	12	18	18	8	7	63
17	Marshall-Olkin	11	17	17	9	9	63
19	Joe	19	19	19	19	19	95
20	Galambos	20	20	20	20	20	100

The joint probability contours indicate a broadly negative dependence between mean monthly temperature anomaly (Variable 1) and mean monthly rainfall anomaly (Variable 2) under both SSP2-4.5 and SSP5-8.5. Fig. 21 depicts low to slightly negative rainfall anomalies are associated with relatively higher temperature anomalies for SSP2-4.5 during 2021-2060. It suggests warm-dry condition, whereas higher rainfall anomalies correspond to comparatively lower temperature anomalies indicates wet-cool conditions. A similar inverse pattern persists during 2061-2100, although the range of temperature anomaly shifts upward, implying a stronger warming signal in the later period (Fig. 22). Fig. 23 illustrates the same negative dependence is evident for 2021-2060 under SSP5-8.5 and becomes more pronounced during 2061-2100 (Fig. 24), when very high temperature anomalies are mostly linked to low or near-zero rainfall anomalies.

Overall, the copula analysis shows that under both SSP2-4.5 and SSP5-8.5 scenarios, the future relationship between mean monthly temperature anomaly and mean monthly rainfall anomaly is marked by a continuous negative dependence. The findings suggest that whereas wetter months often have comparatively smaller temperature anomalies, warmer months are more likely to be linked to rainfall shortages. This pattern emphasizes the growing probability of warm-dry conditions in the future, especially under the higher-

emission SSP5-8.5 scenario and in the far future, which could exacerbate water scarcity, drought stress and climate-related risks.

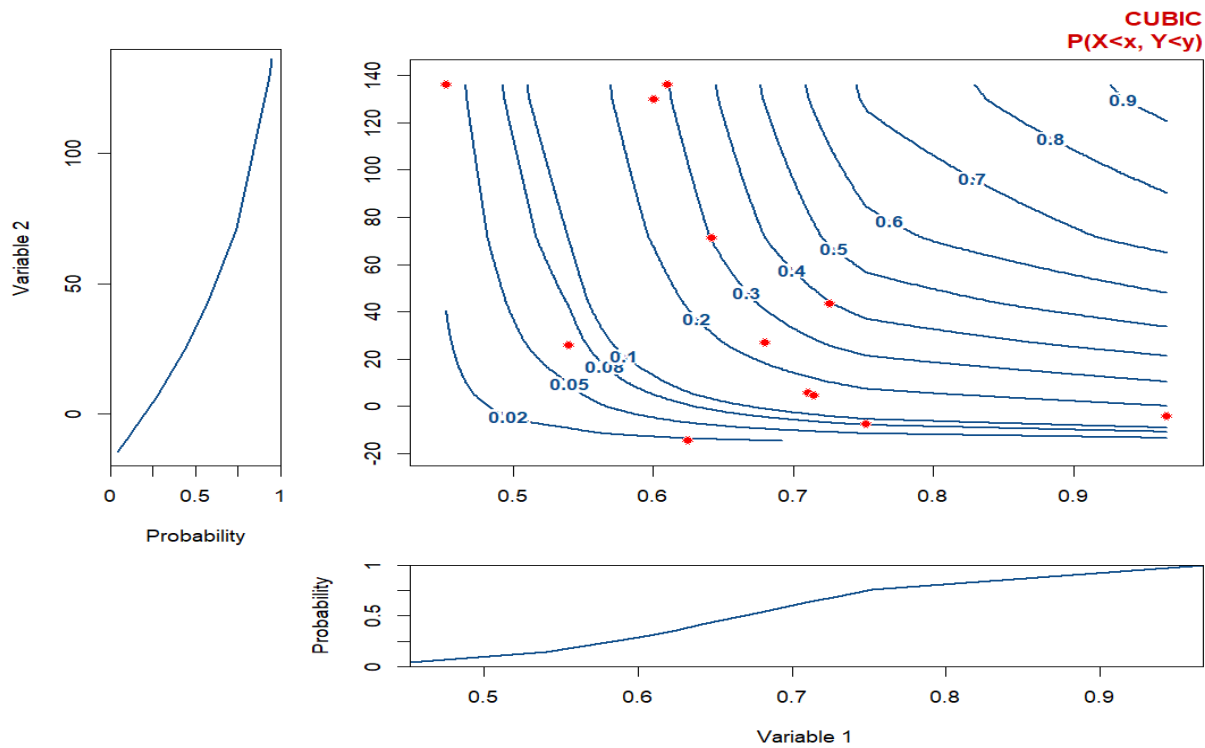


Fig. 21 | Copula joint probability of temperature and rainfall anomaly from SSP2-4.5 2021- 2060

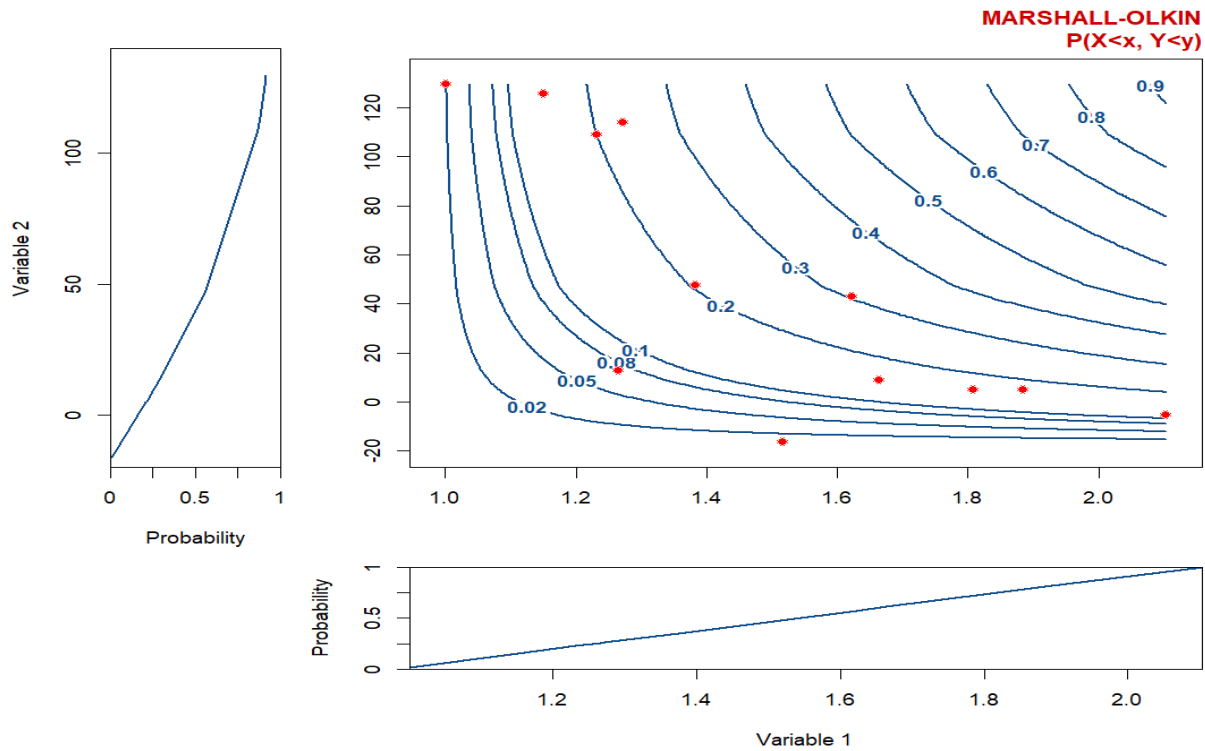


Fig. 22 | Copula joint probability of temperature and rainfall anomaly from SSP2-4.5 2061- 2100

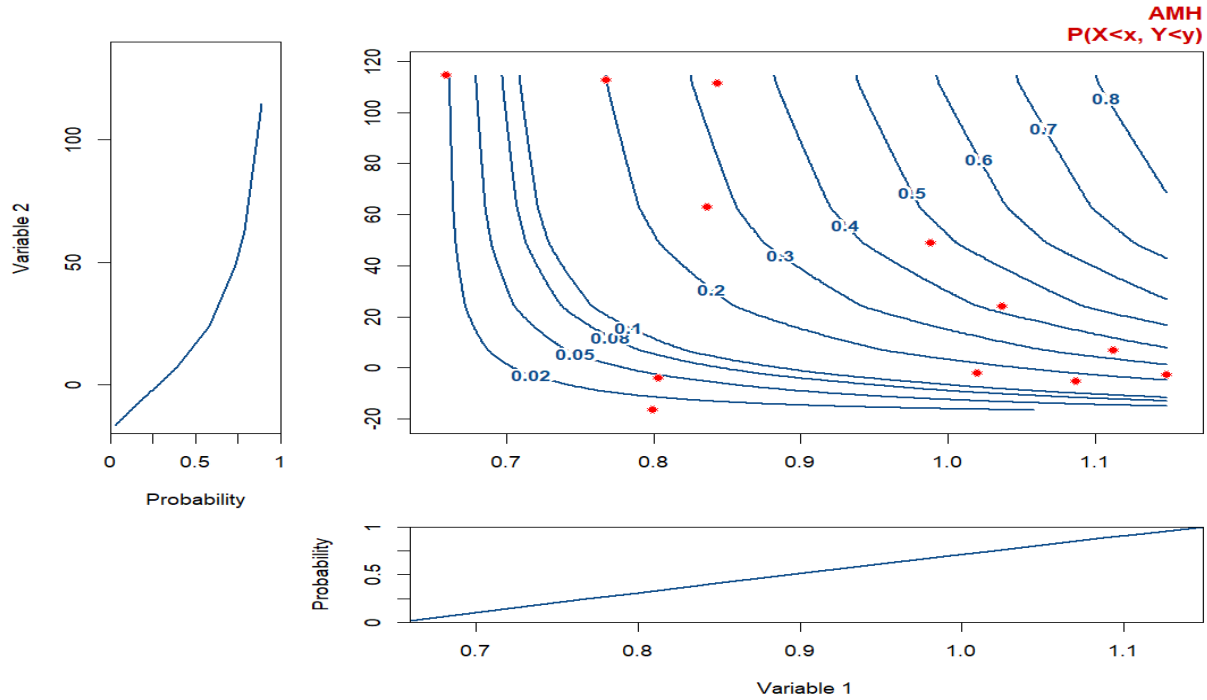


Fig. 23 | Copula joint probability of temperature and rainfall anomaly from SSP5-8.5 2021-2060

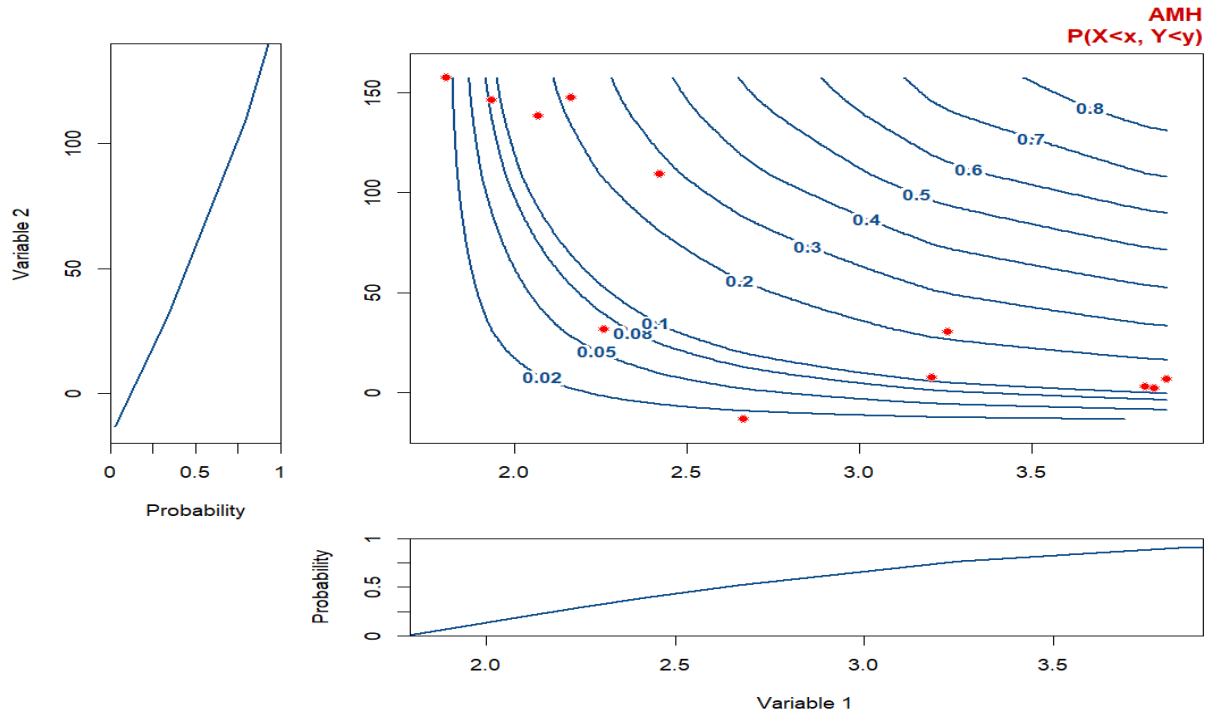


Fig. 24 | Copula joint probability of temperature and rainfall anomaly from SSP5-8.5 2061-2100

Conclusion:

From this study it is clear that the hydroclimatic problems of the Khulna region are going to be more severe in the future due to climate change. Khulna is a low-lying coastal district in the south-west of Bangladesh, already facing several climate-induced stresses including salinity intrusion, freshwater scarcity, tidal

flooding, drainage congestion, waterlogging and reliance on climate-sensitive livelihoods. Hence, a sound scientific basis for future projections is essential extremes to support robust adaptation and water resources management strategies.

We evaluated future changes in temperature, rainfall, hydroclimatic extreme indices, seasonal variability and compound risks via copula based joint probability, using three CMIP6 models (MPI-ESM1-2-LR, EC-Earth3 and BCC-CSM2-MR) under SSP2-4.5 and SSP5-8.5 scenarios. The finding indicates a persistent warming trend with both maximum and minimum temperatures rising and nighttime warming being particularly significant. Heat related extremes (warm days, warm nights, warm spells) will increase, while cold extremes will decline. Rainfall projections are more complex: although annual and monsoon rainfall to rise their distribution will become increasingly uneven. Monsoon months (June to September) are likely to experience more intense wet spells. It will worsen waterlogging and drainage problems while the dry and pre-monsoon seasons will see longer consecutive dry days. It will intensify water scarcity and salinity stress. This results in two opposing but related stressors.

The seasonal integration confirms this asymmetry: pre-monsoon warming with rainfall deficits will drive evaporation and salinity pressure while monsoon excess rainfall will elevate flood risks. The copula-based analysis reveals a robust negative dependence between temperature and rainfall anomalies which means above average temperatures strongly increase the likelihood of below average rainfall (warm-dry events). This tendency is especially pronounced under SSP5-8.5 and in the late-century period. The joint probability analysis produced compelling evidence that the temperature anomaly and rainfall are likely to occur together in the future, increasing the dangers and difficulties, surpassing those presented by specific incidents alone and (Hao et al. 2018) have made similar observation.

Overall, this study shows that the climate of Khulna is likely to be warmer, more variable and more extreme in the future. Water management must be integrated rather than single-hazard due to this "two-ended" climate stress, which alternates between droughts and floods. The results emphasize the critical need for better freshwater storage and drainage, salinity management, heat-risk readiness, and climate-smart farming. This study offers useful scientific information to help policymakers create sustainable adaptation and catastrophe risk reduction plans for the Khulna region by examining the combined effects of temperature and rainfall.

681 **References**

- 682 Bador M, Boé J, Terray L, Alexander LV, Baker A, Bellucci A, Haarsma R, Koenigk T, Moine MP,
683 Lohmann K, Putrasahan DA (2020) Impact of higher spatial atmospheric resolution on precipitation
684 extremes over land in global climate models. *J Geophys Res Atmos* 125(13):e2019JD032184.
685 <https://doi.org/10.1029/2019JD032184>
- 686 Brunner MI, Slater L, Tallaksen LM, Clark M (2021) Challenges in modeling and predicting floods and
687 droughts: A review. *WIREs Water* 8(3):e1520. <https://doi.org/10.1002/wat2.1520>
- 688 Dasgupta S, Hossain MM, Huq M, Wheeler D (2015) Climate change and soil salinity: The case of coastal
689 Bangladesh. *Ambio* 44(8):815–826. <https://doi.org/10.1007/s13280-015-0681-5>
- 690 Dewan C (2021) Misreading the Bengal delta: Climate change, development, and livelihoods in coastal
691 Bangladesh. University of Washington Press
- 692 Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE (2016) Overview of the
693 Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci*
694 *Model Dev* 9(5):1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- 695 Ghulami M, Gourbesville P, Audra P, Shie-Yui L (2022) Performance evaluation of CORDEX South Asia
696 models for projections of precipitation over the Kabul basin, Afghanistan. *LHB* 108(1):2095936.
697 <https://doi.org/10.1080/27678490.2022.2095936>
- 698 Giorgi F, Gutowski WJ Jr (2015) Regional dynamical downscaling and the CORDEX initiative. *Annu Rev*
699 *Environ Resour* 40:467–490. <https://doi.org/10.1146/annurev-environ-102014-021217>
- 700 Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level: the
701 CORDEX framework. *WMO Bull* 58(3):175
- 702 Hao Z, Hao F, Singh VP, Zhang X (2018a) Changes in the severity of compound drought and hot extremes
703 over global land areas. *Environ Res Lett* 13(12):124022. <https://doi.org/10.1088/1748-9326/aace85>
- 704 Hao Z, Singh VP, Hao F (2018b) Compound extremes in hydroclimatology: a review. *Water* 10(6):718.
705 <https://doi.org/10.3390/w10060718>
- 706 Huq H (2013) Hydro-meteorological trends in southwest coastal Bangladesh: perspectives of climate
707 change and human interventions. *Am J Clim Chang* 2(1):47–60
- 708 Ilori OW, Ajayi VO (2020) Change detection and trend analysis of future temperature and rainfall over
709 West Africa. *Earth Syst Environ* 4(3):493–512. <https://doi.org/10.1007/s41748-020-00174-8>
- 710 Kamruzzaman M, Shahid S, Islam AT, Hwang S, Cho J, Zaman MAU, Ahmed M, Rahman MM, Hossain
711 MB (2021) Comparison of CMIP6 and CMIP5 model performance in simulating historical precipitation
712 and temperature in Bangladesh: a preliminary study. *Theor Appl Climatol* 145(3):1385–1406.
713 <https://doi.org/10.1007/s00704-021-03691-0>

714 Kamruzzaman M, Wahid S, Shahid S, Alam E, Mainuddin M, Islam HT, Thorp KR (2023) Predicted
715 changes in future precipitation and air temperature across Bangladesh using CMIP6 GCMs. *Heliyon*
716 9(5):e16012. <https://doi.org/10.1016/j.heliyon.2023.e16012>

717 Kendall MG (1975) Rank correlation methods. Charles Griffin & Co. Ltd., London

718 Kopp RE, DeConto RM, Bader DA, Hay CC, Horton RM, Kulp S, Oppenheimer M, Pollard D, Strauss BH
719 (2017) Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level
720 projections. *Earth's Future* 5(12):1217–1233. <https://doi.org/10.1002/2017EF000663>

721 Lee H, Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne P, Trisos C, Romero J, Aldunce P, Barret
722 K, Blanco G (2023) IPCC, 2023: Climate change 2023: Synthesis report, summary for policymakers.
723 Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel
724 on climate change. IPCC, Geneva, Switzerland, pp 1–34. <https://doi.org/10.59327/IPCC/AR6-9789291691647>

726 Legg S (2021) IPCC, 2021: Climate change 2021-the physical science basis. *Interaction* 49(4):44–45.
727 <https://doi.org/10.1071/INTv49n4p44>

728 Mann HB (1945) Nonparametric tests against trend. *Econometrica* 13(3):245–259.
729 <https://doi.org/10.2307/1907187>

730 Mazhar MMI, Abid AA, Jyoti LTZ, Siddikui A, Sultana N (2024) Assessing the dynamics of climate
731 change in Khulna city: A comprehensive analysis of Temperature, Rainfall, and humidity trends. *Int J Sci*
732 *Eng* 1(1):10–62304

733 Mishra V, Bhatia U, Tiwari AD (2020) Bias-corrected climate projections for South Asia from coupled
734 model intercomparison project-6. *Sci Data* 7(1):338. <https://doi.org/10.1038/s41597-020-00681-1>

735 Morshed MM, Al Mujtabe A, Tahmid T (2026) Spatio-temporal growth and urban polycentricity of
736 secondary cities: The case of Khulna, Bangladesh. *J Urban Manag.*
737 <https://doi.org/10.1016/j.jum.2024.10.001>

738 Murshed S, Griffin AL, Islam MA, Wang XH, Paull D (2022) Assessing multi-climate-hazard threat in the
739 coastal region of Bangladesh by combining influential environmental and anthropogenic factors. *Prog*
740 *Disast Sci* 16:100261. <https://doi.org/10.1016/j.pdisas.2022.100261>

741 Nengzouzam G, Hodam S, Bandyopadhyay A, Bhadra A (2020) Spatial and temporal trends in high
742 resolution gridded rainfall data over India. *J Earth Syst Sci* 129(1):232. <https://doi.org/10.1007/s12040-020-01496-5>

744 Nicholls RJ, Lincke D, Hinkel J, Brown S, Vafeidis AT, Meyssignac B, Hanson SE, Merkens JL, Fang J
745 (2021) A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nat Clim*
746 *Chang* 11(4):338–342. <https://doi.org/10.1038/s41558-021-00993-8>

747 O'Neill BC, Tebaldi C, Van Vuuren DP, Eyring V, Friedlingstein P, Hurtt G, Knutti R, Kriegler E,
748 Lamarque JF, Lowe J, Meehl GA (2016) The scenario model intercomparison project (ScenarioMIP) for
749 CMIP6. *Geosci Model Dev* 9(9):3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>

750 O'Neill SM, Carey AJ, Harding LB, West JE, Ylitalo GM, Chamberlin JW (2020) Chemical tracers guide
751 identification of the location and source of persistent organic pollutants in juvenile Chinook salmon
752 (*Oncorhynchus tshawytscha*), migrating seaward through an estuary with multiple contaminant inputs. *Sci*
753 *Total Environ* 712:135516. <https://doi.org/10.1016/j.scitotenv.2019.135516>

754 Pandey BK, Khare D, Kawasaki A, Mishra PK (2019) Climate change impact assessment on blue and green
755 water by coupling of representative CMIP5 climate models with physical based hydrological model. *Water*
756 *Resour Manag* 33(1):141–158. <https://doi.org/10.1007/s11269-018-2131-1>

757 Rahman S, Rahman MA (2015) Climate extremes and challenges to infrastructure development in coastal
758 cities in Bangladesh. *Weather Clim Extrem* 7:96–108. <https://doi.org/10.1016/j.wace.2014.07.005>

759 Rana MM, Adhikary SK (2023) Climate change projection over southwest coastal region of Bangladesh
760 using statistical downscaling model. In: 6th International Conference on Civil Engineering for Sustainable
761 Development (ICCSD 2022), AIP Publishing LLC, p 050016. <https://doi.org/10.1063/5.0130630>

762 Raymond C, Horton RM, Zscheischler J, Martius O, AghaKouchak A, Balch J, Bowen SG, Camargo SJ,
763 Hess J, Kornhuber K, Oppenheimer M (2020) Understanding and managing connected extreme events. *Nat*
764 *Clim Chang* 10(7):611–621. <https://doi.org/10.1038/s41558-020-0790-4>

765 Şen Z, Şişman E (2024) Risk attachment Sen's Slope calculation in hydrometeorological trend analysis.
766 *Nat Hazards* 120(4):3239–3252. <https://doi.org/10.1007/s11069-023-06323-9>

767 Shahid M, Dumat C, Khalid S, Niazi NK, Antunes PM (2016) Cadmium bioavailability, uptake, toxicity
768 and detoxification in soil-plant system. *Rev Environ Contam Toxicol* 241:73–137.
769 https://doi.org/10.1007/398_2016_8

770 Shahid S (2010) Rainfall variability and the trends of wet and dry periods in Bangladesh. *Int J Climatol*
771 30(15):2299–2313. <https://doi.org/10.1002/joc.2059>

772 Tabari H (2020) Climate change impact on flood and extreme precipitation increases with water
773 availability. *Sci Rep* 10(1):13768. <https://doi.org/10.1038/s41598-020-70816-2>

774 Tabari H, Willems P (2023) Sustainable development substantially reduces the risk of future drought
775 impacts. *Commun Earth Environ* 4(1):180. <https://doi.org/10.1038/s43247-023-00841-2>

776 Taylor KE (2001) Summarizing multiple aspects of model performance in a single diagram. *J Geophys Res*
777 *Atmos* 106(D7):7183–7192. <https://doi.org/10.1029/2000JD900719>

778 Tebaldi C, Debeire K, Eyring V, Fischer E, Fyfe J, Friedlingstein P, Ziehn T (2021) Climate model
779 projections from the scenario model intercomparison project (ScenarioMIP) of CMIP6. *Earth Syst Dynam*
780 12(1):253–293. <https://doi.org/10.5194/esd-12-253-2021>

781 Tootoonchi F, Haerter JO, Rätty O, Grabs T, Sadegh M, Teutschbein C (2020) Copulas for hydroclimatic
782 applications—a practical note on common misconceptions and pitfalls. *Hydrol Earth Syst Sci Discuss*
783 2020:1–31. <https://doi.org/10.5194/hess-26-1217-2022>

784 Trenberth KE, Dai A, Van Der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J (2014) Global
785 warming and changes in drought. *Nat Clim Chang* 4(1):17–22. <https://doi.org/10.1038/nclimate2067>

786 Zhang L, Zheng Q, Liu Y, Liu S, Yu D, Shi X, Xing S, Chen H, Fan X (2019) Combined effects of
787 temperature and precipitation on soil organic carbon changes in the uplands of eastern China. *Geoderma*
788 337:1105–1115. <https://doi.org/10.1016/j.geoderma.2018.09.043>

789 Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, van den Hurk B, AghaKouchak
790 A, Jézéquel A, Mahecha MD, Maraun D (2020) A typology of compound weather and climate events. *Nat*
791 *Rev Earth Environ* 1(7):333–347. <https://doi.org/10.1038/s43017-020-0060-z>

792 Zscheischler J, Westra S, Van Den Hurk BJ, Seneviratne SI, Ward PJ, Pitman A, AghaKouchak A, Bresch
793 DN, Leonard M, Wahl T, Zhang X (2018) Future climate risk from compound events. *Nat Clim Chang*
794 8(6):469–477. <https://doi.org/10.1038/s41558-018-0156-3>

795 **Statements and Declarations:**

796 **Funding:** The authors did not receive any specific funding for this work.

797 **Competing Interest:** The authors have no relevant financial or non-financial interests to disclose.

798 **Author Contributions:**

799 **Sudipto Kumar Paul:** data curation, analysis, conceptualization, writing original draft, visualization,
800 investigation, software. **Md. Tanbhir Rahman:** software, formal analysis, writing original draft, editing,
801 validation.

802 **Data Availability Statement:** The accompanying author can provide the data supporting the study's
803 conclusions upon reasonable request.

804