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Future Prediction of Consecutive Dry Days (CDD) in Rapti River Basin Using Model ACCESS-CM2 Climate Projection

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Authors' contributions

This work was carried out in collaboration among all authors. Author SK designed the study, performed the statistical analysis, managed the literature searches. Author VS and SS collected data and guidance of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

The Rapti River basin in India is a region increasingly vulnerable to extreme precipitation events, which pose significant challenges to water resource management and flood mitigation. This study investigates the extreme precipitation patterns in the Rapti River Basin, India, by analyzing historical and projected data using advanced climate models and indices. Utilizing the Expert Team on Climate Change Detection and Indices (ETCCDI) framework, we focus on Consecutive Dry Days (CDD). The study evaluates the trends under different global warming scenarios of 1.5˚C, 2˚C, and 3˚C, employing ACCESS-CM2 Model. The findings reveal significant variations in the trends and magnitudes of CDD across the different warming levels. At 1.5˚C, CDD shows a decreasing trend. At 2˚C, models project a continued decrease in CDD. At 3˚C, mixed trends are observed with notable increases in CDD, highlighting the potential for prolonged wet periods and

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increased flood risks. The study underscores the impact of climate change on the hydrological behavior of the Rapti River Basin, emphasizing the need for adaptive water resource management strategies. It provides valuable insights into the future precipitation trends in the Rapti River Basin, guiding the development of strategies to enhance resilience against climate-induced hydrological changes.

Keywords: Consecutive dry days; rapti river basin; climate projection; ETCCDI indices.

1. INTRODUCTION

The increasing impact of climate change on hydrological systems is a critical concern for water resource management, agriculture, and environmental sustainability. The Rapti River Basin, a significant tributary of the Ghaghara River in northern India, has been experiencing frequent extreme weather events, particularly prolonged dry periods, known as Consecutive Dry Days (CDD). Understanding and predicting these CDD trends under future climate scenarios is essential for developing effective adaptation and mitigation strategies.

Climate change, driven by anthropogenic activities, has led to significant alterations in global weather patterns, including increased frequency and intensity of extreme events [1]. The Intergovernmental Panel on Climate Change (IPCC) projects that with rising global temperatures, the variability and intensity of precipitation events will become more pronounced [2]. This has significant implications for regions like the Rapti River Basin, where agriculture and livelihoods are heavily dependent on consistent and predictable rainfall patterns.

Recent studies have highlighted the importance of modeling climate impacts on hydrological processes to understand future risks and inform policy decisions [3,4]. Process-based models, such as the Soil and Water Assessment Tool (SWAT), have been widely used to simulate the effects of climate change on water resources [5]. However, the application of climate projection models, such as ACCESS-CM2, provides a more detailed and localized understanding of future climate scenarios.

The Rapti River Basin has been prone to both droughts and floods, with historical records indicating severe flooding events in 1992, 1998, 2000, 2008, 2014, 2017, 2018, 2019, and 2020 [6]. These events underscore the basin's vulnerability to extreme weather and the necessity for robust predictive models to guide water resource management and agricultural planning. With the projected increase in global temperatures, it is crucial to assess how these changes will influence the occurrence and duration of CDD in the basin.

Therefore, this study aims to understand the rainfall characteristics of the Rapti River Basin. It includes an analysis of daily, seasonal, and annual rainfall using gridded rainfall data for the Rapti Basin. The study also focuses on examining the temporal variability of rainfall with ETCCDI indices, analyzing trends in the gridded rainfall data, and understanding the rainfall characteristics of the basin. Additionally, the research aims to determine the change point in rainfall patterns within the basin and relate this change point to flooding events. The findings indicate that flooding in the basin increases after the identified change point. Gorakhpur, situated in the downstream area of the basin, is the most flood-prone region, despite experiencing the highest number of consecutive dry days. Rainfall in the upstream areas significantly contributes to flooding in Gorakhpur.

This study aims to investigate the variability and trends in extreme precipitation within the Rapti River Basin from the historical data, 1971 to 2014 provided by Indian Meteorological Data, Pune and the projected data, 2015 to 2100 using bias corrected CMIP6 Datasets. By employing an iterative Mann-Kendall trend test, we seek to provide a comprehensive understanding of historical precipitation extremes and their potential future trajectories. Understanding these patterns is crucial for developing effective strategies to mitigate the adverse effects of climate change and to enhance the resilience of the communities dependent on the Rapti River Basin.

2. MATERIALS AND METHODS

2.1 Study Area

The Rapti River Basin is located primarily in the northern part of India, within the state of Uttar Pradesh. The basin stretches approximately between the latitudes of 26.5°N to 28.5°N and the longitudes of 82.5°E to 84.5°E. In India, the Rapti River flows through several districts including Bahraich, Shravasti, Balrampur, Siddharthnagar, Gorakhpur, and Sant Kabir Nagar. The total area covered by the Rapti River Basin in India is roughly around 30,000 square kilometers. This area is characterized by a mix of agricultural land, forests, and urban settlements, with the river playing a significant role in the region's agriculture and economy [7].

The geography of the Rapti River Basin is diverse, encompassing the Terai plains at the foothills of the Himalayas. This region is known for its fertile soil, making it an important agricultural zone. The terrain is generally flat with some undulating areas, particularly closer to the river. The basin is prone to flooding during the monsoon season due to the flat topography and heavy rainfall [8,9].

The climate of the Rapti River Basin is predominantly subtropical, with distinct seasons: Summer (March to June): Hot and dry, with temperatures ranging from 30°C to 45°C.

Monsoon (July to September): Marked by heavy rainfall, with the region receiving an average annual precipitation of about 1,200 to 1,500 mm. This period is crucial for replenishing water resources but also brings the risk of floods.

Winter (October to February): Mild and dry, with temperatures ranging from 5°C to 25°C [10,11].

The temperature in the Rapti River Basin varies significantly with the seasons:

Summer: High temperatures often exceed 40°C during peak periods.

Monsoon: Temperatures are relatively lower than in summer, ranging from 25°C to 35°C, but humidity levels are high.

Winter: Temperatures can drop to around 5°C during the coldest months, with daytime temperatures ranging between 15°C and 25°C.

2.2 Metreological Data

The rainfall datasets (1971-2014) was collected from the Indian Meteorological Department (IMD), Pune, and the long-term annual data (2015-2100) for CDD, i.e., the maximum annual number of consecutive dry days (when precipitation < 1.0 mm),obtain from Centre for Climate Change Research, Pune were used in this study. The bias-corrected CMIP6 datasets used in the study are available at https://zenodo.org/record/3873998#.Y7xgvnZBy0 1 for the Indian region at 0.25° × 0.25° grids given by Aadhar and Mishra [12].

2.3 Mann- Kendall Test for Trends

The Mann-Kendall test is a non-parametric statistical test used to detect trends in time series data. It is particularly useful for identifying monotonic trends in environmental data, such as precipitation or temperature, without requiring the data to follow a specific distribution. The test is named after [13 and 14], who developed it in the late 20th century.

The Mann-Kendall test statistic (S) is calculated based on the number of positive and negative differences between data points.

For a time series of n data points {x1,x2,..............,xn}:

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \tag{1}$$

Where,

$$sgn(x_j - x_i) = \begin{Bmatrix} 1\ if(x_j - x_i) > 0 \\ 0\ if(x_j - x_i) = 0 \\ -1\ if(x_j - x_i) < 0 \end{Bmatrix} \tag{2}$$

$$VAR(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \tag{3}$$

Where tirepresents the number of data points in the ith tied group, m is the total number of tied groups (a tied or connected group consists of a set of data points with the same value), and n is the total number of data points.

The standard test statistic Z is calculated using the following formula:

$$Z = \begin{cases} \frac{s-1}{\sqrt{VAR(s)}} if s > 0 \\ 0\ if s = 0 \\ \frac{s+1}{\sqrt{VAR(s)}} if s < 0 \end{cases} \tag{4}$$

The statistical significance Z of the test statistics is evaluated at three different levels of significance: 1%, 5%, and 10%. If the time series exhibits a strong lag-1 serial correlation, the Mann-Kendall (MK) test with pre-whitening is employed, as recommended by Yue et al. [15].

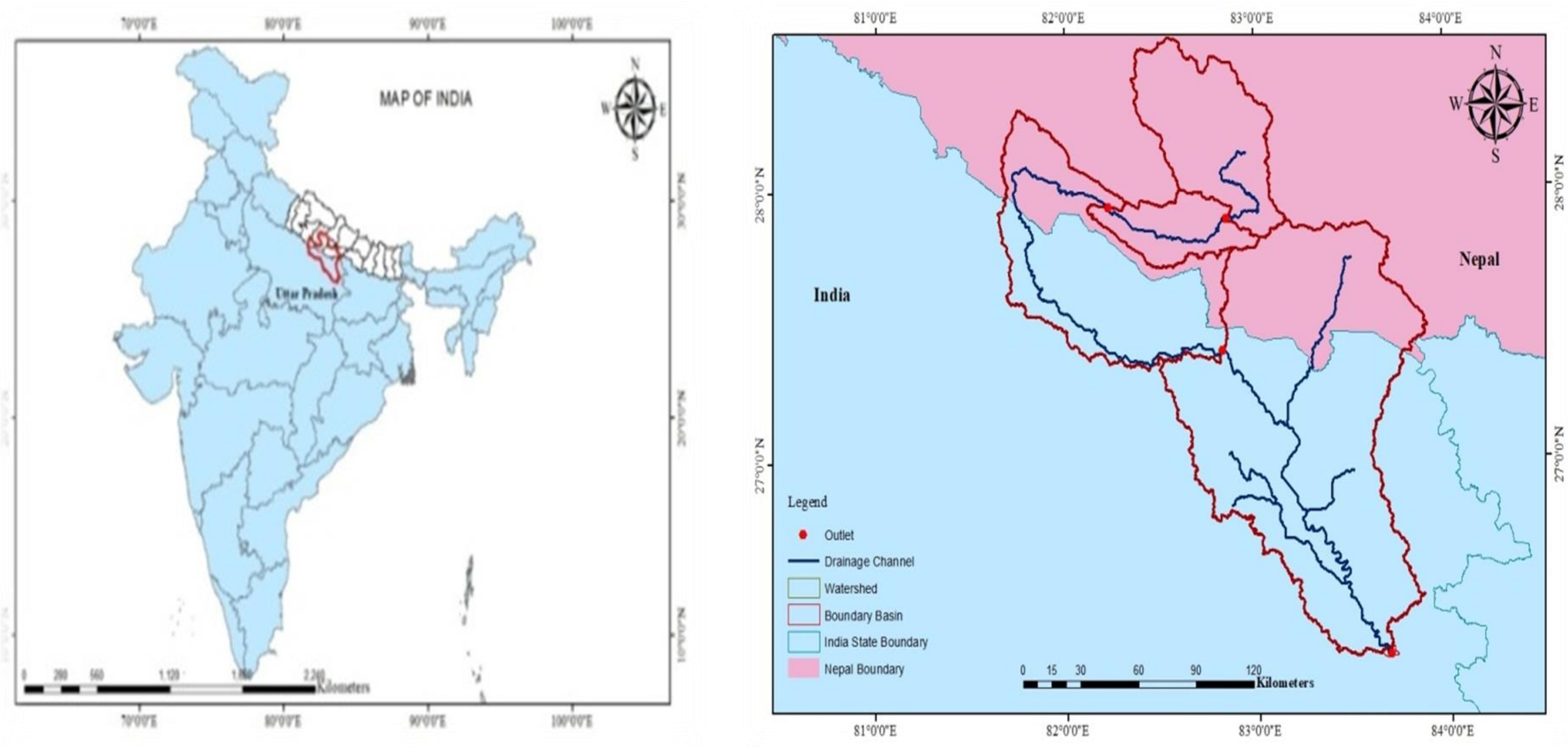

Fig. 1. Location of the study area

Table 1. 59 Stations located in India and Nepalof Rapti River basin

Stations	Latitude	Longitude	Stations	Latitude	Longitude
01	26.375	83.375	31	28.375	81.625
02	26.375	83.625	32	27.875	81.875
03	26.375	83.875	33	28.125	81.875
04	26.625	83.125	34	28.375	81.875
05	26.625	83.375	35	27.875	82.125
06	26.625	83.625	36	28.125	82.125
07	26.625	83.875	37	27.875	82.375
08	26.875	82.625	38	28.125	82.375
09	26.875	82.875	39	28.375	82.375
10	26.875	83.125	40	28.625	82.375
11	26.875	83.375	41	27.875	82.625
12	27.125	82.125	42	28.125	82.625
13	27.125	82.625	43	28.375	82.625
14	27.125	82.875	44	28.625	82.625
15	27.125	83.125	45	27.625	82.875
16	27.125	83.375	46	27.875	82.875
17	27.125	83.625	47	28.125	82.875
18	27.375	82.125	48	28.375	82.875
19	27.375	82.375	49	28.625	82.875
20	27.375	82.625	50	27.625	83.125
21	27.375	82.875	51	27.875	83.125
22	27.375	83.125	52	28.125	83.125
23	27.375	83.375	53	28.375	83.125
24	27.375	83.625	54	27.625	83.375
25	27.625	81.875	55	27.875	83.375
26	27.625	82.125	56	27.625	83.625
27	27.625	82.375	57	27.875	83.625
28	27.625	82.625	58	27.375	83.875
29	27.875	81.625	59	27.625	83.875
30	28.125	81.625			

Table 2. Precipitation indices used in this study

Index	**Precipitation** Duration	**Definition**	**Unit**
CDD	Consecutive Dry Days	Maximum annual number of consecutive dry days (i.e., when precipitation < 1 mm)	days

2.3.1 Sen's slope estimator

To quantify the magnitude of the trend, Sen's Slope Estimator is often used. It calculates the median slope between all pairs of data points.

$$\beta = Median\left[\frac{x_j - x_i}{j-i}\right] \text{ for all i } < j \qquad (5)$$

Where 1<j<i<n and β is the robust estimate of the trend magnitude. A positive value of β indicates an 'upward trend', while a negative value of β indicates a 'downward trend' (Xu et al., 2007). Xjrepresents the data value at time j, and Xi represents the data value at an earlier time i.

The relative change is calculated using the following equation [16]:

$$\mathrm{RC} = \frac{\mathrm{n}*\beta}{|\mathrm{x}|} * 100 \qquad (6)$$

Where, |x|is the absolute average value of the time series, n is the length of the time series, and β is the trend slope estimated using Sen's median estimator.

2.4 Shared Socioeconomic Pathways (SSPs)

Shared Socioeconomic Pathways (SSPs) are a set of scenarios used to model and understand potential future global changes in climate, economics, and society. Developed as part of the framework for climate change research, SSPs help in examining how different societal trends might influence greenhouse gas emissions, climate policies, and adaptive capacities [17,18]. They are integral to the Coupled Model Intercomparison Project Phase 6 (CMIP6) and are used in conjunction with Representative Concentration Pathways (RCPs) to provide a comprehensive view of possible futures.

SSPs are used in various fields of research and policy-making to explore and plan for future scenarios: SSPs are combined with RCPs to create integrated scenarios that model both socioeconomic and climate changes. This helps in understanding the potential impacts of different levels of greenhouse gas emissions. Researchers use SSPs to assess the impacts of climate change on various sectors, including agriculture, water resources, health, and infrastructure. These assessments help identify vulnerabilities and inform adaptation strategies.

2.5 Extreme Precipitation Indices

Extreme precipitation indices are quantitative measures used to assess and characterize extreme rainfall events. These indices help in understanding the frequency, intensity, duration, and spatial extent of extreme precipitation, which are crucial for studying climate variability, assessing water resources, and managing risks associated with floods and droughts. Here are some common extreme precipitation indices. The 11 precipitation indices are categorized based on their characteristics into measures of precipitation intensity, frequency, and duration across various precipitation schemes, as outlined in reference [19]. Using the Expert Team on Climate Change Detection and Indices (ETCCDI) indexes, the characteristics of extreme rainfall are assessed. ETCCDI provided twenty-seven core indices to determine the characteristics of precipitation and temperature [20]. Among these indices, CDD (Consecutive Dry Days) is used in this study to measure precipitation characteristics. The descriptions of the indices used are provided in Table 2.

2.6 Projected Changes of Precipitation Extremes at 1.5 °C, 2 °C and 3°C GWLs

Understanding the projected changes in precipitation extremes at various global warming levels (GWLs) is crucial for anticipating future climate impacts on the Rapti River Basin [21-22]. The analysis focuses on three key warming thresholds: 1.5°C, 2°C, and 3°C above pre-industrial levels. These projections are based on climate model simulations and provide insights into how increasing global temperatures may alter extreme precipitation patterns in the basin.

3. RESULTS AND DISCUSSION

3.1 Annual Precipitation Extremes

We evaluated four precipitation extremes using Model ACCESS-CM2, under various global warming levels of 1.5˚C, 2˚C, and 3˚C, across multiple time scales.

The range of maximum Consecutive Dry Days (CDD) values at 1.5˚C (2020-2031) varies between 208 days and 49 days for the ACCESS-CM2 Model, ssp 585, with the minimum value ranging from 72 days to 28 days.

The highest CDD value at 2˚C (2032-2050) for ACCESS-CM2 Model, ssp 585, spans between 166 days and 60 days, while the lowest value varies from 102 days to 22 days.

The highest CDD value at 3˚C (2051-2060) for ACCESS-CM2 Model, ssp 585, varies between 136 days and 53 days, with the lowest value ranging from 68 days to 24 days.

3.2 Annual Trend Analysis of Extreme Precipitation Indices

During the period of 2020-2031 at 1.5˚C, under Model ACCESS-CM2 (M1), ssp585, the Consecutive Dry Days (CDD) show a notable decrease in trend, with a reduction of -0.34 (-0.45), corresponding to a decrease in slope of -1.08 days per year. In contrast, for Model ACCESS-ESM1-5 (M2), there is a more significant decrease in trend, amounting to -2.90 (-1.43), resulting in a decrease in slope of -6.49 days per year.

Under Model ACCESS-CM2, ssp585, at 2˚C (2032-2050), there is a notable decrease in trend for Consecutive Dry Days (CDD) of -0.08 (-0.93), resulting in a decrease in slope of -8.07 days per year.

At 3˚C (2051-2060), under Model M1, ssp585, there is a substantial decrease in trend for Consecutive Dry Days (CDD) of -1.59 (-1.45), resulting in a decrease in slope of -3.42 days per year.

Table 3. Detail of selected climate models of CMIP6 for the study

Sr. No.	CMIP 6 Model	Description	Precipitation indices under GWLs								
			CDD			CDD			*CDD*		
			1.5˚C	2˚C	3˚C	1.5˚C	2˚C	3˚C	1.5˚C	2˚C	3˚C
1	M1	ACCESS-CM2	2020-2031	2032-2050	2051-2060	2020-2031	2032-2050	2051-2060	2020-2031	2032-2050	2051-2060

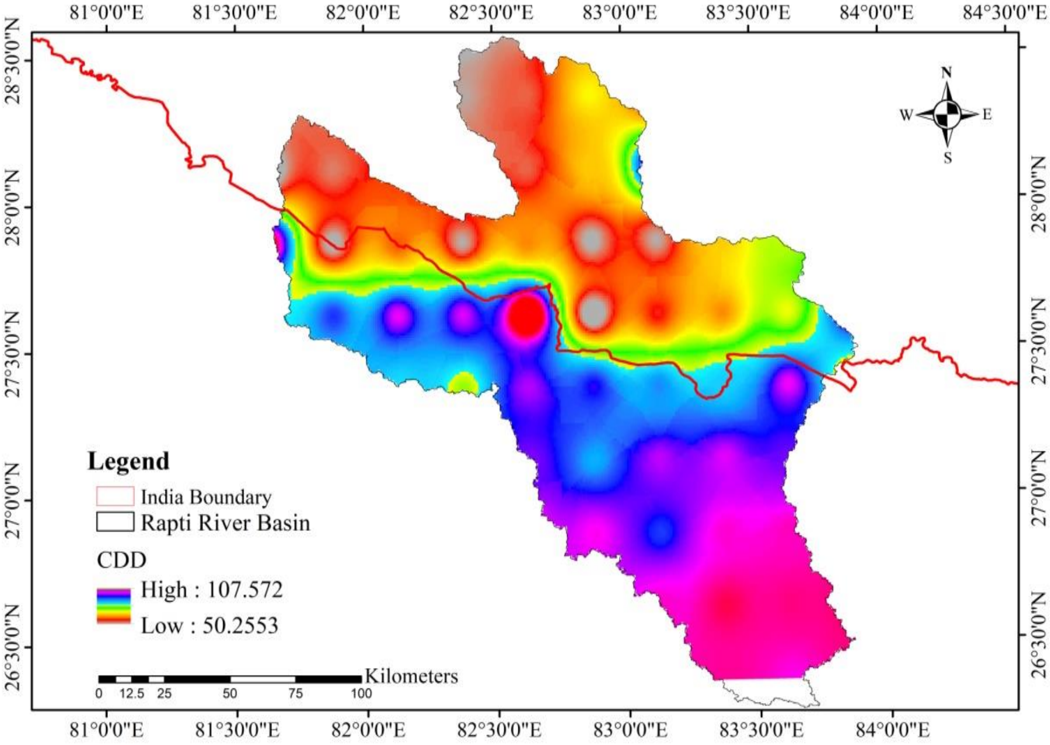

Fig. 2. Consecutive Dry Days (CDD) atACCESS-CM2 model for 1.5˚

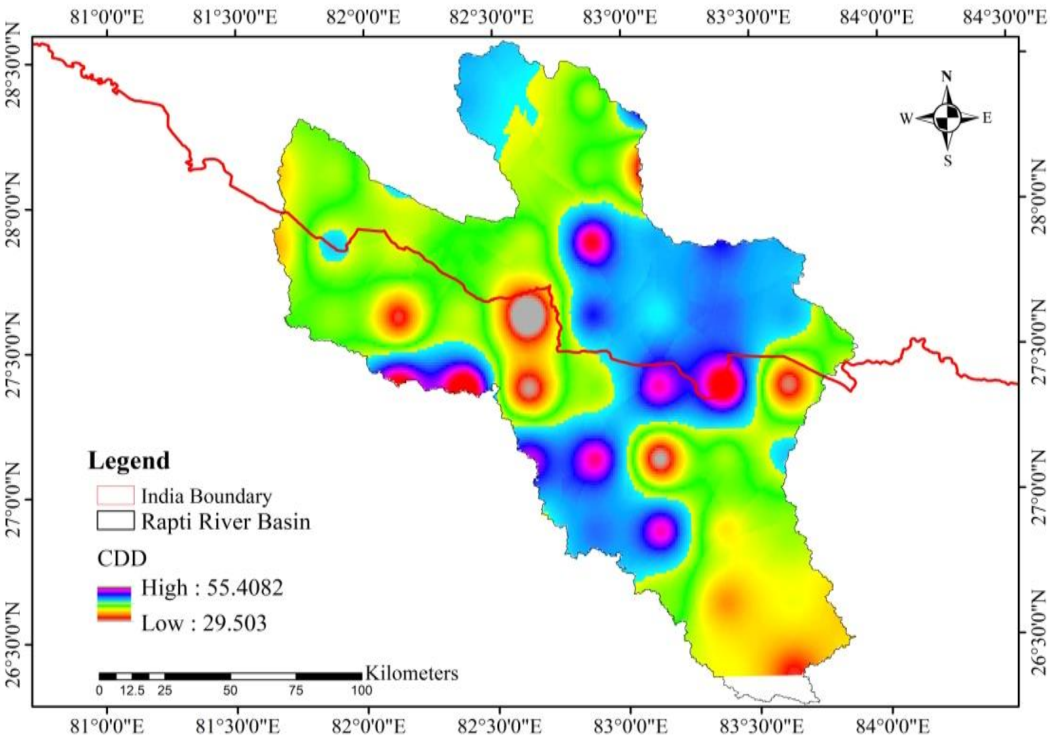

Fig. 3. Consecutive Dry Days (CDD) atACCESS-CM2 model for 2˚

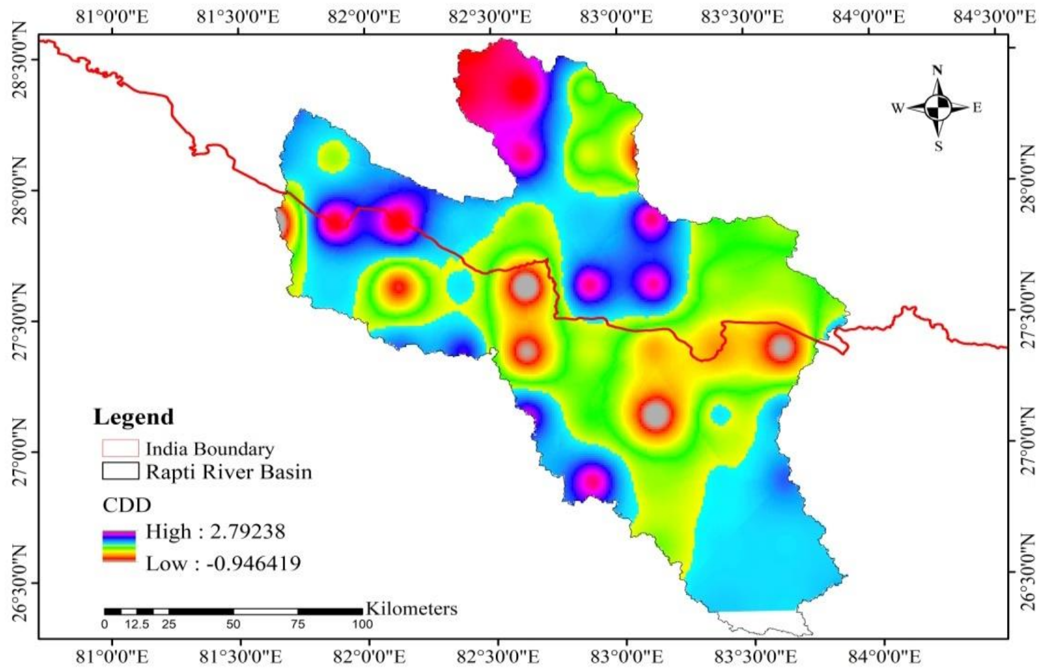

Fig. 4. Consecutive Dry Days (CDD) atACCESS-CM2 modelfor3˚

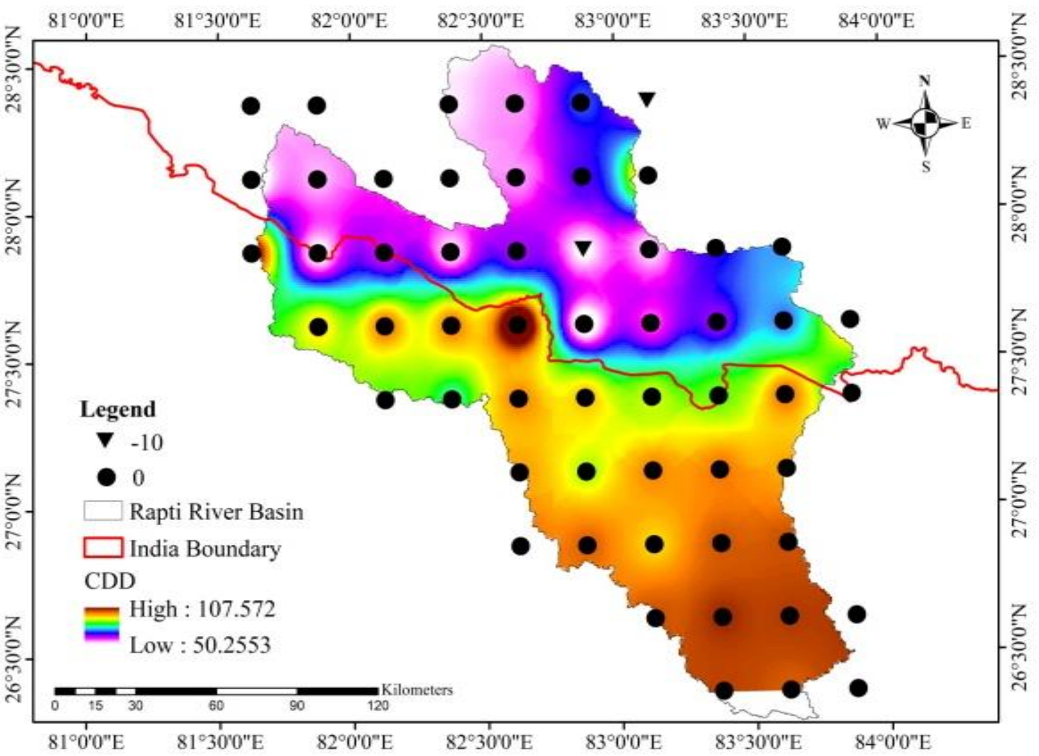

Fig. 5. Trends of Consecutive Dry Days (CDD) at ACCESS-CM2 model for 1.5˚

Here, ▼= -10 indicate a decrease in the number of consecutive dry days by 10 days

●= 0 indicates no change in the number of consecutive dry days

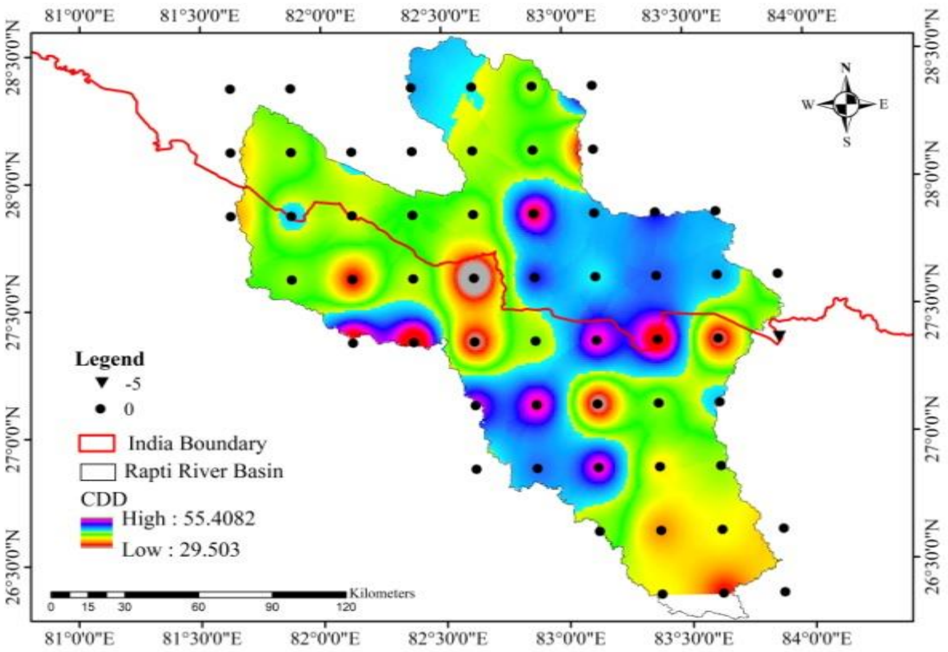

Fig. 6. Trends of Consecutive Dry Days (CDD) atACCESS-CM2 model for 2˚

Here, ▼ = -5 indicate a decrease in the number of consecutive dry days by 5 days.

● = 0 indicates no change in the number of consecutive dry days

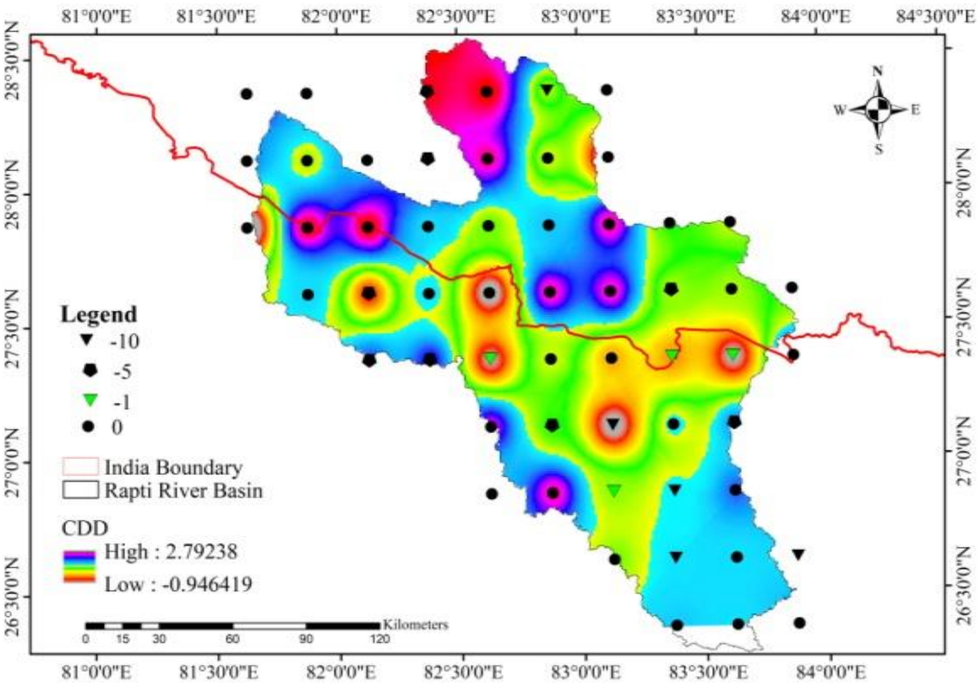

Fig. 7. Trends of Consecutive Dry Days (CDD) at ACCESS-CM2 model for 3˚

Here, ● = 0 indicates no change in the number of consecutive dry days

▼ = -1 indicate a decrease in the number of consecutive dry days by 1 day

⬟ = -5 indicate a decrease in the number of consecutive dry days by 5 days

3.3 Discussion

The study focused on predicting future trends in consecutive dry days (CDD) within the Rapti River Basin using the ACCESS-CM2 climate projection model. Understanding the projected changes in CDD is crucial for water resource management, agricultural planning, and mitigating potential drought impacts in the region. The findings provide valuable insights into the future climate dynamics of the Rapti River Basin and highlight areas of concern for policymakers and stakeholders.

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- **Future Projections of Consecutive Dry Days:** The analysis revealed a significant increase in the number of CDD in the future, particularly under higher emission scenarios. The projections indicate that the frequency and duration of dry spells are likely to intensify, which can have severe implications for water availability, agriculture, and ecosystem health in the basin. The increase in CDD is more pronounced during the dry season, exacerbating the stress on water resources during critical periods.
- **Implications for Water Resources**: An increase in CDD directly impacts the hydrological cycle, reducing streamflow and groundwater recharge rates. This can lead to a depletion of water resources, affecting both surface and subsurface water availability. The findings suggest that the Rapti River Basin may face significant water scarcity issues in the future, necessitating proactive measures in water management and conservation strategies. The need for efficient water storage, distribution systems, and sustainable groundwater management practices becomes paramount to mitigate the adverse effects of prolonged dry periods.
- **Agricultural Impacts**: Agriculture, being the primary livelihood for many inhabitants of the Rapti River Basin, is highly vulnerable to changes in precipitation patterns. Extended periods of consecutive dry days can severely affect crop yields, soil moisture levels, and overall agricultural productivity. The study underscores the necessity for adaptive agricultural practices, such as drought-resistant crop varieties, improved irrigation techniques, and soil moisture conservation methods. Policymakers should prioritize the development and dissemination of these practices to ensure food security in the face of changing climate conditions.
- **Drought Preparedness and Management**: The projected increase in CDD highlights the urgent need for comprehensive drought preparedness and management plans. This includes the establishment of early warning systems, drought monitoring networks, and community-based drought response strategies. Integrating climate projections into local and regional planning can enhance the resilience of communities and ecosystems to future drought conditions.

4. CONCLUSION

This study provides a comprehensive analysis of extreme precipitation events in the Rapti River Basin, India, utilizing multiple models and indices to evaluate both historical and projected trends.

- The findings highlight significant variations in the trends and magnitudes of Consecutive Dry Days (CDD) across different global warming levels of 1.5˚C, 2˚C, and 3˚C.
- The analysis indicates that the Rapti River Basin is experiencing significant changes in precipitation patterns, driven by climate change. Under the various models and scenarios analyzed, the results show both increases and decreases in the trends of CDD with notable variations in the slopes, reflecting the complex and dynamic nature of the basin's hydrological response to global warming.
- Specifically, at 1.5˚C, there is a decreasing trend in CDD, suggesting variability in dry spells. At 2˚C, the models project a further decrease in CDD, indicating a shift towards more frequent wet spells. At 3˚C, while some models show a continued decrease in CDD, others indicate a significant increase in CDD, implying potential risks of prolonged wet periods and associated flood events.
- These findings underscore the critical need for adaptive water resource management strategies in the Rapti River Basin. The projected changes in extreme precipitation events, including increased frequency and intensity of both droughts and floods, pose significant challenges to agriculture, infrastructure, and livelihoods in the region.

This research emphasizes the importance of continuous monitoring and assessment of precipitation trends using advanced climate models and indices. Policymakers and stakeholders must prioritize the development of robust adaptation and mitigation strategies to address the impacts of climate change on the Rapti River Basin, ensuring sustainable water resource management and resilience of the local communities to future climatic extremes.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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