Analysis of rainfall epochs in changing climate of Kangsabati river basin, India

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ABSTRACT
Climate change directly or indirectly impacts the global atmosphere composition, which poses major environmental concern. The implications of climate change show noticeable change in rainfall patterns and onset worldwide. Prior knowledge of information of rainfall data is vital for many applications. In the present study, the onset, withdrawal, and duration of monsoon period have been studied for Purulia and Ranibandh locations in the Kangsabati river basin area for the period 2015 to 2022. The observed data were analysed and compared with the model data of CMIP6 GCM's for 4 scenarios. Statistical parameters such as probability density function (PDF), Cumulative Distribution Function (CDF), Coefficient of determination (R^2), and Root Mean Square Error (RMSE) were employed to evaluate the precision of matching between observed and modelled rainfall data. For onset, withdrawal, and duration of monsoon period, under 4 scenarios of Shared Socioeconomic Pathways (SSPs), highest R^2 values range between 0.46 and 0.75 for CanESM5, EC-Earth3-veg and ACCESS-CM2 for Purulia and Ranibandh locations. For the duration of monsoon period between onset and withdrawal, R^2 value of 0.54 and 0.46 has been observed for CanESM5-SSP370 and ACCESS_CM2-SSP126 for Purulia and Ranibandh respectively. On the other hand, for Purulia and Ranibandh, the lowest RMSE values has been observed for the model CanESM5, EC-Earth3-veg and ACCESS-CM2 for onset, withdrawal and monsoon period. The study identifies CanESM5, EC-Earth3-veg, and ACCESS-CM2 as the top-performing CMIP6 GCM models for accurately simulating monsoon dynamics onset, withdrawal, and monsoon length – in the Kangsabati basin, specifically in Purulia and Ranibandh locations. With these best performing models on projecting the precipitation for 2023 to 2100 for Purulia and 2022 to 2100 for Ranibandh, a very negligible shift has been observed in the onset and withdrawal periods. Overall, this study contributes to our understanding of rainfall patterns and monsoon dynamics, offering valuable insights for both climate modelling and water resource management in the region.

KEYWORDS
climate change; precipitation projection; rainfall patterns; water resource management

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1. Introduction

The climate of a region encompasses the long-term average weather patterns, while climate change refers to statistical alterations in the average state of the climate and its key components over a significant duration. As defined in Article 1 of the United Nations Framework Convention on Climate Change, climate change is a shift attributed to human activity, directly or indirectly impacting the global atmosphere's composition, surpassing natural variability. Undoubtedly, climate change stands out as a major environmental concern in the twenty-first century, causing apprehension in economic, societal, and international scientific and political spheres. Its repercussions, particularly the rise in extreme weather events, significantly affect agriculture, ecosystems, and water resources (Arnell and Reynard 1996; Kumar et al. 2020), posing substantial challenges to global industrial systems and supply chains (Papadopoulos and Balta 2022).

According to the Intergovernmental Panel on Climate Change (IPCC 2023), earth's surface temperature was around 1.1 °C above the period 1850–1900 in 2011–2020, with larger increases over land than over the ocean. Climate fluctuations and changes impact virtually every individual globally, with South and Southeast Asian nations facing disproportionate effects due to poverty and complex socio-economic issues (Omerkhil et al. 2020). India, with its developing economy and diverse geographic regions, is particularly sensitive to climate hazards. Over half of India's population resides in rural areas, heavily dependent on climate-sensitive sectors like agriculture, fisheries, and forestry. Rural communities, constituting 70% of the population, are particularly vulnerable (Parry et al. 2007).

A notable consequence of the Earth's surface temperature increase is the atmosphere's increased water-holding capacity by approximately 7% per 1 °C rise, directly leading to intensified rainfall (Tabari 2020). Recent research highlights an increase in extreme rainfall occurrences and their intensity within a warming climate (Roxy et al. 2017). The non-stationary approach, considering changing climates and escalating urbanization, is deemed more appropriate for evaluating extreme rainfall (Vinnarasi and Dhanya 2022).

Historical climate model simulations, primarily assessing models' capabilities in replicating average and extreme precipitation, are crucial for climate projections. The Coupled Model Intercomparison Project (CMIP) has evolved through various phases, with CMIP6 being the latest. CMIP6 introduces advancements in spatial resolution, physical parameterizations, and the inclusion of additional Earth system processes compared to its predecessors (Eyring et al. 2016; Chen et al. 2020). Despite discrepancies, CMIP6 demonstrates improved precipitation simulation abilities (Abbas et al. 2022; Abbas et al. 2023; Towheed and Roshni 2021). However, a thorough investigation is required to assess CMIP6 models' enhancements in simulating precipitation across different scales.

Researchers and policymakers are interested in evaluating the accuracy of CMIP6 Global Climate Models (GCMs) in representing global and regional climate patterns and predicting changes in extreme precipitation under new emissions scenarios. However, despite the improvements and efficacy of current CMIP6 models in conjunction with SSPs, there is still very limited studies on anticipated rainfall extremes, particularly for Kangsabati river basin. Additionally, studies focusing on GCMs for climate change research in Kangsabati river basin was found scarce. Therefore, this study emphasizes the need for reliable assessments of extreme rainfall for designing infrastructure and flood protection, determining rainfall frequency, comparing predictive approaches, and estimating risks associated with extreme damage. Hence, the objectives of this study are to (i) Evaluate the comparative performance of observed data with different climate change models CMIP6 model data for 4 SSP scenarios at Purulia – the Ranibandh gauging stations, using different Goodness_of_fit statistics, for Onset, Withdrawal, Length of monsoon rainy days (ii) To determine the projected precipitation changes for the Onset, Withdrawal and Length of monsoon rainy days, for the period 2023 to 2100 for Purulia and 2022 to 2100 for Ranibandh, based on the best performing CMIP6 GCMs for 4 scenarios. Given the prevalence of natural disasters in this region and the critical shortage of water for agricultural, industrial, and domestic purposes, this study is essential for identifying extreme hydro-meteorological factors in climate change scenarios. This understanding will facilitate effective water management for sustainable agriculture and help mitigate natural disasters such as floods and droughts (Kumar and Singh 2024). The study's outcomes aim to provide valuable insights for water resource policymakers and decision-makers to make informed decisions in the face of climate change challenges.

2. Study Area and Data Collection

The Kangsabati River Basin is a sub-basin of the lower Ganga plain in West Bengal. The Kangsabati River is a non-perennial alluvial river which originates from the eastern part of the Chotta Nagpur plateau i.e. at the Jhalda block of Purulia district. It then flows through the districts of Purulia, Bankura, West and East Midnapore and meets River Rupnarayan before it falls into the Bay of Bengal. The upper course of the river flows in the Purulia district, middle course flows through Bankura and West Midnapur while the lower course of the river is in East Midnapur where the river meets River Rupnarayan.

The study area of the Kangsabati River basin extends from 23°28′15.6″ N 85°57′3.6″ E and

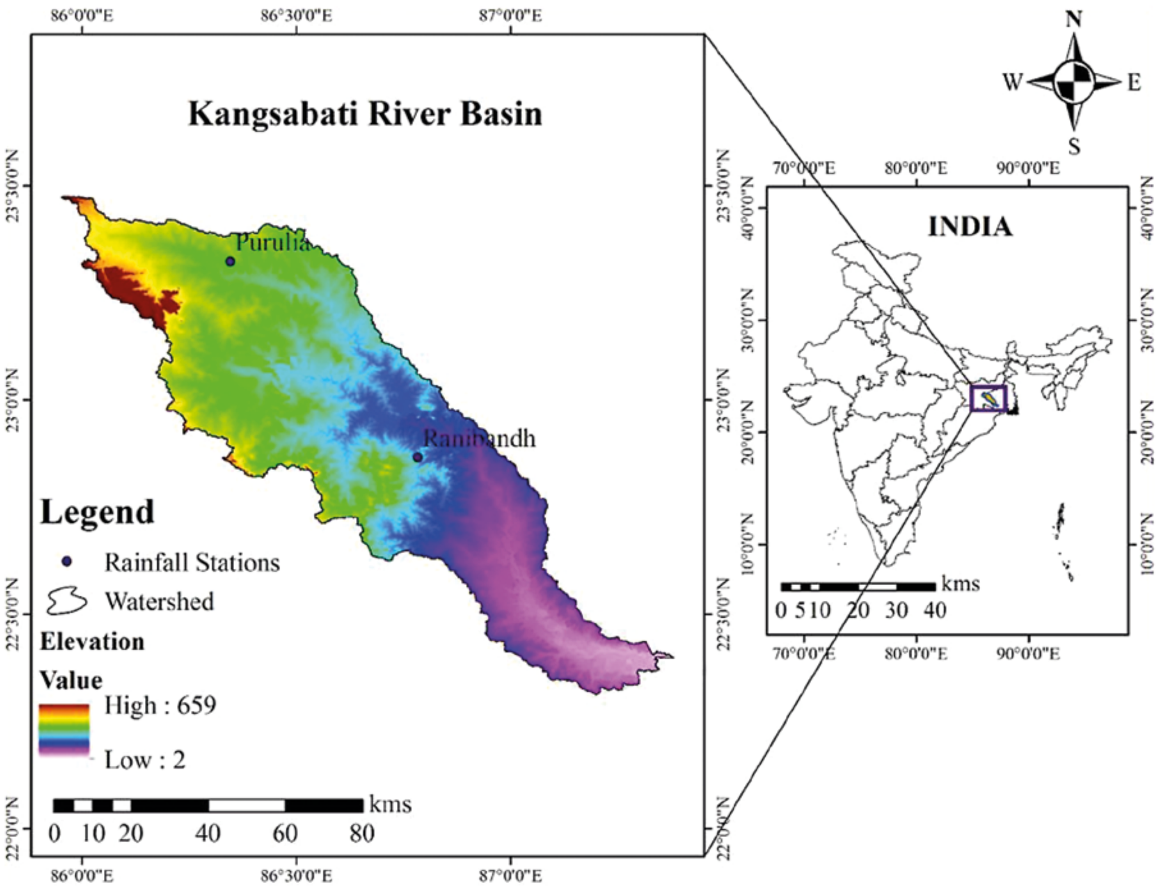

Fig. 1 Catchment area of the Kangsabati River Basin.

22°23′56″ N 87°22′40.8″ E, with a total area of 9658 km^2 is shown in Fig. 1. In 1956, Mukutmanipur Dam or Kangsabati dam, was constructed at the border of Purulia and Bankura districts near Mukutmanipur, creating a large reservoir, also known as the Kangsabati Irrigation Project/Kangsabati Reservoir Project, developed to provide water for the irrigation of Bankura and Midnapore districts. The temperature varies from 27 °C to 45 °C during summer, 6 °C to 25 °C during winter and the annual rainfall varies from 960 mm to 1822 mm with an average of 1370 mm (Central Ground Water Board 2014–15). However, 80–85 percent of the total rainfall is received during the three to four months of the monsoon period from June to September. The land is undulated and lateritic.

2.1 Datasets

The observational data utilized in this research consists of daily rainfall records obtained from IMD, Pune, covering the period of 1982 to 2022 for Purulia and 1990 to 2021 for Ranibandh. We scrutinized three CMIP6 models from the CMIP6 database website (https://esgf-node.llnl.gov/search/cmip6), as detailed in Tab. 1. Unlike CMIP5, the latest generation of CMIP6 models features updated specifications for concentration, emission, and land-use scenarios, along with a revised start year (CMIP6: 2015, CMIP5: 2006) for future scenarios. In this phase, Shared Socioeconomic Pathways (SSPs) are amalgamated with the Representative Concentration Pathways (RCPs) of CMIP5. These SSPs are based on five narratives representing different levels of socioeconomic development (Riahi et al. 2017): sustainable development (SSP1), middle-of-the-road development (SSP2), regional rivalry (SSP3), inequality (SSP4), and fossil fuel-driven development (SSP5). Detailed descriptions of the SSPs are available in O’Neill et al. (2016).

Tab. 1 List of CMIP6 models used in this study.

GCM	Research Center	Resolution
ACCESS-CM2	Australian Community Climate and Earth System Simulator – Climate Modelling2	1.88 × 1.25
CanESM5	Canadian Earth System Model version 5, CanESM5, Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Canada	2.81 × 2.77
EC-Earth3-veg	One of the EC – Model Earth configurations for CMIP6, Royal Netherlands Meteorological Institute	.7 × .7

2.2 Methods/Model Performance Criteria

Rainy days are defined as days when the rainfall exceeds the threshold of 2.5 mm or 0.1 inches (Epifani et al. 2004; Tilya and Mhita 2007). Onset is the first day when rainfall exceeds the defined threshold after a consecutive dry period, identified as the onset date. Withdrawal is defined as the last day when rainfall exceeds the threshold of 2.5 mm before a dry period. The duration of each monsoon period was calculated by subtracting the onset date from the withdrawal date. Statistical analysis was conducted to determine the relationship between the model and observed data.

The assessment of CMIP6 models' ability to replicate extreme rainfall, in comparison to observed data, involved employing Root Mean Square Error (RMSE) and Coefficient of determination (R^2) metrics (Ongoma et al. 2018; Dibaba et al. 2019). An R^2 close to 1 indicates a good correlation while values approaching zero indicated poor model performance with a weak correlation (Chai and Draxler 2014; Demissie and Sime 2021; Sime and Demissie 2022). While R^2 tells you about correlation between two datasets,

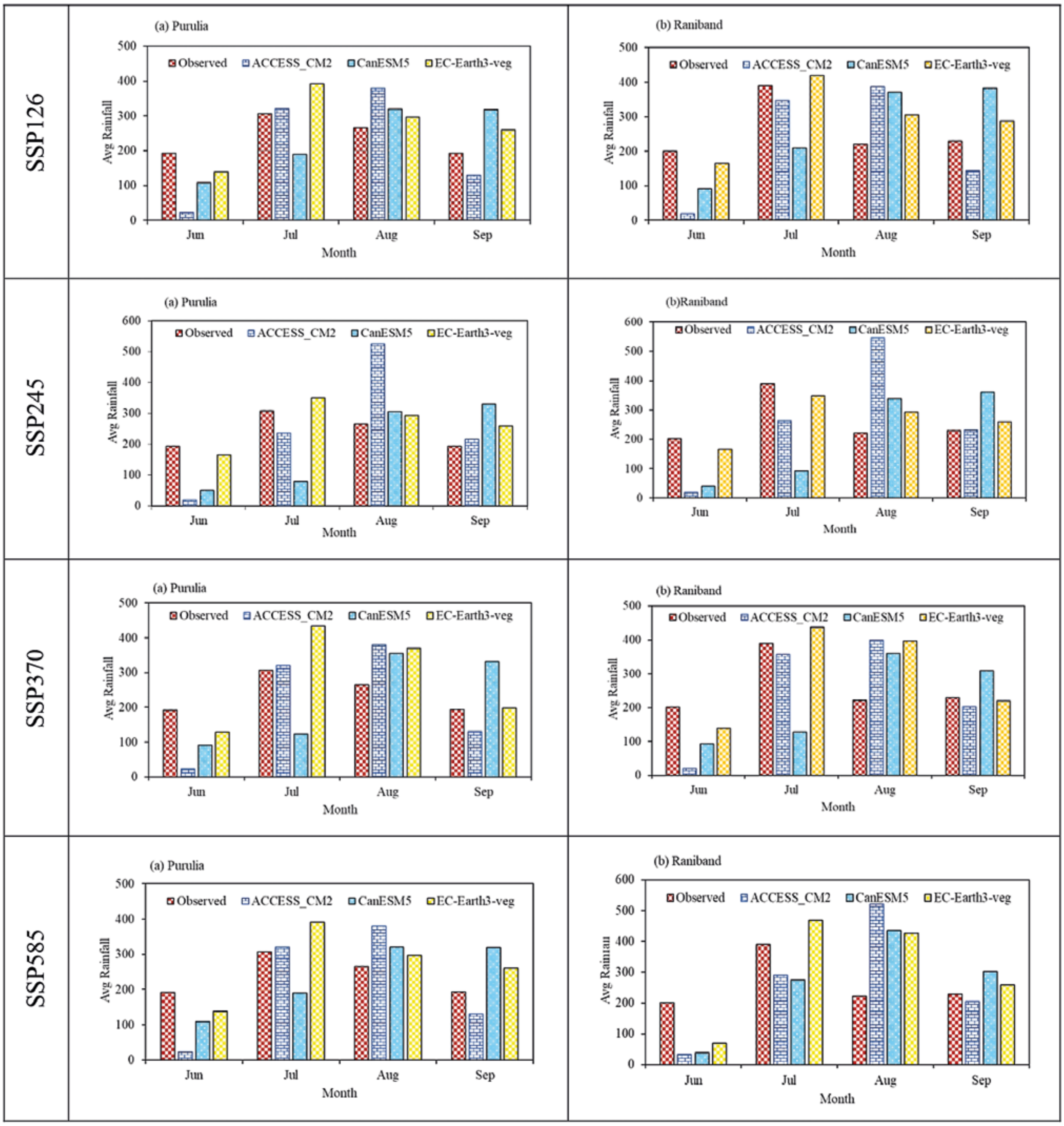

Fig. 2 Monthly Average rainfall data comparison between Observed IMD data set and 3 climatic model data sets for 4 scenarios from 2015 to 2022 for both Purulia and Ranibandh locations.

RMSE tells you about the difference between them. A low RMSE means less difference between model data and observed measurements and hence better performance and vice versa. Ideal Value of R^2 is 1 and ideal value of RMSE is 0.

The specific equations for calculating R^2 and RMSE are outlined in equations (1) and (2), respectively.

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - O_m)(S_i - S_m)}{\sqrt{\sum_{i=1}^{n}(O_i - O_m)^2}\sqrt{\sum_{i=1}^{n}(S_i - S_m)^2}}\right]^2 \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \quad (2)$$

Where S_i is simulated or model data and O_i is the observed value of the climate variable, i refers to the simulated and observed pairs, n is the total number of pairs, and m refers to mean extreme rainfall.

3. Results and Discussion

3.1 Comparison with Global dataset

Spatio-temporal trends in rainfall is assessed using historical rainfall datasets. Analysis of rainfall is important for many reasons. It can help to understand the effects of climate change and variability on water resources, ecosystems, floods, and droughts. It

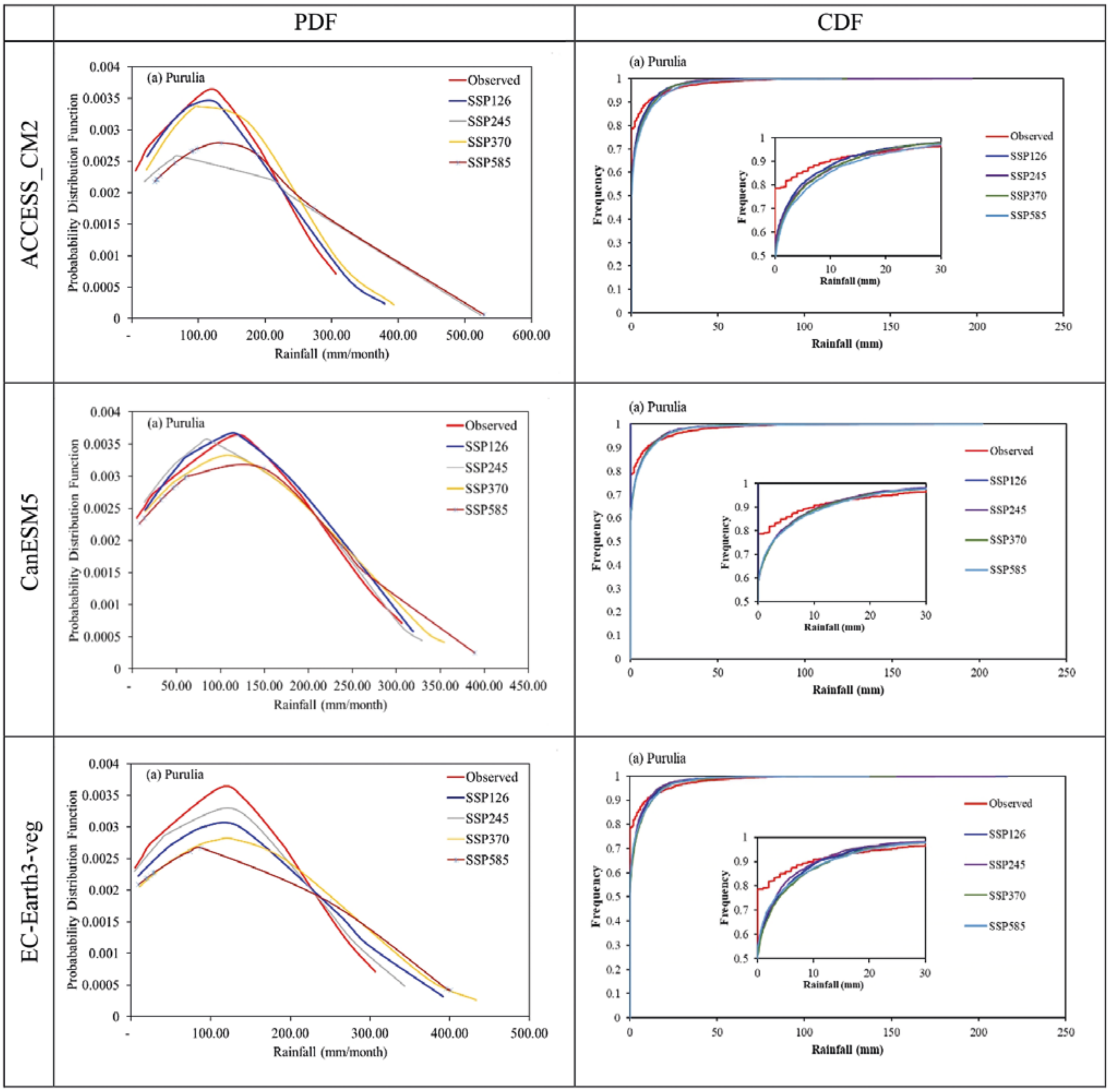

Fig. 3a Comparison of PDF and CDF plots of monthly variation of Observed data and 3 models for Purulia during the period 2015–2022.

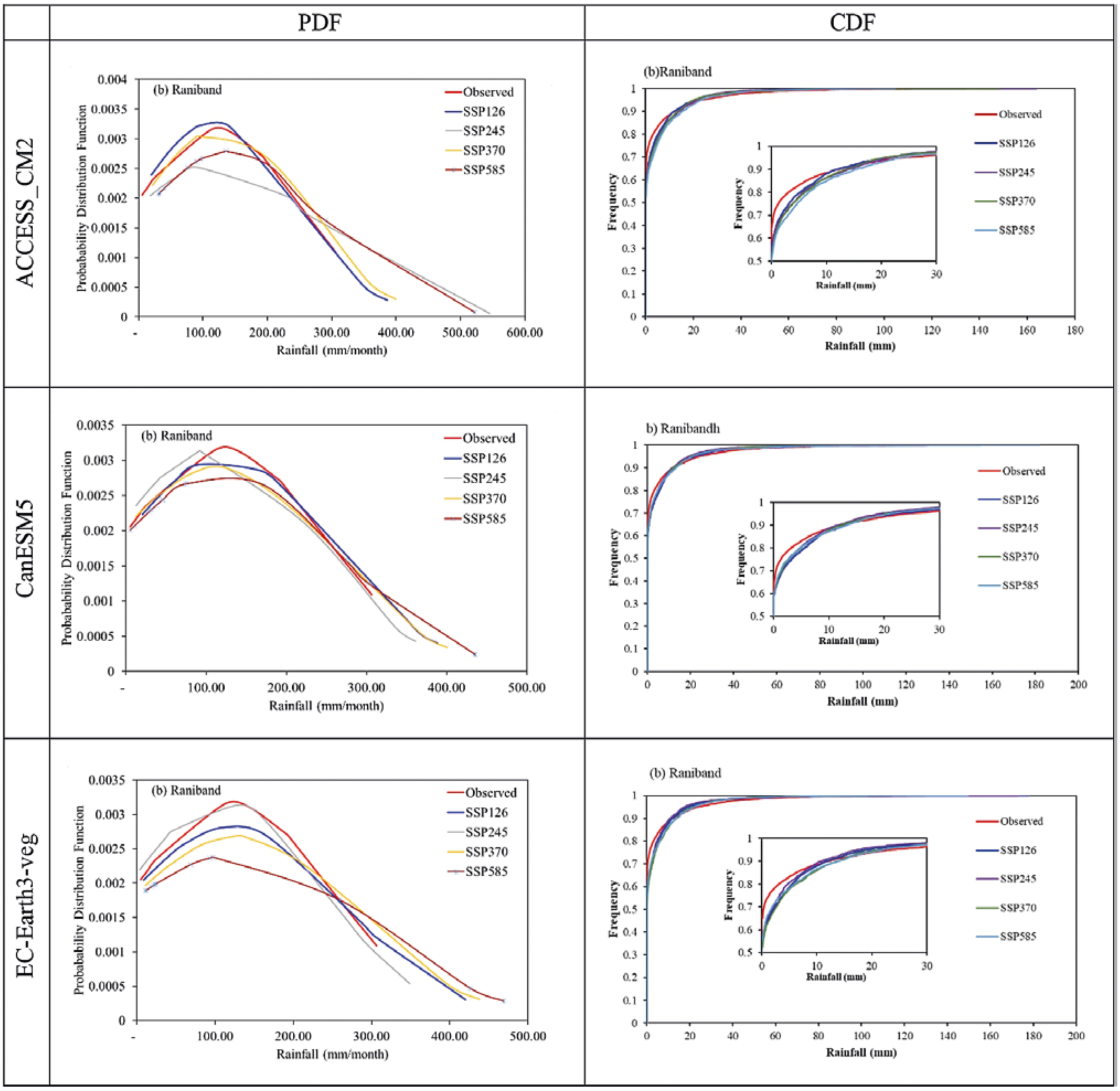

Fig. 3b Comparison of PDF and CDF plots of monthly variation of observed data and 3 models for Ranibandh during the period 2015–2021.

can provide information on the spatial and temporal variability of precipitation, as well as its trends and anomalies. It can support hydrological modelling and forecasting, climate monitoring and analysis, agricultural and water resource management, and disaster risk reduction and humanitarian response.

Here the spatio-temporal changes in rainfall of observed data and model data with four scenarios of each model has been analysed using the monthly average data of monsoon season i.e. June to September from 2015 to 2022 for Purulia and Ranibandh. Three GCM models ACCESS-CM2, CanESM5 and EC-Earth3-veg having four land scenarios namely SSP126, SSP245, SSP370 and SSP585 have been used in the study.

From the analysis of Fig. 2, it is found that among the datasets of three models, EC-Earth3-veg matches more with the observed data of both Purulia and Ranibandh. This alignment implies that EC-Earth3-veg would be better able to represent the regional rainfall variability and local climatic dynamics. Because the model accurately simulates monsoonal precipitation, it may be able to reproduce actual rainfall patterns due to its detailed depiction of atmospheric processes and land-atmosphere interactions.

3.2 Comparison of PDF and CDF

The probability density function (PDF) and cumulative distribution function (CDF) of rainfall for each year at two stations are plotted and shown in Fig. 3. A comparison of the probabilities shows good agreement between the IMD and model data. PDF plots were generated to compare the observed data with climate rainfall data for two stations over the period from 2015 to 2022 for Purulia and 2015 to 2021 for Ranibandh. These plots provide insights into the mean and variance of the chosen data and allow for a visual comparison between the observed and climate-derived rainfall (Fig. 3a and 3b). The PDF plots were constructed by plotting the range of rainfall intensity on the x-axis, measured in millimetres per month, and the corresponding frequency of events falling within each range of rainfall intensity on the y-axis.

Figures 3a and 3b shows that the models ACCESS-CM2 and EC-Earth3-veg, under scenarios SSP126 and SSP370 for both Purulia and Ranibandh, are very close to the observed datasets, indicating that most of the rainfall datasets lie in the range of 100 to 200 mm/month. The observed agreement between the modelled and actual data indicates that the chosen climate models are capable of accurately simulating the features of regional rainfall. Understanding long-term climate trends and evaluating the possible effects of climate change on precipitation patterns in Purulia and Ranibandh depend on this agreement. Furthermore, these models well reflect the central tendency and variability of rainfall distribution, as evidenced by the similarity in mean and variance between the observed and modelled datasets. All things considered, the PDF analysis clearly validates climate models' ability to replicate past rainfall patterns for these two locations. These models may be used to confidently predict future rainfall variability under various climate change scenarios, as evidenced by the high degree of agreement between observed and modelled data. The CanESM5 model also shows a significant correlation with the observed datasets under all examined scenarios. The accuracy of this model in replicating the regional rainfall distribution is further supported by the CanESM5 simulations' preponderance of rainfall falling between 100 and 200 mm/month. The reliability of these estimates is demonstrated by the consistency of trend across several climate models and scenarios.

The CDF analysis further highlights the differences in maximum daily rainfall values between observed

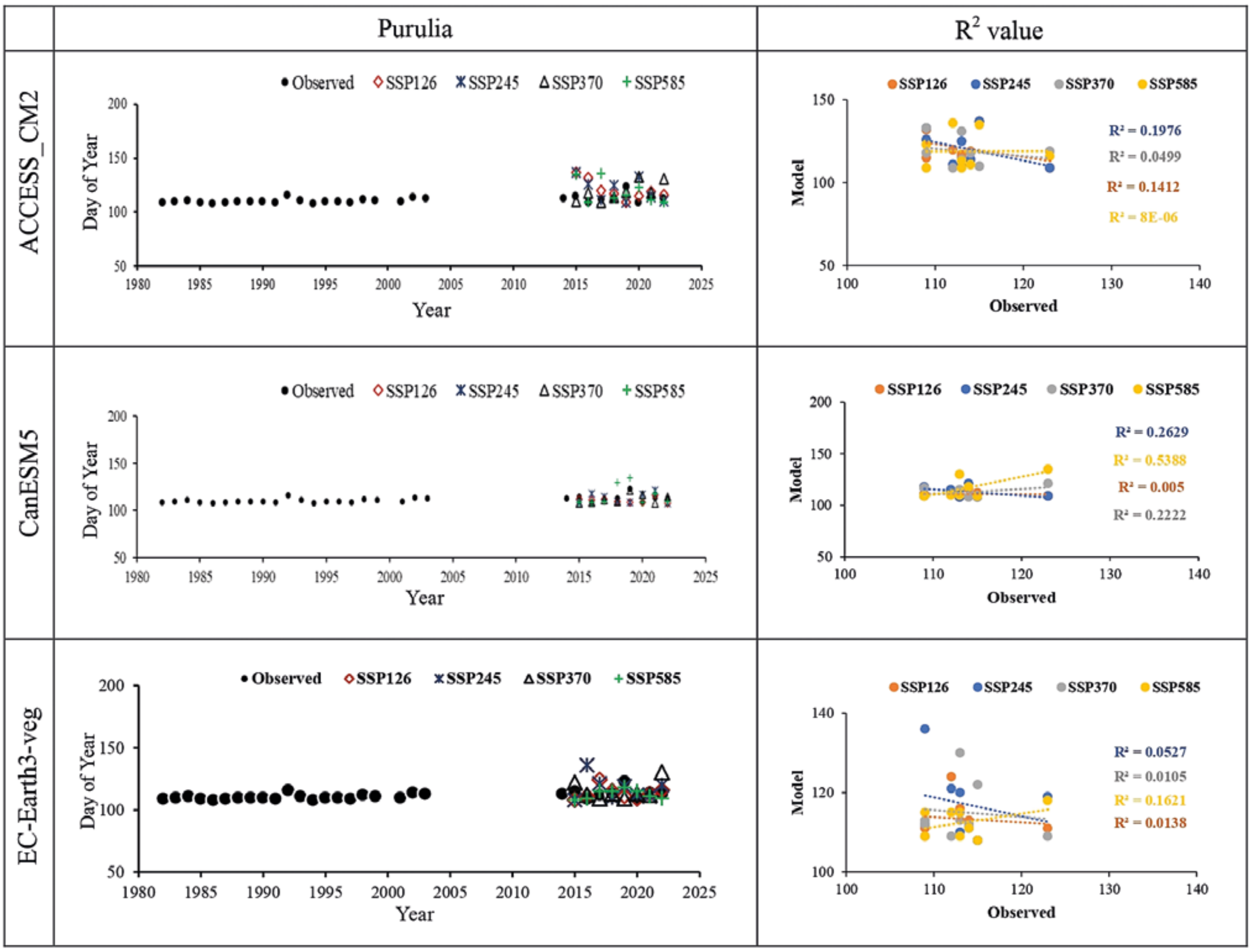

Fig. 4a Monsoon season onset plot of observed and model data for Purulia and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2022.

and modelled datasets. It represents the probability that the precipitation value falls below a certain threshold. The CDFs of observed daily rainfall and the raw datasets from three climate models are plotted for Purulia, as shown in Figure 3a and 3b. The magnitudes of the CDFs from ACCESS-CM2, CanESM5, and EC-Earth3-veg are much higher than the observed CDF, especially for the maximum cumulative distribution. This is because the three climate models produce higher maximum daily rainfall, as shown earlier. Thus, EC-Earth3-veg exhibits a larger maximum CDF rainfall value (Max rain = 216.71 mm), CanESM5 (Max rain = 201.82 mm) surpasses ACCESS-CM2 (Max rain = 197.06 mm), and the observed data (Max rain = 175 mm) for Purulia and CanESM5 exhibits a larger maximum CDF rainfall value (Max rain = 181.75 mm), EC-Earth3-veg (Max rain = 177.98 mm) surpasses ACCESS-CM2 (Max rain = 163.93 mm), and the observed data (Max rain = 129.30 mm) for Ranibandh. This discrepancy indicates that extreme rainfall events are often overestimated by climate models, which should be taken into account in upcoming assessments of the effects of climate change and adaptation plans.

3.3 Onset of Monsoon

Generally, there is no coherent spatial pattern to monsoon onset or withdrawal based on precipitation, a finding consistent with other monsoon regions (Marteau et al., 2009). While the absence of any spatially coherent monsoon advancement or retreat may seem unusual, it's worth noting that our study domain is much smaller than that of many monsoon studies.

The onset day for each year of the observed data i.e. from 1982 to 2022 and 1990 to 2021 has been plotted along with a comparison made between the observed and the 3 climatic model data for 4 scenarios in Purulia and Ranibandh respectively. The graphic representation of this data along with the R^2 value obtained for each scenario of the 3 models for Purulia and Ranibandh locations are shown in Fig. 4a and Fig. 4b.

The R^2 values were calculated for onset of monsoon data for Purlia and Ranibandh stations and is shown in Tab. 2 (rounded off to two decimals). In Purulia, under the SSP585 scenario of CanESM5 model, a notably higher R^2 value of 0.54 is observed, surpassing all other datasets of ACCESS_CM2 and EC_Earth3-veg

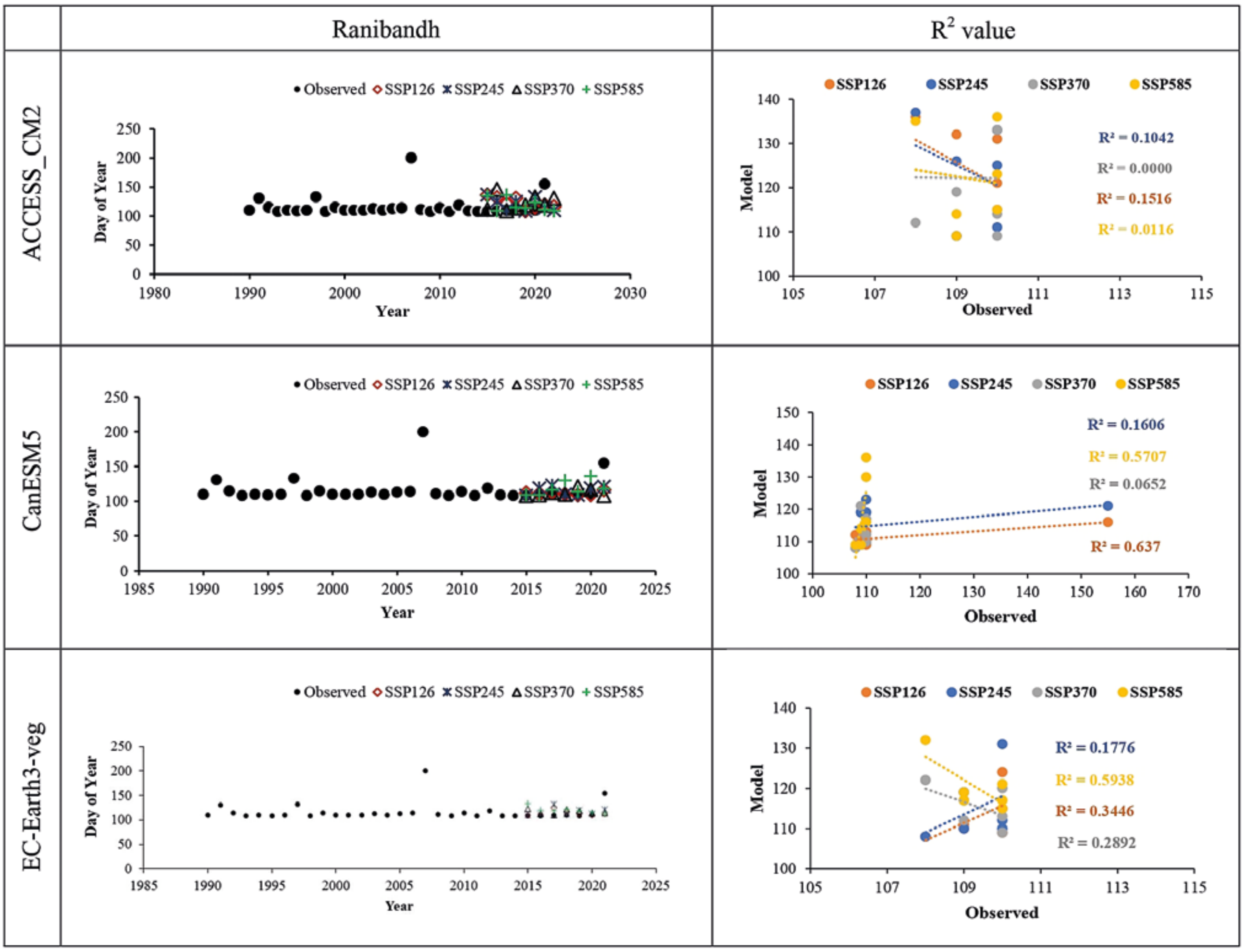

Fig. 4b Monsoon season onset plot of observed and model data for Ranibandh and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2021.

Tab. 2 The R^2 values for Purulia and Ranibandh for Onset of Monsoon data.

		SSP126	SSP245	SSP370	SSP585
Purulia	ACCESS_CM2	0.1400	0.20	0.05	0.000008
	CanESM5	0.0050	0.26	0.22	**0.540000**
	EC_Earth3-veg	0.0100	0.05	0.01	0.160000
Ranibandh	ACCESS_CM2	0.1500	0.10	0.00	0.010000
	CanESM5	**0.6400**	0.16	0.07	0.570000
	EC_Earth3-veg	0.3500	0.18	0.29	0.590000

Tab. 3 The R^2 values for Purulia and Ranibandh for Withdrawal of Monsoon data.

		SSP126	SSP245	SSP370	SSP585
Purulia	ACCESS_CM2	0.0400	0.09	0.24	0.0042
	CanESM5	0.0600	0.24	0.14	0.1400
	EC_Earth3-veg	0.2900	0.08	0.05	**0.7500**
Ranibandh	ACCESS_CM2	0.2900	0.11	0.16	0.5100
	CanESM5	0.0002	0.24	0.05	0.3700
	EC_Earth3-veg	**0.5600**	0.27	0.09	0.1200

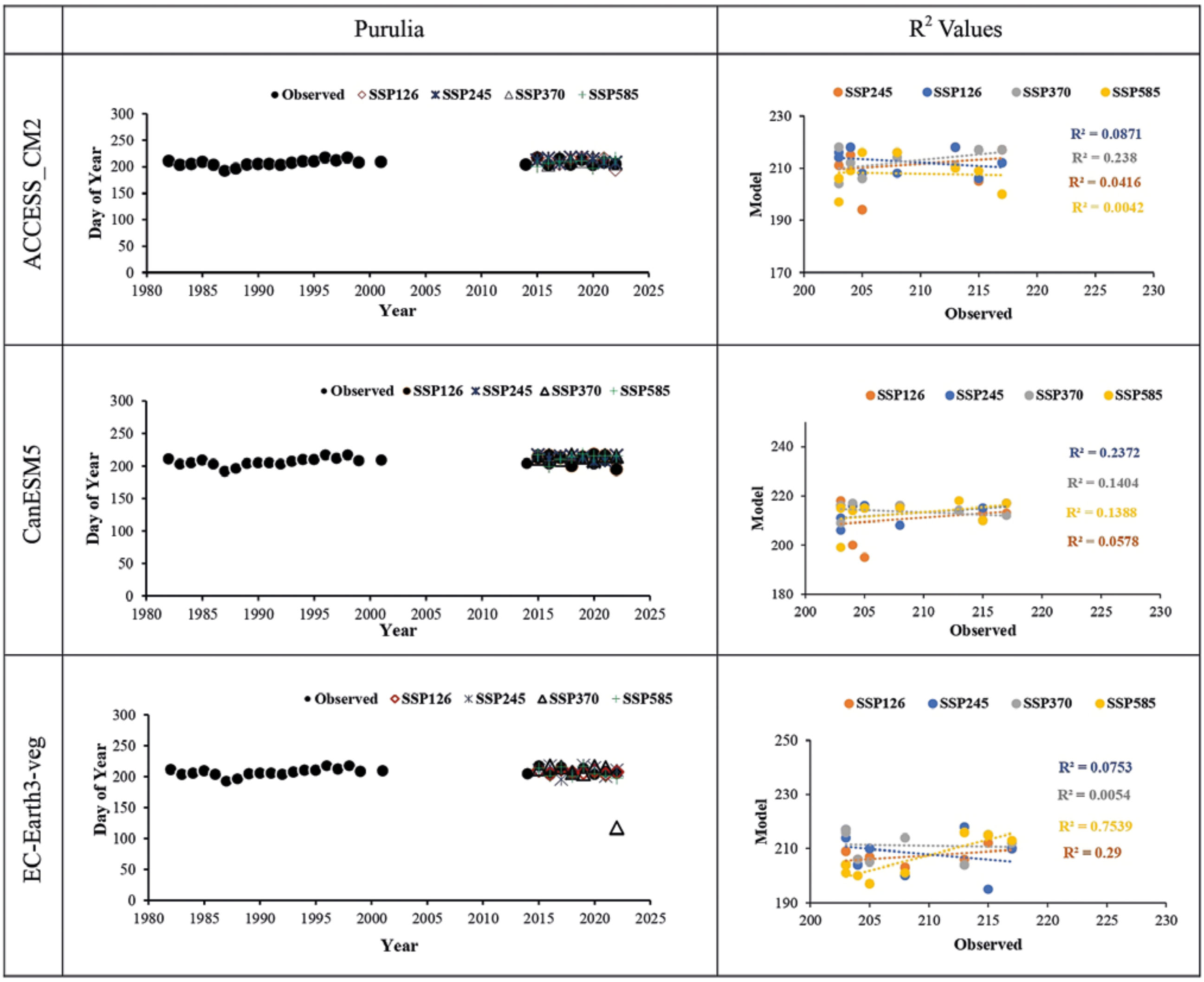

Fig. 5a Monsoon season withdrawal plot of observed and model data for Purulia and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2022.

model. This higher value indicates a strong and positive relationship between the observed onset days and model data in the Purulia region. The superior performance of CanESM5 over the other models may be attributed to its advanced representation of climate processes and interactions, which could be particularly relevant in the context of the socio-economic and environmental conditions prevalent in Purulia. Similarly, in the Ranibandh region, the R^2 value reaches 0.64 under SSP126 scenario for CanESM5 model, surpassing all other models.

This elevated value indicates a robust and significant relationship between the model and observed data in the Ranibandh region. Overall, these findings underscore the varying degrees of relationship strength observed across different climate models in the specified scenarios, with moderate to strong associations between the observed and modelled data of CanESM5 in Purulia and Ranibandh for SSP585 and SSP126 respectively.

3.4 Withdrawal of Monsoon

Similar to the onset day, withdrawal day for each year of the observed data i.e. from 1982 to 2022 and 1990 to 2021 has also been plotted along with a comparison made between the observed and the 3-model data for 4 scenarios in Purulia and Ranibandh respectively. The graphic representation of this data along with the R^2 value obtained for each scenario of the 3 models is shown in Fig. 5a and Fig. 5b.

The R^2 values were calculated for withdrawal of monsoon data for Purlia and Ranibandh stations and is shown in Tab. 3 (rounded off to two decimals). In the case of withdrawal, in both Purulia and Ranibandh, the data set of EC-Earth3-veg with R^2 value of 0.75 in Purulia under the scenario SSP585 and 0.56 in Ranibandh under the scenario SSP126, surpasses all other model datasets. The R^2 value of 0.74 and 0.56 suggests a strong and positive relationship between the observed and model data in the scenario of

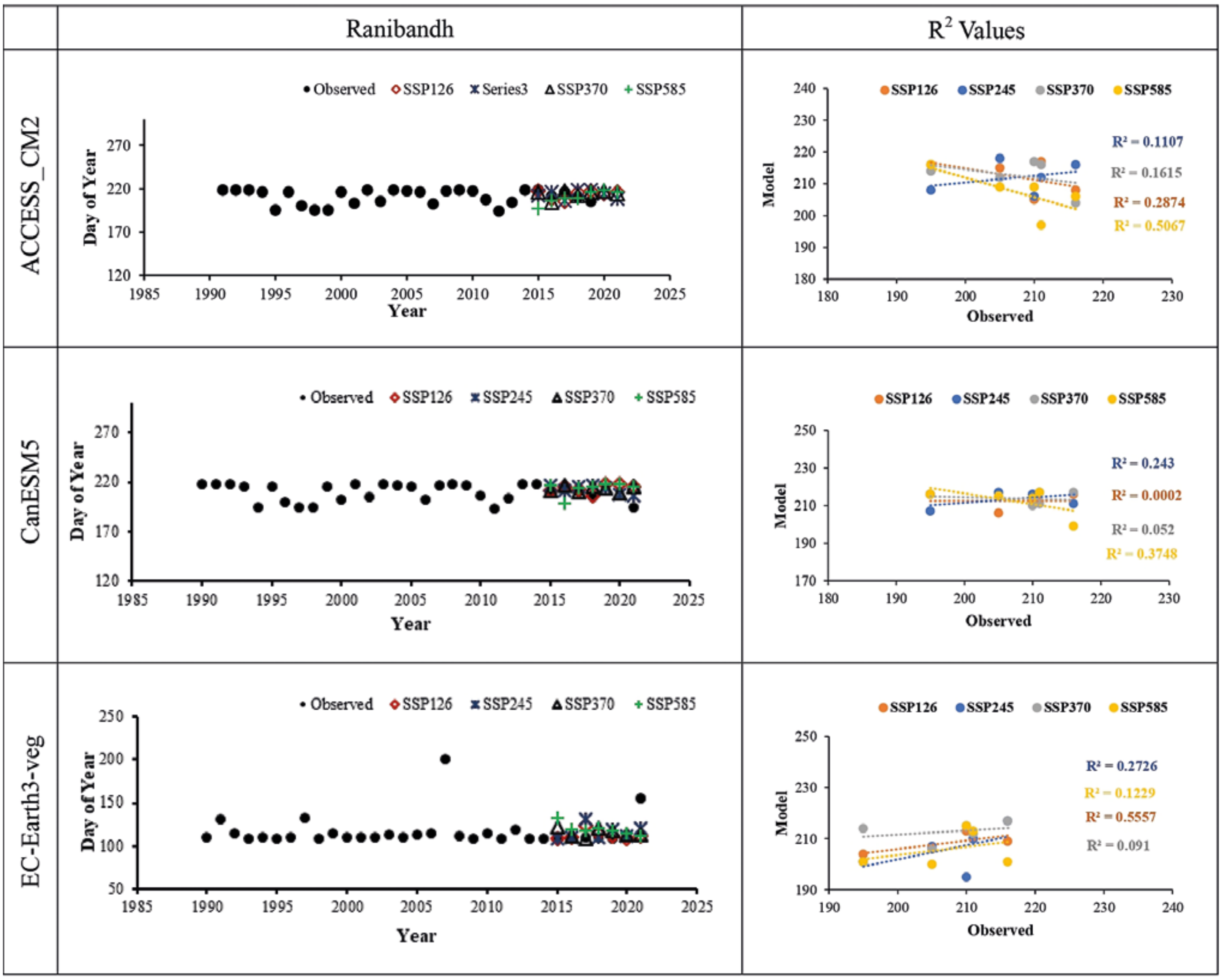

Fig. 5b Monsoon season withdrawal plot of observed and model data for Ranibandh and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2021.

SSP585 and SSP 126 respectively. Overall, these findings underscore the varying degrees of relationship strength observed across different climate models in the specified scenarios, with notable instances of moderate to strong associations between the observed and modelled data.

3.5 Analysis of Monsoon period

The duration of each monsoon period per year is calculated by subtracting the onset date from the withdrawal date. The monsoon period obtained for the observed data is compared with the model data for both Purulia and Ranibandh location points, as per Fig. 6a and Fig. 6b.

In the examination of the duration of rainy days, the Ranibandh station, as simulated by the ACCESS_CM2 model under the SSP126 scenario, yields an R^2 coefficient of 0.46 (Tab. 4), indicating a considerable degree of explanatory power between the observed and modelled datasets. Transitioning to the Purulia region, under the CanESM5 model SSP370 scenario,

Tab. 4 The R^2 values for Length of Rainy Days in Purulia and Ranibandh.

		SSP126	SSP245	SSP370	SSP585
Purulia	ACCESS_CM2	0.002	0.1032	0.1200	0.360
	CanESM5	0.210	0.3300	**0.5400**	0.100
	EC_Earth3-veg	0.170	0.3300	0.0025	0.011
Ranibandh	**ACCESS_CM2**	**0.460**	0.0200	0.1300	0.290
	CanESM5	0.063	0.1930	0.0250	0.042
	EC_Earth3-veg	0.108	0.2500	0.1360	0.002

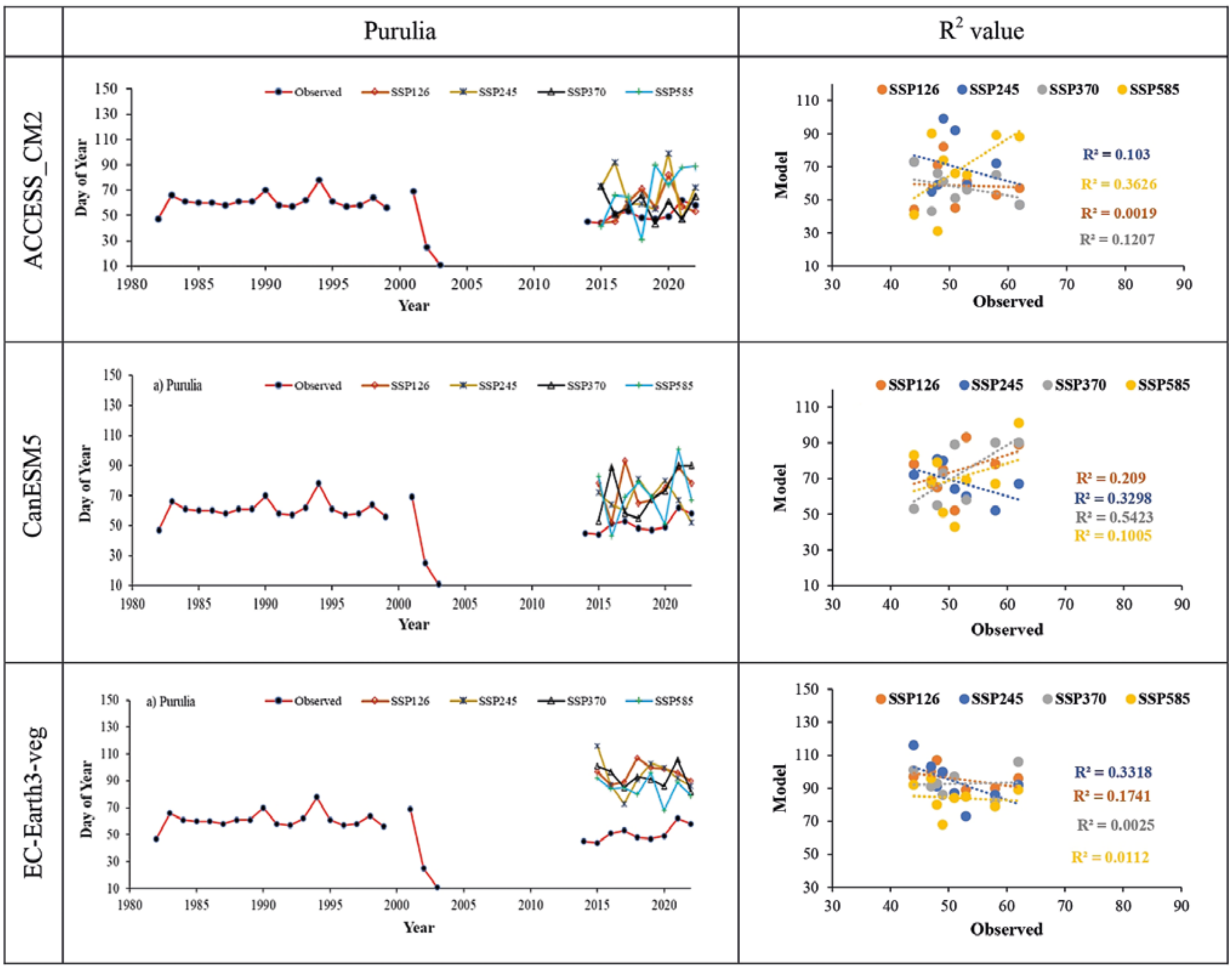

Fig. 6a Monsoon season length plot of observed and model data for Purulia and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2022.

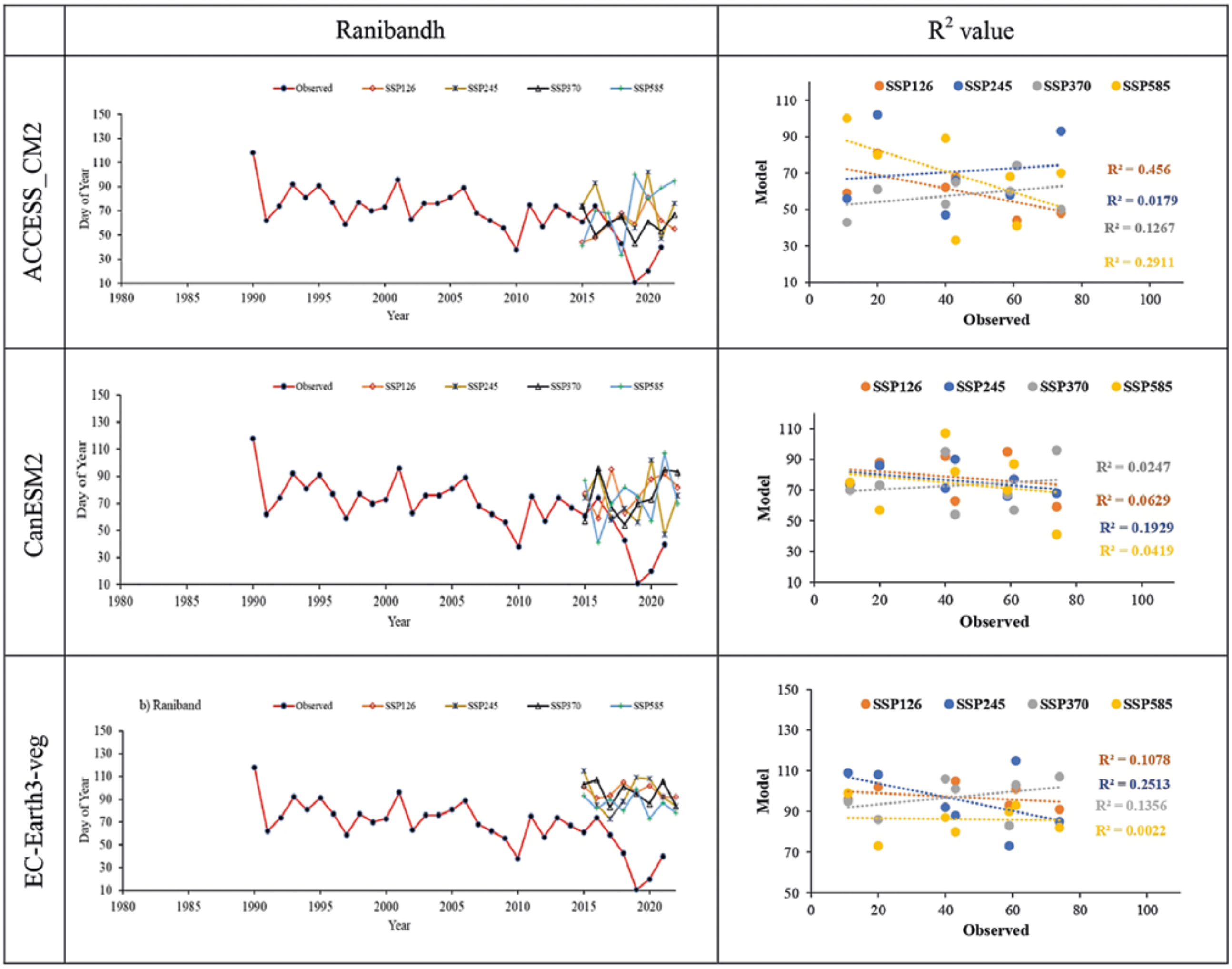

Fig. 6b Monsoon season length plot of observed and model data for Ranibandh and correlation (R^2) plots between the observed data sets and climatic model datasets for the time period 2015–2021.

a notably elevated R^2 coefficient of 0.54 is discerned, surpassing those within the ACCESS_CM2 model datasets. The high R^2 value denotes very good relationship between the observed and modelled data specifically within the Purulia domain.

3.6 RMSE plot for Monsoon Onset, Withdrawal and Monsoon period

Root Mean Square Error (RMSE) between observed and model data concerning monsoon onset days, monsoon withdrawal days, and the length of rainy days were calculated and is plotted in Fig. 7.

From Tab. 5 for monsoon onset, ACCESS-CM2 model under the scenario SSP245 exhibits highest RMSE value with RMSE value of 14.57 days in Purulia and 22.57 days in Ranibandh. For length of rainy days, the model EC_Earth3_veg in the scenario SSP126 and 245 exhibits highest RMSE value of 45 days and 60 days in Purulia and Ranibandh respectively. While for monsoon withdrawal, EC_Earth3-veg in the scenario SSP585 exhibits highest RMSE value of 10.5 days in Purulia and CanESM5 in the scenario SSP585 exhibits a value of 13.28 days.

Higher RMSE value like this suggests a significant discrepancy between the model predictions and the observed onset of the monsoon. This discrepancy is attributed to its representation of heavier rainfall compared to the Kangsabati river basin, resulting in larger errors across all models.

Conversely, in Purulia and Ranibandh respectively, the model dataset of CanESM5 displays lowest RMSE values i.e. lowest value of 4.5 days and 15 days for monsoon onset, EC-Earth3-veg model gives the lowest RMSE values of 4.3 days and 5.3 days for withdrawal while model ACCESS_CM2 gives reduced RMSE values of 14 days and 24 days, indicating a closer agreement between model predictions and observed rainfall data. Under the SSP585 scenario, the EC-Earth3-veg model and under the scenario SSP370, the CanESM5 model closely approximates observed values, highlighting its effectiveness in simulating monsoon water withdrawal and monsoon length in the Kangsabati basin in Purulia and Ranibandh.

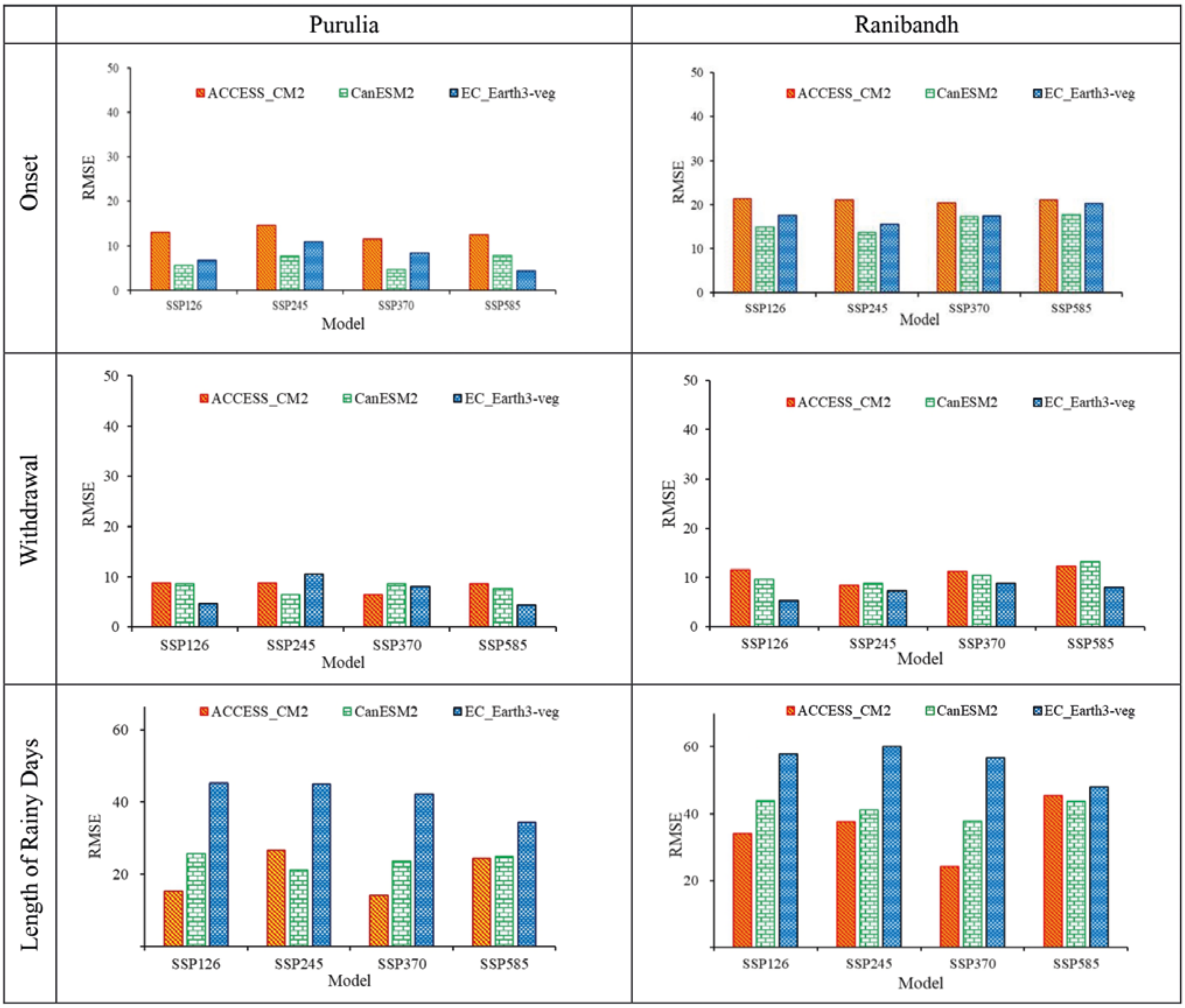

Fig. 7 Bar plot of the RMSE for each climatic model with the Observed rainfall data during the period 2015–2022 for Purulia and 2015–2021 for Ranibandh locations.

Tab. 5 Highest and Lowest RMSE Values for Monsson onset, withdrawal and length of rainydays.

	Purulia		Ranibandh	
	Highest RMSE	Lowest RMSE	Highest RMSE	Lowest RMSE
Onset	ACCESS_CM2, SSP245 (14.57)	CanESM5, SSP370 (4.5)	ACCESS_CM2, SSP245 (22.57)	CanESM5 SSP126 (15)
Withdrawal	EC_Earth3_veg, SSP245 (10.5)	EC_Earth3_veg, SSP585 (4.3)	CanESM5, SSP585 (13.28)	EC_Earth3_veg, SSP126 (5.3)
Length of rainy days	EC_Earth3_veg, SSP126 and SSP245 (45)	ACCESS_CM2, SSP370 (14)	EC_Earth3_veg, SSP245 (60)	ACCESS_CM2, SSP370 (24)

3.7 Projected precipitation changes for the onset, withdrawal and length of rainy days

From the analysis of the results, the best performing CMIP6 GCM for Monsoon onset for Purulia is CanESM5 in the scenario SSP585 and for Ranibandh is CanESM5 in the scenario SSP126. Hence the projected onset days of particular years have been plotted with the selected models only and is shown in Fig. 8. The plot shows that there are regular fluctuations in the onset days of Purulia with days ranging from 108 to 125 days. In Ranibandh, the onset days fluctuations are evident after the year 2060, which ranges from 108 to 137 days. A slight increase in the onset period is observed for both sites, indicating a slight shift of the monsoon period.

For withdrawal, the best performing CMIP6 GCMs for Monsoon Withdrawal are EC-Earth3-veg in the

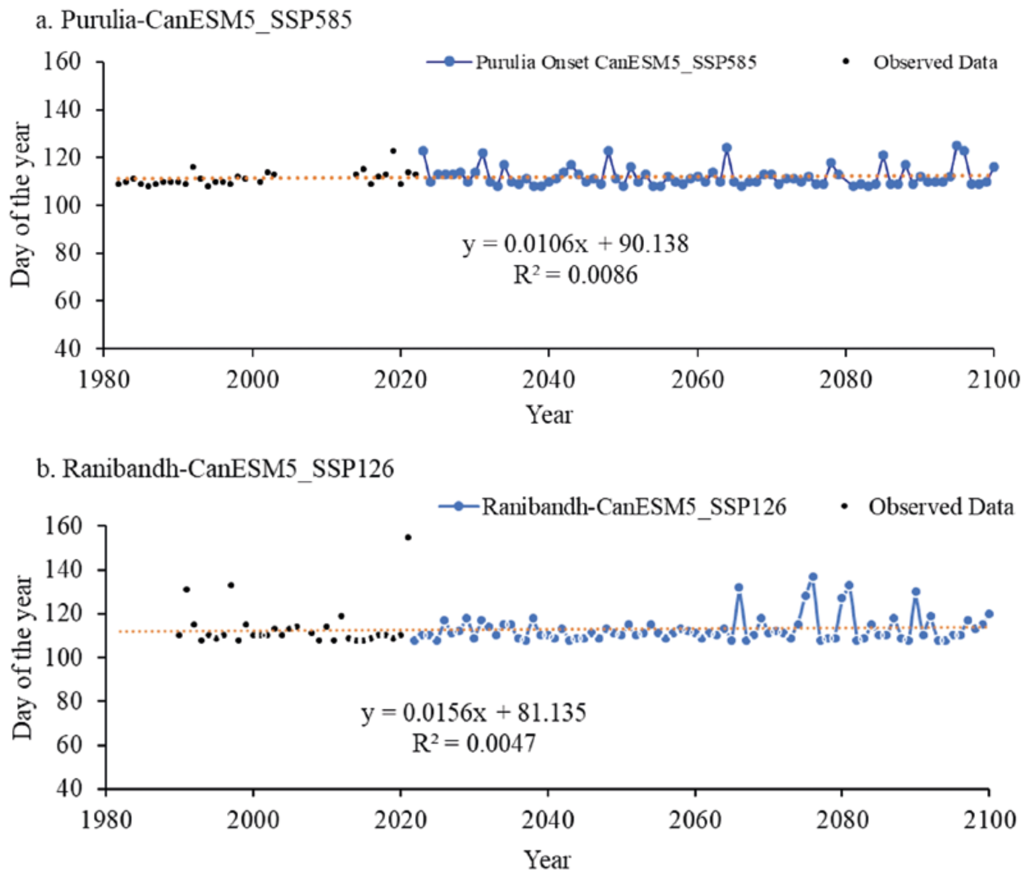

Fig. 8 Plot of onset days for the projected time period 2023–2100 for Purulia and 2022–2100 for Ranibandh locations.

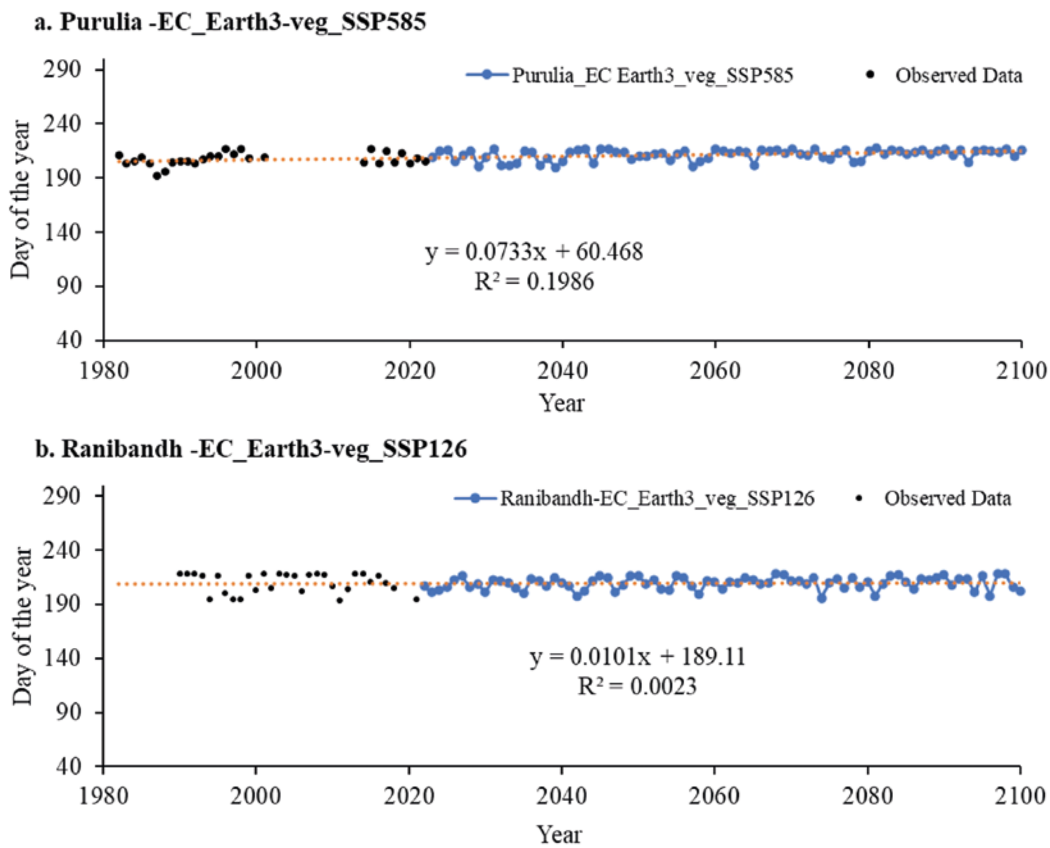

Fig. 9 Plot of withdrawal days for the projected time period 2023–2100 for Purulia and 2022–2100 for Ranibandh locations.

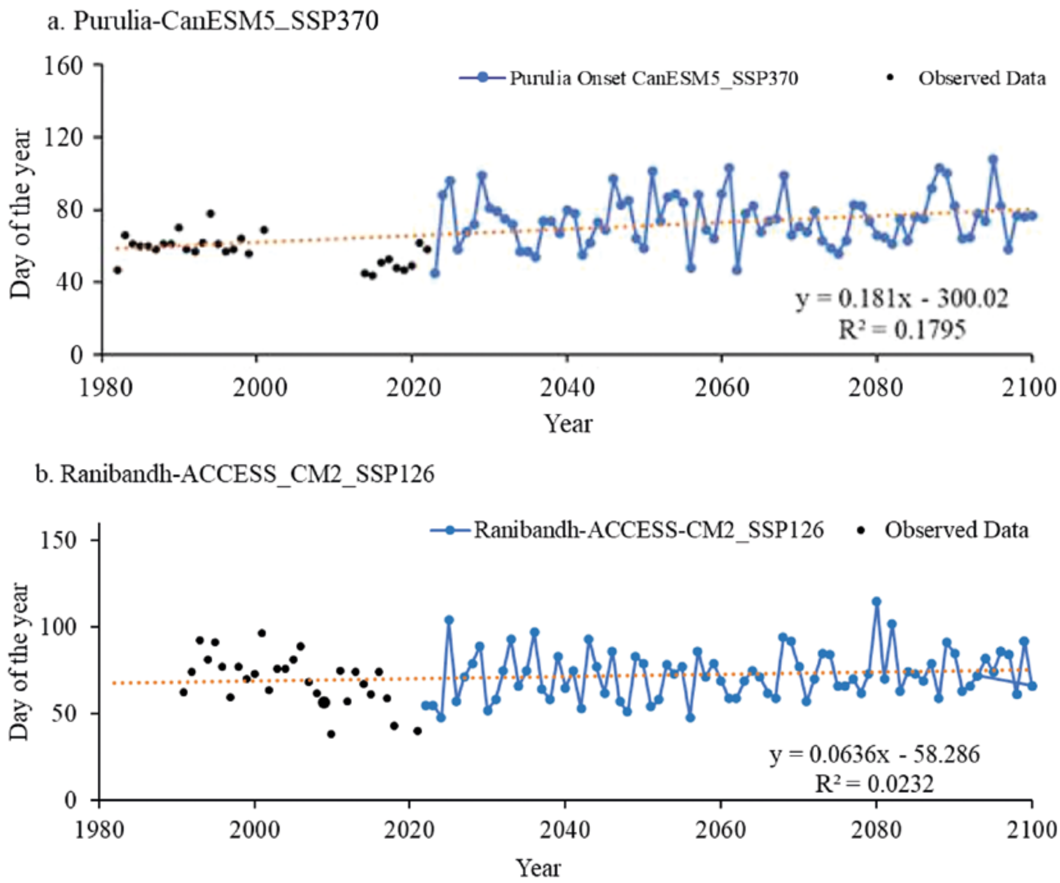

Fig. 10 Plot of number of rainy days in the length of rainy days for the projected time period 2023–2100 for Purulia and 2022–2100 for Ranibandh locations.

scenario SSP585 for Purulia and EC_Earth3_veg in the scenario SSP126 for Ranibandh. As shown in Fig. 9, a slight increase in the withdrawal period is observed for both sites, this indicates a shift of the monsoon period.

From the previous results, it has been observed that the best performing CMIP6 GCM models for number of rainy days in monsoon period are CanESM5 in the scenario SSP370 and ACCESS_CM2 in the scenario SSP126 for Purulia and Ranibandh respectively. The fluctuations are very evident for both stations.

The plot shows that there are large fluctuations in the number of rainy days of Purulia with days ranging from 45 to 108 days. In Ranibandh, also there is large fluctuations in the number of rainy days ranges from 48 to 115 days. From Fig. 10 the overall trend line for number of rainy days is increasing. For Fig. 8, Fig. 9 and Fig 10, the dotted line indicates the trend of datasets of onset days, withdrawal days and the length of rainy days during the time period 1982–2100 for Purulia and 1990–2100 for Ranibandh locations.

4. Conclusions

The comparison of probability density functions (PDF) and cumulative distribution functions (CDF) demonstrates a commendable agreement between observed and modelled rainfall data, highlighting the reliability of models like ACCESS-CM2, CanESM5, and EC-Earth3-veg in capturing rainfall intensity over the study duration. Our findings reveal intriguing patterns in climatological dates for monsoon onset and withdrawal across different climate models. Despite the lack of a coherent spatial pattern in monsoon advancement or retreat, averaging onset, withdrawal, and monsoon season length across all stations facilitates meaningful comparisons against other climate datasets. The nuanced nature of the relationships between observed and modelled data underscores the complexity of climate modelling, with varying degrees of relationship strength identified across different models and scenarios.

For onset, withdrawal and duration of monsoon period, under the scenario SSP585 and SSP126, highest R^2 value of 0.5388 and 0.6370, 0.7539 and 0.5557 and 0.5423 and 0.4560 has been observed for CanESM5, EC-Earth3-veg and ACCESS-CM2 for Purulia and Ranibandh respectively. While for duration of monsoon period between onset and withdrawal, R^2 value of 0.5423 and 0.4560 has been observed for CanESM5-SSP370 and ACCESS_CM2-SSP126 for Purulia and Ranibandh. On the other hand, for Purulia and Ranibandh, the lowest RMSE values has been observed for the model CanESM5, EC-Earth3-veg and ACCESS-CM2 for onset, withdrawal and monsoon length.

Thus, among the 3 CMIP6 GCM models, the best performing models, i.e the models which exhibit closer agreement with observed rainfall data in simulating monsoon dynamics in the Kangsabati basin for onset, withdrawal and monsoon length, in Purulia and Ranibandh are CanESM5, EC-Earth3-veg and ACCESS-CM2. With these best performing models on projecting the precipitation for 2023 to 2100 for Purulia and 2022 to 2100 for Ranibandh, a very negligible shift has been observed in the onset and withdrawal periods.

The analysis reveals varying relationship strengths between observed and modelled data, emphasizing the significance of these models in capturing onset and withdrawal patterns under different scenarios. Furthermore, the analysis of rainy day duration highlights significant correspondence between observed and modelled datasets, particularly in specific regions and model configurations. However, the variations in R^2 values across different models and scenarios emphasize the need for careful consideration of model performance in different contexts. The visualization of RMSE for monsoon onset, withdrawal, and duration of monsoon period provides valuable insights into model performance. Across all scenarios, discrepancies in the representation of rainfall are evident, with some models displaying higher RMSE values. Conversely, certain models, such as CanESM5, EC-Earth3-veg under the SSP585 and SSP126 scenario, exhibit closer agreement with observed rainfall data in Purulia and Ranibandh, highlighting their effectiveness in simulating monsoon dynamics in the Kangsabati river basin.

Overall, this study contributes to our understanding of rainfall patterns and monsoon dynamics, offering valuable insights for both climate modelling and water resource management in the region. Further research is warranted to refine model outputs and improve our understanding of the complex interactions driving rainfall variability. The future scope of this study includes refining climate models to enhance the accuracy of rainfall simulations and better capture monsoon dynamics. Further exploration of model uncertainty and the integration of observational data could improve confidence in projected rainfall patterns and their implications for water resource management. Engaging stakeholders and fostering interdisciplinary collaboration are crucial for translating research findings into actionable strategies for adaptation and policy development.

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