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ARTICLE

Sub-Seasonal Variability of Summer Monsoon Rainfall in CMIP6 Simulation over the Gangetic Plain of India

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ABSTRACT

This current research work is focused on the performance of the Coupled Model Intercomparison Project (CMIP6) models in replicating Indian Summer Monsoon (ISM) rainfall patterns, mainly focusing on the Gangatic Plain, spanning from 1979 to 2014. The evaluation employs rigorous validation against rainfall data from the Indian Meteorological Department (IMD) and includes models with a resolution of 100km or less. Results highlight three standout models—CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2—for their commendable accuracy in capturing rainfall distribution in the Gangatic Plain. Monthly assessments reveal that these models closely mimic observed rainfall, unlike other models such as CMCC-CM2-HR4, CNRM-CM6-1-HR, EC-Earth3-CC, and MPI-ESM1-2-HR, which fail to replicate observed rainfall patterns. The simulated seasonal cycle of rainfall in CMCC-CM2-SR5 aligns well with observed patterns, especially for July, August, and September. Although there are some amplitude differences, CMCC-CM2-SR5 accurately represents the range and median of observed rainfall during these months. Interannual fluctuations in mean rainfall during the JJAS period can also be derived from observed data. Furthermore, CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2 successfully capture interannual variability in July, August, and September, indicating substantial rainfall variability on a sub-seasonal scale across the Indian subcontinent. However, the assessment emphasizes the need for improved accuracy in depicting rainfall variability in CMIP6 models to bridge existing gaps between simulated and observed rainfall. Nevertheless, the study emphasizes the ongoing necessity for enhancements to ensure more accurate simulations and a closer match to actual rainfall variability in the examined CMIP6 models.

Keywords: Coupled Model Intercomparison Project Phase 6; Indian Summer Monsoon; Gangatic Plain; Indian Meteorological Department; Rainfall Patterns; Resolution

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1. Introduction

The Indian Summer Monsoon (ISM), the lifeline of the Indian Economy, remains for four months i.e. June-July-August-September (JJAS) over India because of the land-sea heating contrast between the Indian Ocean and a large Indian land mass. Of all the monsoon systems discovered worldwide, the ISM is the fastest and most potent [1].

The variability is shown in IMS in timespans ranging from Intraseasonal to Interannual [2], and around 80% of the rainfall produced during ISM (JJAS) and rainfall extremes i.e. Floods and droughts are caused by irregular pattern of rainfall during ISM, especially over the Indian subcontinent's northern plains, and have had a significant impact on the use of water resources with agriculture. The geographical and temporal variability of rainfall has been predicted to vary in recent decades, although there has been no discernible effect of global warming on the long-term series of All India Summer Monsoon Rainfall [3–5]. However, a notable pattern is seen at the regional level [6,7]. The AMIP stands for Atmospheric Model Inter-comparison Project, which carried out the global model inter-comparison work that started in the late 1980s [8–10]. In previous studies, researchers [9,11–19] have looked at how well climate models simulate rainfall variability. The inherent bias [20] is employed in 20 Atmospheric Global Circulation Models (AGCMs) operating under the Atmospheric Model Intercomparison Project (AMIP), and their analysis demonstrated that models are not yet advanced enough to reproduce year-to-year variation in Indian Summer Monsoon Rainfall (ISMR) [21]. However, modeling studies have been conducted to explore future summer monsoon rainfall patterns across different emission scenarios. In evaluating the climate models, the ISMR shows little change [22–24]. Coupled Model Inter-comparison Project (CMIP) tests using climate models have also been conducted [14,25–28]. For control runs and idealized 1% per year CO_2 rise experiments in climate models in the 1990s, the World Climate Research Programme (WCRP) coordinated CMIP [28]. The CMIP underwent many further stages, known as CMIP2 and CMIP2+ [25,27,29]. In Coupled Model Intercomparison Phase 3 (CMIP3), the changes in East Asian monsoon mean precipitation and its variability and using the t-test and F-ratio, respectively, to assess their statistical significance [30]. For CNRM-CM3 and UKMOHadCM3, the variations in mean precipitation ranged from 0.6% to 14%. In addition, they looked at the variability of precipitation during the Summer Monsoon in South Asia in IPCC models Assessment Report 4 (IPCC AR4) [31]. Out of the twenty-two (22) models of the IPCC AR4 that could capture 500–900 mm of precipitation in the summer monsoon season, only nineteen (19) models did so. This simulated mean precipitation ranges between 500 and 900 with a 3 to 13% coefficient of variance in the IPCC AR4 report. Under a CO_2 doubling scenario, an eight percent rise in the average amount of monsoon precipitation is anticipated. In scenarios B1, A1B, and A2, the CMIP3 data collection was used to explore how the South Asian summer monsoon might react to a temporary increase in future human radiative forcing during the years 2031–2050 and 208–1100 [32]. Selected ten (10) models' predictions of seasonal monsoon rainfall variations revealed an uptick in precipitation across the southern regions of India and the western equatorial Indian Ocean [33]. The potential upcoming modifications to ISMR in CMIP3 data for the A2, B1, and A1B scenarios [34]. The suppression of ISMR going forward owing to the degradation concerning the monsoon circulation using a high-resolution nested model [35]. Using CMIP5 and CMIP3 data, research is being carried out when the Indian Summer Monsoon arrives in a variety of approaches. A 3.2%/K rise in global mean precipitation is seen in CMIP5, the RCP 4.5 experiment (2075–1999), and there is a greater increase in annual mean precipitation across the Asian monsoon area than in CMIP3 models [36]. The global monsoons in an atmosphere-ocean general circulation model that is completely connected and proposed the intensification of summer monsoons in the future in light of the growing moisture under CO_2 forcings [37]. The rainfall patterns in monsoon regions under different radiative forcings protected for the 21st century of CMIP5 [38]. The complex behavior in the Hamburg COSMOS models, including changes in rainfall distribution skewness and an increase in episodes of monsoon failure [39]. The climate model performance in reproducing observed ISMR variability in CMIP5 data and predicted ISMR future forecasts [40]. The ISMR variability in 20 CMIP5 models from the mid-19th century to the end of the twenty-first century and concluded that considerable increases in ISMR and sub-seasonal variability would be expected under unrestricted climate change [41,42]. In CMIP5 historical and climate change simulations, the worldwide monsoons, including statistical assessment of changes in the pattern of Asian summer monsoon rainfall [43]. In addition to addressing cyclonic circulation and the resulting ISMR deficit the value of the variability of Northwest Pacific (NWP) circulation in forecasting summer monsoon precipitation across South Asia [44]. The capabilities of CFSv2 in modeling the ISMR and select areas that need significant development for higher Indian summer monsoon forecast skills [45]. To assess advancements in the ability to anticipate outcomes in both the CFSv1 and CFSv2 models given the current beginning circumstances, they have run 30 years' worth of anticipated system outages. Consequently, the model's simulations of Intraseasonal and interannual variability may be evaluated alongside the data. In the future climate, the CMIP6 models display higher sensitivity to greenhouse gas emissions over South Asia compared with the CMIP5 models [46]. The model BCC-CSM2-MR and BCC-ESM1 which are performing well in the Indian peninsula in CMIP5, perform well in CMIP6 also to simulating JJAS rainfall in comparison to recorded precipitation in IMD [47]. It shows that CMIP6 models are far better than CMIP5. The CMIP6 model (BCC-CSM2-MR and BCC-ESM1) performs well in simulating JJAS rainfall contrasted with the IMD rainfall that has been recorded.

In previous studies, the evaluation of ISM rainfall and associated circulation pattern in CMIP6 simulation is not examined on the sub-seasonal scale over the Gangatic plain, although it is an important region of India since rainfall variability largely influences rice production. The present paper evaluates the model's performance in simulating sub-seasonal rainfall over the Gangatic Plain of India. Section 2 contains specifics about the models, data, and experiments while section 3 describes the CMIP6 model's effectiveness of rainfall simulation under Historical Experiments. Section 4 discusses conclusions.

2. Study Area and Data

In the study area, the Gangatic Plain of India comprises meteorological sub-divisions of three states namely Uttar-Pradesh (East), Bihar, and West-Bengal (as shown in **Fig.1**) and monsoon rainfall is analyzed over these areas. The lists of the CMIP6 models used during the historical trial in CMIP6 data are included in **Table 1**. The selection of seven (7) models is based on either nominal surface horizontal resolution of 100km or less, as the area of study is relatively smaller and a greater number of grids may fall over the study area. The Historical experiment incorporates models from 1850 to 2014, which is analogous to the 20th-century simulation (20C3M) of CMIP5 and CMIP3, in which external forcing varying through time and greenhouse gases, the solar constant, ozone, and volcanic activity, CO_2 and aerosols are some of the external driving factors. The 1850–2014 forced data comes from observation. The simulated rainfall during the historical assessment for the years 1979 to 2014 is compared with observed rainfall from The Global Precipitation Climatology Project (GPCP) and the India Meteorological Department (IMD) for the same years to assess the performance of the models in simulating past rainfall. The resolution of the IMD data set is 0.25×0.25 while that of GPCP is less than or equal to 1.0×1.0. Detailed information on the dataset, resolution, and country/institution is provided in **Table 1**.

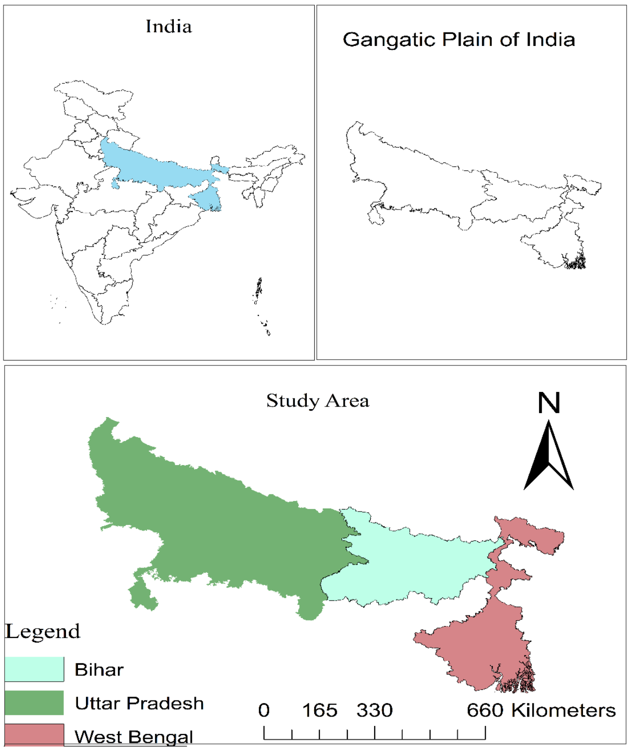

Figure 1. Study area comprising West Bengal, Bihar and Uttar Pradesh.

Table 1. Details of the considered models and observed data.

CMIP-6 Model's Name (Resolution 1 or Less Than 1)	Country's Name	Horizontal Surface Resolution
CMCC-CM2-HR4 [48]	ITALY	1×1
CNRM-CM6-1-HR [49]	FRANCE	0.5×0.5
CMCC-ESM2 [50]	ITALY	1×1
CMCC-CM2-SR5 [51]	ITALY	1×1
EC-EARTH3-ARCCHEM [52]	EUROPE	0.7×0.7
EC-EARTH-3-CC [52]	EUROPE	0.7×0.7
MPI-ESM1-2-HR [53]	GERMANY	0.9×0.9
Observed data	**Country's Name**	**Horizontal Surface Resolution**
IMD [54]	INDIA	0.25×0.25

3. CMIP6 Model Performance

The simulated rainfall in models of CMCC-CM2-SR5, EC-Earth3-AerChem, CMCC-ESM2, CMCC-CM2-HR4, CNRM-CM6-1-HR, EC-Earth3-CC, and MPI-ESM1-2-HR is contrasted with observed gridded rainfall data of IMD to get insights into the rainfall distribution patterns (1979–2014).

Figure 2 visually depict the geographical distribution of simulated rainfall in the aforementioned climate models, overlaying them with the observed rainfall data from IMD. It has been observed that the models' ability to replicate the observed rainfall patterns shows the disparities or similarities between the simulations and actual observations [55,56]. Such variations in the layout of the sub-seasonal rainfall among the models may be because of variations in horizontal and vertical resolutions as well as representation of components namely atmosphere, land surface and vegetation, biogeochemistry (land and ocean), atmospheric chemistry, ocean, sea ice, lake treatment [57–60]. It is reported that the EC-Earth3 model simulated precipitation rate showed biases to a lesser extent inside the hemisphere that is northern in comparison with the observational dataset Project for Global Precipitation Climatology [61] .The negative biases appear in the simulation of different versions of CMCC models [60]. The positive biases are noticed in simulated rainfall in MPI-ESM-LR and MPI-ESM-HR against GPCP rainfall [62] .The simulated rainfall over the part of the Gangetic plain in MPI-ESM1-2-HR failed to reproduce the observed rainfall pattern [56]. Nation, among the models, lack of appropriate representation of known physical processes, such as cloud processes, radiative processes, and boundary-layer processes, which interact with each other on many temporal and spatial scales and are not sufficiently resolved on the model's sub-grid scales and therefore incorporated different parameterization schemes could be able to produce different rainfall pattern in different climate models simulated rainfall against the observed rainfall pattern [63–65].

Major parameterization schemes such as clouds [66–68], convection [69,70], boundary layer, and vertical diffusion: surface fluxes of momentum, heat, water vapor, and cloud water [71], radioactivity in the SW [72], LW [73], and water vapor effect [74] has been incorporated in CMCC-CM2-SR5, CMCC-ESM2, and CMCC-CM2-HR4 models. In the climate models, when matched with observed IMD rainfall, we gain insights into the strengths and limitations of the climate models for replicating the rainfall patterns over the Gangatic Plain of India. Such evaluations are essential to enhancing the accuracy and reliability of climate models, our understanding of regional climate dynamics, and aiding in climate change projections for the Gangatic Plain of India.

Figure 3 presents a graphical representation of the daily climatology of predicted rainfall in seven historical climate models, along with the observed data from the Department of Meteorology in India (IMD) represented by a blue line. This visualization allows us to compare and assess each individual's model performance in simulation of rainfall against the actual observations recorded by the IMD. In this specific analysis [75] However, we can rely on the summarize and assess how well each model's simulation of rainfall compares to the IMD's observed data [55].

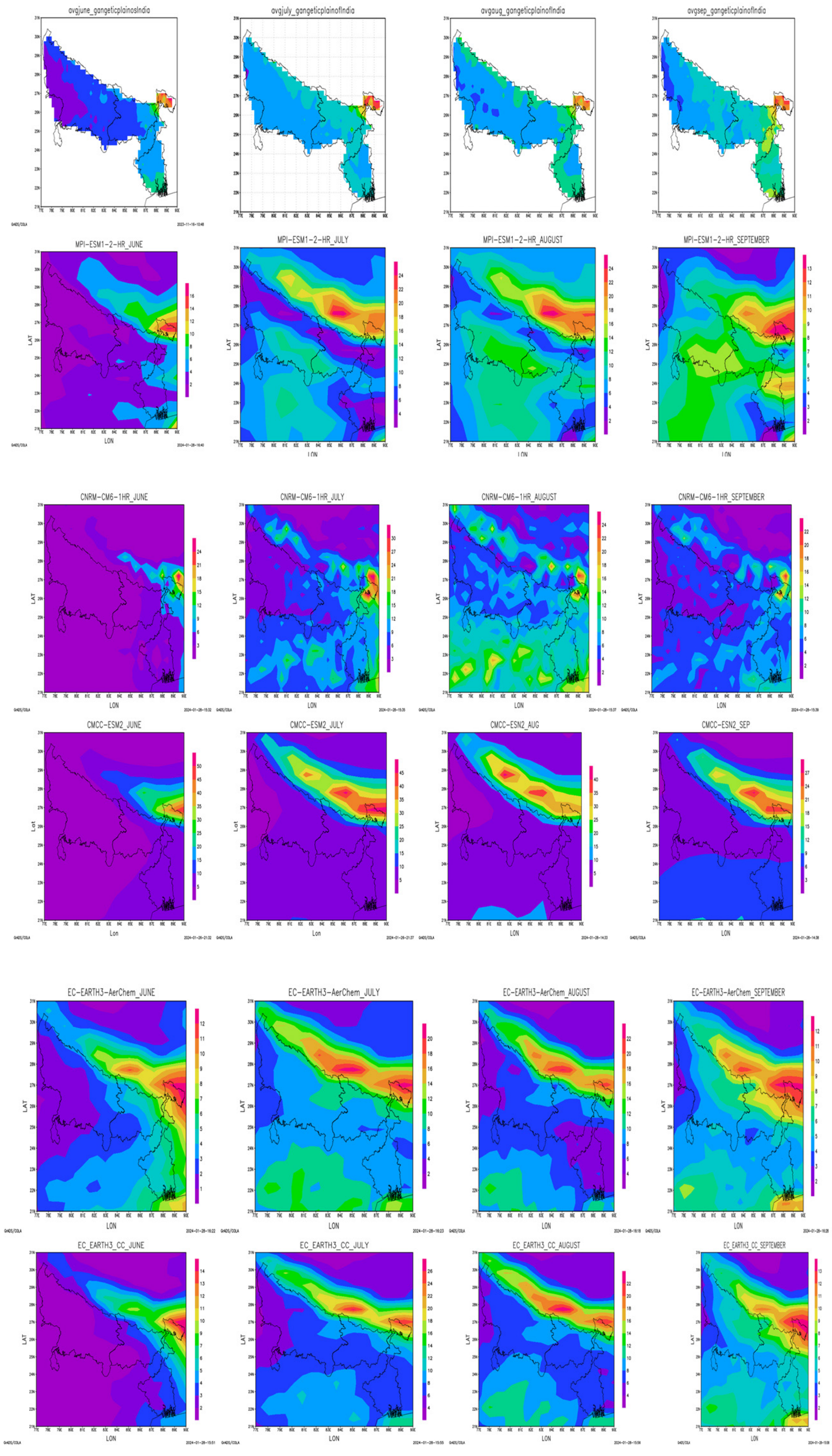

Figure 2. *Cont.*

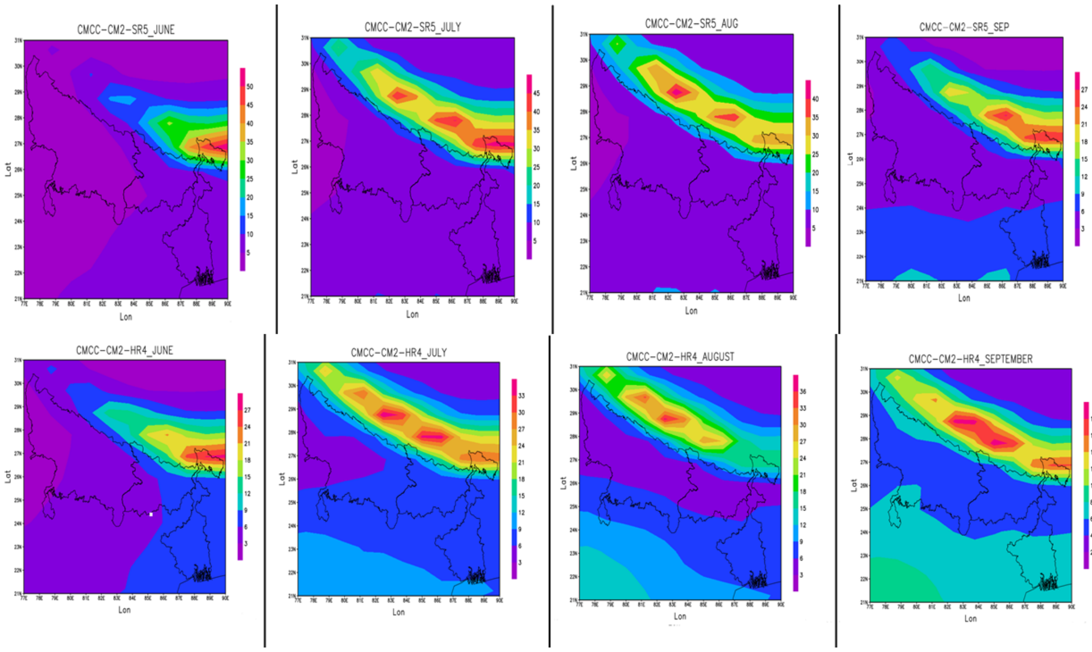

Figure 2. Spatial monthly variation of rainfall in June, July, August and September.

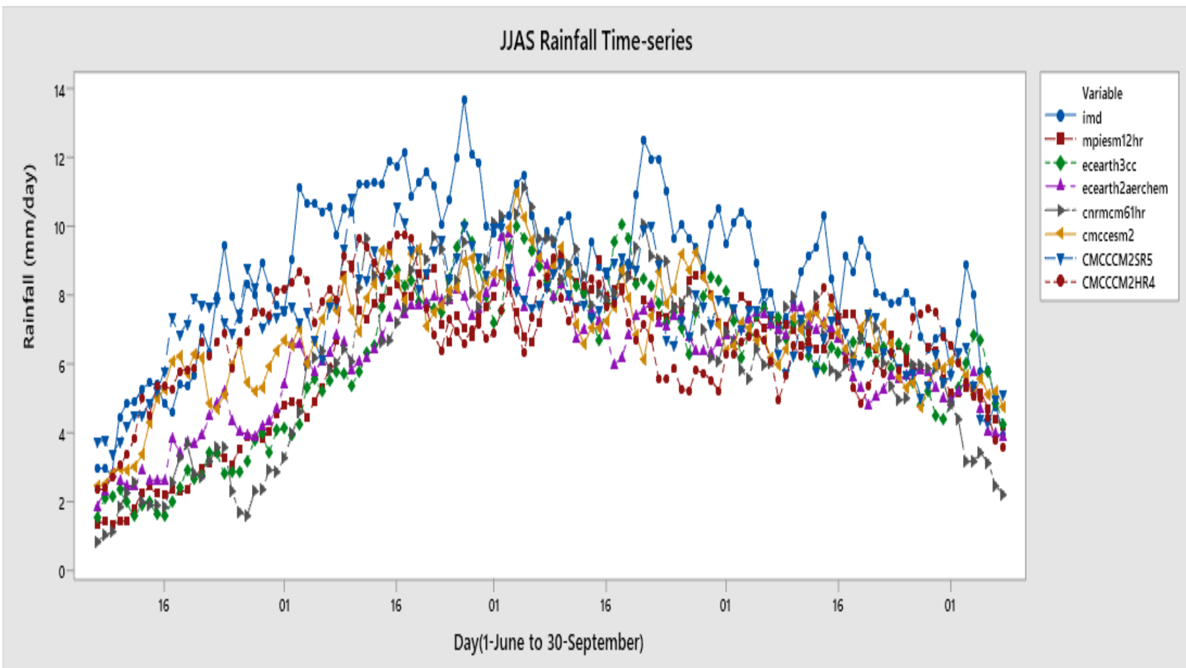

Figure 3. Climatological daily average (1 June–30 September) rainfall during considered period.

Several key factors need to be considered to evaluate the models' performance. Firstly, the comparison between the modeled predictions and the observed data is crucial to identify any discrepancies or similarities. By visually examining the plotted lines in **Figure 3**, we can gain a qualitative understanding of how closely the models' simulations align with the actual rainfall patterns observed by the IMD. Additionally, quantitative measures can be employed to provide a more objective assessment. Statistical metrics such as correlation coefficients, root mean square errors (RMSE), and bias can be calculated to quantify the degree of agreement between the models' simulations and the observed rainfall data. A higher correlation coefficient and lower RMSE and bias values indicate a better match between the models and the actual observations. Noteworthy is the fact that the evaluation should consider the geographical and chronological scales at which the models operate. Different models may exhibit varying degrees of accuracy in capturing regional or local rainfall patterns. Therefore, the assessment should take into account the specific geographical context and the temporal resolution of the data. By summarizing the findings from the study was conducted [55]. We can gain insights into the comparative accuracy of all models in recreating the trends in rainfall. This summary would provide information on the strengths and weaknesses of each model, helping researchers and stakeholders make informed decisions based on the reliability and skill of these climate models. In conclusion, although specific details about the models [75] might be difficult to obtain, it is possible to summarize and assess the way in which seven historical climate models by comparing their simulations of rainfall with the IMD's observed data. By combining qualitative analysis with quantitative metrics, we can gain valuable insights into the accuracy and reliability of these models, ultimately contributing to a better understanding of rainfall patterns and their implications for climate studies and water resource management.

To quantitatively compare the performance of rainfall simulations in models to observations, Taylor's diagram approach, as introduced by Taylor in 2001, is employed. This approach provides a comprehensive and graphic depiction of the degree of similarity between the simulated rainfall patterns in the models and the observed data.

Figure 4 illustrates Taylor's diagram, which is constructed to assess the quantitative performance of the rainfall simulations. In this diagram, each model is represented by a data point, and its location and proximity to the reference point (in this case, the observed data) indicate the model's similarity to the observations. The radial separation from the point of origin in Taylor's diagram is inversely proportional to the departure from the mean of a pattern. This means that models with a smaller radial distance have a closer agreement with the observed rainfall variability in terms of its spread. Models that exhibit a larger radial distance indicate greater variability compared to the observations. The separation between the testing area (model simulation), as well as the reference area (observed data), is proportional to the cantered root mean square (RMS) variation between the two domains. This measure quantifies the overall dissimilarity between the model's rainfall simulation and the observed data, taking into account both the size and geographical dispersion. The azimuthal location of the test field in Taylor's diagram determines the association between the model simulation and the observed data. Models that closely align with the observed rainfall patterns will have a higher correlation, indicating a better match in terms of spatial arrangement and timing. By analyzing Taylor's diagram, the model EC-Earth3-AerChem corresponds to point D, the CMCC-ESM2 to point E, and the CMCC-CM2-SR5 to point F. These models demonstrate the closest agreement with the observational data from the IMD. Conversely, however, the remaining four models do not exhibit assimilation with the observational data, indicating a potential discrepancy or limited accuracy in their rainfall simulations.

The study conducted for this assessment [76], allowing for a clear understanding of the model's performance and how well they capture the observed rainfall patterns. By considering Taylor's diagram and the associated analysis, researchers and stakeholders can make informed decisions based on the models' reliability and suitability for specific applications related to rainfall studies and water resource management. In summary, Taylor's diagram approach provides a useful tool for comparing the numerical results of rainfall simulations in models to observed data. By examining the radial distance, separation, and azimuthal location in the diagram, we can assess the similarity, dissimilarity, and correlation between the model simulations and the observed rainfall patterns. This approach allows for a more thorough assessment of the models' performance and facilitates the identification of models that best capture the observed rainfall characteristics.

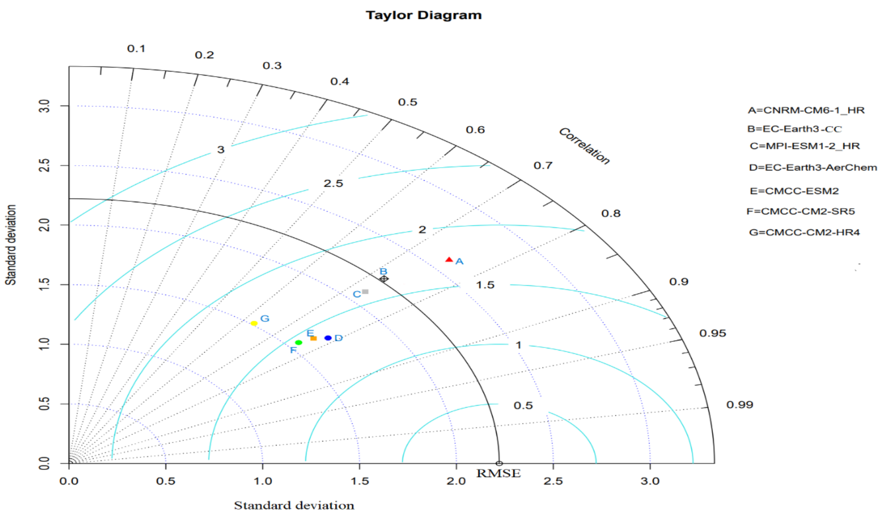

Figure 4. Taylor diagram for the considered models.

In **Figure 5**, a set of boxplots is presented, illustrating the scores among the CMIP6 models for the correlation between observed rainfall (IMD) and the CMIP6 simulation. These boxplots give a graphic depiction of the statistical distribution of correlation scores among the different models, highlighting the range of performance across the ensemble. The box in each plot represents the interquartile range (IQR), which encompasses the middle 50% of the data. The lower and upper edges of the box denote the percentiles of 25 and 75 respectively, while the line inside the box represents the median correlation value. As the box gets longer, it shows the spread of the correlation scores within the interquartile range. Outliers, represented by circles, are data points that fall outside the whiskers of the boxplot, indicating extreme values or data points that deviate significantly from the majority. These outliers might suggest models that perform exceptionally well or poorly in terms of their correlation with the observed rainfall data. By examining the boxplots, we can gain insights into the variability and performance of the CMIP6 models' ability to replicate the observed rainfall patterns. Models with higher median correlation values and narrower interquartile ranges indicate better agreement with the observed data, suggesting greater accuracy and reliability. The analysis [77] provides valuable information on how well the CMIP6 models performed, specifically focusing on the correlation between the observed rainfall data from IMD and the CMIP6 simulations. This assessment allows for a comparative evaluation of the model's capacity to record the observed rainfall patterns and provides insights into the model's strengths and weaknesses. By considering the boxplots and examining the statistical distribution of correlation scores, researchers and stakeholders can identify models that exhibit higher correlation values and therefore offer better agreement with the observed rainfall data. Conversely, models with lower correlation scores may require further investigation and potential refinement. Overall, **Figure 5**, which displays the boxplots of correlation scores, serves as a valuable tool for assessing the CMIP6 models' ability to accurately simulate rainfall patterns compared to the observed data. By analyzing the interquartile range, median values, and outliers, researchers can obtain an understanding of the range of model performance and come to wise judgments regarding the selection and utilization of models for various applications related to rainfall studies, climate change assessments, and water resource management.

Figure 6 presents a regression analysis of the CMIP6 models with the IMD observational data. This analysis aims to investigate the connection between the simulated rainfall in the CMIP6 models and the observed data, allowing for a quantitative assessment of how well the models capture the observed rainfall patterns. By conducting a regression analysis, researchers can ascertain the nature and degree of the connection between the model simulations and the observed data. The analysis involves fitting a regression line that represents the best-fit relationship between the two variables, with the incline of the line indicating the magnitude of the relationship.

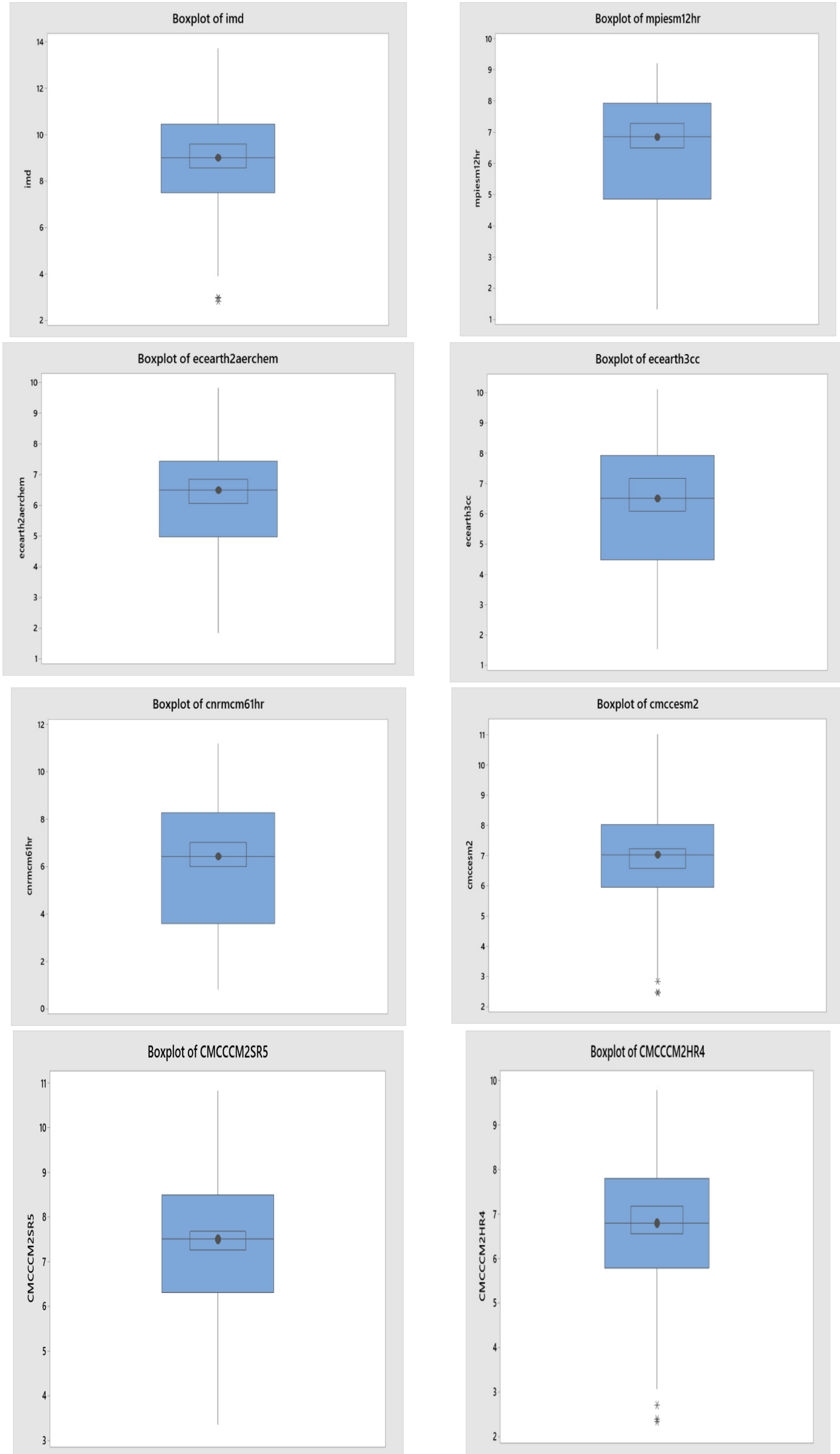

Figure 5. Box plots of IMD observed and models simulated rainfall.

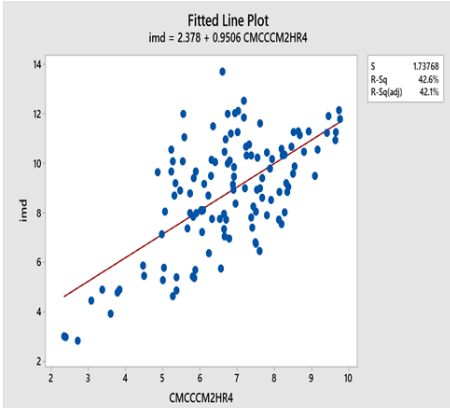

Figure- 6(A) CMCC-CM2-HR4

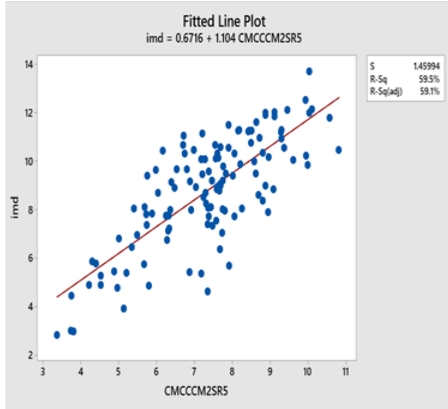

Figure- 6(B) CMCC-CM2-SR5

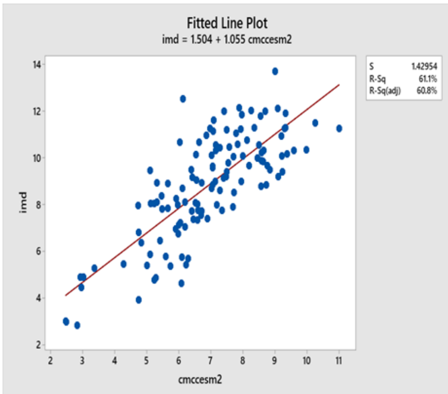

Figure- 6(C) CMCC-ESM2

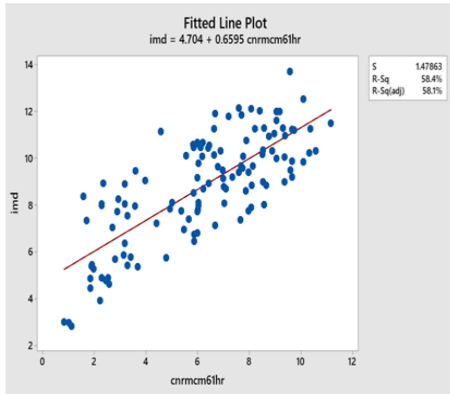

Figure- 6(D) CNRM-CM6-1_HR

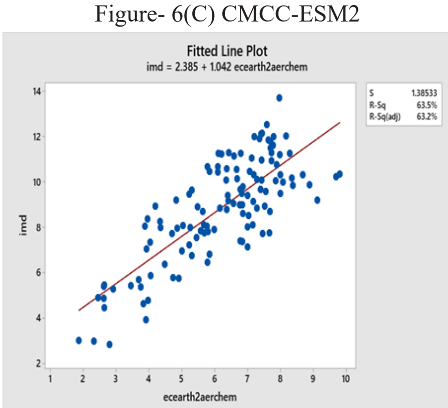

Figure- 6(E) EC-Earth3_AerChem

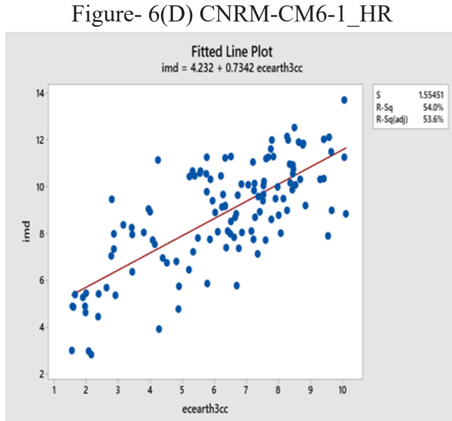

Figure- 6(F) EC-Earth3_CC

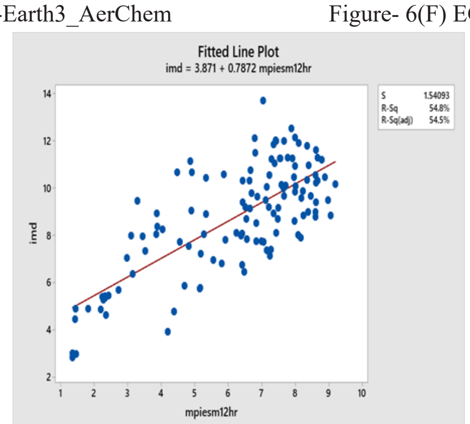

Figure- 6(G) MPI

Figure 6. Scatter plots between IMD observed (**A**) and models simulated rainfall (**B**–**G**).

According to the outcomes of the regression analysis, it is evident that certain CMIP6 models exhibit a stronger alignment with the IMD observational data. Specifically, the CMIP6 models CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2 demonstrate the closest agreement with the observed data. The term "best suited" suggests that these models have higher regression coefficients, indicating a stronger correlation or association between their simulated rainfall and the observed data. This implies that these models more accurately capture the rainfall patterns observed by the IMD. Conversely, other CMIP6 models might exhibit weaker regression coefficients, suggesting a less robust relationship with the observed data. These models might have a higher degree of uncertainty or larger deviations from the observed rainfall patterns. The findings mentioned herein indicate that the CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2 models perform well in terms of their regression analysis with the IMD observational data. These models demonstrate a better ability to reproduce the observed rainfall patterns, providing researchers and stakeholders with increased confidence in their simulation results. Overall, the regression analysis in **Figure 6** provides valuable insights into the CMIP6 models' performance in the IMD observational data. It allows for a quantitative assessment of the model's capacity to record the observed rainfall patterns and identifies models that exhibit a stronger alignment with the observations. These findings can guide further analysis, decision-making, and model selection in various applications related to rainfall studies, climate change assessments, and water resource management

4. Conclusions

The assessment focuses on evaluating the ability of different CMIP6 models to reproduce rainfall patterns on seasonal and monthly scales for the Summer Monsoon in India (ISM) season from 1979 to 2014. The validation process involves comparing the rainfall recorded through the Indian Meteorological Department (IMD) with the simulations from CMIP6 models with a resolution equal to or less than 100 km. The analysis specifically focuses on the Gangatic Plain region of India. The findings of the validation reveal that among the CMIP6 models analyzed, three models stand out for their good performance in capturing the rainfall patterns in the Gangatic Plain. These models are CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2. These models demonstrate a higher level of accuracy in representing the regional rainfall distribution in the Gangatic Plain compared to the other models. When assessing the monthly rainfall patterns, the simulations from CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2 closely resemble the actual rainfall observations in the Gangatic Plain. Conversely, however, the simulations from CMCC-CM2-HR4, CNRM-CM6-1-HR, EC-Earth3-CC, and MPI-ESM1-2-HR do not match the observed rainfall in the region. The simulated seasonal cycle of rainfall in CMCC-CM2-SR5 aligns well with the observed pattern, albeit with some differences in amplitude. In particular, for July, August, and September, the CMCC-CM2-SR5 simulation accurately represents the range and median of observed rainfall [78] .The interannual fluctuation of mean rainfall during the JJAS period can also be obtained from the observed data. Furthermore, the simulations from CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2 successfully capture the fluctuations between years of rainfall during July, August, and September. This indicates the presence of significant rainfall variability on a sub-seasonal scale across the Indian subcontinent. However, it is mentioned that there is a need for improved accuracy in depicting rainfall variability in the examined CMIP6 models to better match the actual rainfall observations and reduce significant discrepancies between simulated and actual rainfall.

In conclusion, the analysis of the CMIP6 models for the ISM season reveals that CMCC-CM2-SR5, EC-Earth3-AerChem, and CMCC-ESM2 demonstrate better performance when replicating patterns of rainfall in the Gangatic Plain of India. These models exhibit a closer resemblance to observed rainfall variability on both monthly and interannual scales, indicating their suitability for studying and understanding rainfall patterns in the region. Nonetheless, further improvements are necessary to enhance the accuracy of simulated rainfall and better capture the actual variability in the examined CMIP6 models.

Author Contributions

Conceptualization, D.K.T. and P.P.S.; methodology, D.K.T.; software, D.K.T.; validation, D.K.T., P.P.S.; formal analysis, D.K.T.; investigation, D.K.T.; resources, D.K.T.; data curation, D.K.T.; writing—original draft preparation, D.K.T.; writing—review and editing, D.K.T.; visualization, D.K.T.; supervision, P.P.S.; project administration, no one.; funding acquisition, no funding source. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

For the study of the given manuscript, the observed rainfall data is taken from Indian Meteorological Department (IMD) at nominal resolution 0.25x2.5 and for model simulation Coupled Model Intercomparison Project Phase 6(CMIP-6) data was taken and these data-sets are open access for all.

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Conflict of Interest

The authors declare no conflict of interest.

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