Assessment of South Asian summer monsoon climatology based on CMIP5 historical simulations and representative concentration pathways (RCPs)

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Abstract: *The Fifth Assessment Report(AR5) of the Intergovernmental Panel on Climate Change(IPCC) is being prepared using historical simulations as well as representative concentration pathways(RCPs). This paper assesses the fidelity of the state-of-the-art Coupled General Circulation Models (CGCMs) under Coupled Model Intercomparison Project5(CMIP5) in simulating the mean South Asian monsoon climate. An assessment of skills and systematic biases of the historical simulations of 4 CGCMs under CMIP5 reveals that there exists large bias in mean monsoon rainfall simulated by the models as compared to the observed rainfall, marked by overestimated precipitation trend over the equatorial Indian Ocean. The GCMs also exhibit cold bias in simulation of sea surface temperatures (SST) over the equatorial Indian Ocean, emphasizing the need for a better understanding of the SST-rainfall relationship. Under the RCP4.5 scenario, the CGCMs project an all-India JJAS precipitation increase by 3.7-6.6% and a mean monsoon warming of 1.06-2.04°C for 2021-2050 relative to the base period simulations. These results suggests that these new climate projections should be used through incorporation of proper metrics in assessment of future impacts of climate change, thus paving the way for proper adaptation planning.*

Keywords: *South Asian summer monsoon, climate change, CMIP5, representative concentration pathways.*

1. Introduction

South Asian summer monsoon, characterized by the seasonal migration of the zonally oriented belt of precipitation or the tropical convergence zone (TCZ) [1], is one of the most dominant tropical circulation systems in the general circulation of our atmosphere. Accounting for over 70% of the annual rainfall in the Indian sub-continent, this southwest monsoon season is spread over a span of four months (June to September). This monsoon rainfall, marked by its variability in its onset, withdrawal, amount of rainfall and climatic extremes like droughts and floods, is critical to the food, economy and water security of the region. Apart from the challenges of coping with these patterns of climate variability, there is a chief concern about how climate change with progressively increasing greenhouse gases emission scenario may affect the South Asian summer monsoon. Over the past 100 years, changes in many components of the climate system like precipitation, snow cover, sea ice, extreme weather events, etc. have been observed [2], mainly due to increasing anthropogenic activities and industrial revolution. Hence, the impact of global warming on South Asian monsoon and the future monsoon estimates is a prime research focus.

Coupled General Circulation models (CGCMs) are one of the primary tools for deriving projections of future climate change. Previous studies have proven that despite weakening of the dynamical monsoon circulation, atmospheric moisture build up due to increased greenhouse gases and consequent temperature increase results in a larger moisture flux and more precipitation for the Indian monsoon [3] [4]. However, the reliability of the regional climate projections will depend on how well the models are able to simulate the present day monsoon climate. Hence, a higher reliability can be attributed to the GCMs if the models are able to simulate the salient aspects of current climate, thereby replicating the essential physical processes important for the simulation of future climate change.

For the present study, the coupled models of the Coupled Model Intercomparison Project 5 (CMIP5) [5] have been used. To assess the future climate change scenarios, it is necessary to understand the strengths and weaknesses of these climate models. An analysis of CMIP5 models is thus prepared to understand the capability of climate models in simulating the recent past monsoon climate and to assess the model biases.

In this paper, we assess the recent past climate of the South Asian summer monsoon as simulated by four selected CMIP5 models and discuss the systematic biases in simulations of monsoon rainfall, surface temperatures and also the annual cycle of monsoon. Moreover, future precipitation and temperature projections of JJAS summer monsoon for the period 2021-2050 have also been provided. In section 2, the data set used in this study and methodology are discussed while the results obtained from comparative analysis with observed rainfall climatology are highlighted in section 3.

2. Data and Methodology

Rainfall and temperature are the two variables for which detailed observations exist, which have been extensively studied in the context of South Asian summer monsoon. The present study analyses historical simulations as well as future projections of 4 selected GCMs under the RCP4.5 scenario. The newly developed RCP4.5 scenario represents a stabilization scenario where total radiative forcing is stabilized before 2100 by employing a range of technologies and strategies for reducing greenhouse gas emissions [6]. The model data are taken from the Coupled Model Intercomparison Project (CMIP5) for which the variables surface temperature and precipitation are readily available. The selected coupled GCMs are listed in Table 1. Model details and data are available from the Earth System Grid Federation (ESGF) portal of the Program for Climate Model Diagnosis and Intercomparison (PCMDI) website maintained by the Lawrence Livermore National Laboratory, USA.

For validating the model simulations for precipitation, we have used the Global Precipitation Climatology Project (GPCP) rainfall data (available from Jan1979-Dec2005) [7]. The GPCP project was initiated under the World Climate Research Programme (WCRP) to evaluate and provide global gridded data sets of monthly precipitation, based on all suitable observational techniques [2]. The data set is ideally used for the verification of climate model simulations. In order to evaluate surface temperature simulations of the CGCMs, we have used we have used HadCRU absolute temperature climatology data and HadCRUT4 combined land and marine temperature anomalies (http://www.cru.uea.ac.uk/cru/data/temperature/) from 1961-1990.

The region under focus in our study extends from 10°South to 40°North latitude and from 30°East to 180°East longitude. The different CMIP5 model outputs are available on different spatial scales, as shown in Table 1; these outputs for both bias computation and climate projections are regridded to a common spatial scale (same as the observed spatial resolution), using the process of bilinear interpolation. On the other hand, in obtaining annual cycle of monsoon rainfall as well as future projections over the Indian landmass, the oceans and territories outside the geographical borders of India have been masked out.

3. Results

3.1 GCM historical simulations for the mean monsoon seasonal rainfall

The spatial pattern of the mean South Asian monsoon rainfall over the period 1979-2005 for the June-September (JJAS) season, simulated by the 4 CMIP5 GCMs,are shown in Figure 1, along with the observed rainfall (GPCP) climatology. Figure 2 shows the spatial difference plots between the model simulated and observed (GPCP) rainfall. The observed pattern of rainfall maximum over northern parts of Bay of Bengal and Bangladesh is well simulated by at least 3 of the models (NCAR, CCCMA, GFDL). In the CNRM model, the Bay of Bengal rainfall maximum is shifted slightly north-eastwards. The observed GPCP rainfall climatology depicts the other rainfall maximum over the west coast of India, which is well simulated by NCAR, GFDL and CNRM models. In the CCCMA model, this rainfall maximum is shifted slightly south-westwards. On the other hand, the difference plots (Figure 2) reveals that widely variable bias exists in simulating recent past observed South Asian summer monsoon. The most salient aspect of these plots is however, the overestimated rainfall simulation over the equatorial Indian Ocean. This difference, of the order of 2-5mm/day, is widely prevalent in all the four models. One of the possible reasons for this excess rainfall over the equatorial Indian Ocean may be due to the model problems in simulating the northward migration of the continental inter-tropical convergence zone (ITCZ)with the northward migration of solar insolation [2]. Also, a dry bias simulation by at least 2 of the GCMs, namely CCCMA and CNRM, over the Indian landmass is worth mentioning. Moreover, the spatial pattern of least rainfall of the order of 0-1mm/day over the Arabian Desert in Western Asia is well simulated by all the four models.

3.2 Annual cycle of monsoon rainfall over India

The monthly variation of mean rainfall averaged over the Indian landmass for all the four CMIP5 GCMs are shown in Figure 3 along with the observed GPCP seasonality plot. It is to be noted here that in computing the mean monthly rainfall, only nodes within the geographical boundaries of India are considered. Long term mean of observed (GPCP) monthly All-India rainfall values show a prominent seasonality of high rainfall during June, July, August and September (JJAS). Our analysis shows that NCAR and GFDL models replicate this annual cycle reasonably well, with NCAR simulating both the magnitude and the shape of the annual cycle of All-India-Monsoon-Rainfall (AIMR) most accurately with minimum bias. On the other hand, CCCMA fails to capture the July-peak of AIMR, whereas, CNRM, in spite of simulating the shape well, underestimates the observed rainfall trend.

3.3 GCM historical simulations for surface temperatures of JJAS South Asian summer monsoon

In this section, we examine the surface temperature simulations of the CMIP5 GCMs for the South Asian summer monsoon over the period 1961-1990. Sea surface temperature (SST) and rainfall is strongly coupled in the tropics, hence unrealistic simulation of surface temperature may cause unrealistic rainfall distribution. The spatial distribution plots for mean monsoon temperature (°C) based on the historical simulations of the 4 CMIP5 GCMs, along with the observed HadCRU temperature climatology are shown in Figure 4. We find here that the models simulate the spatial pattern of observed temperatures fairly well, marked by temperature maximum over parts of Thar Desert, Rajasthan and temperature minimum over the Himalayan areas.

Figure 5 shows the spatial distribution of the differences between the GCM simulated surface temperature and the observed HadCRU surface temperature simulations during the JJAS season for the South Asian monsoon. We find that the biases are far less pronounced in simulating recent past observed surface temperature, ranging from -2°C to 2°C.The most notable aspect of these plots is the colder surface temperature simulations by at least 2 of the models (CNRM, GFDL) over the Indian Ocean.

As we have seen in section 3.1, most of the models produce excessive precipitation over the Indian Ocean, in spite of the significant cold SST bias. This suggests that deep convection in the models is not controlled solely by SST itself, but some other processes. SST gradient (Lindzen and Nigam, 1987) [8], moisture convergence, or surface heat fluxes also may be responsible. On the other hand, colder SST bias in the coupled models over the Indian Ocean may be due to excessive precipitation as hypothesized by Lin (2007) [9]. Nanjundiah et al (2007) [10] have studied this behaviour of realistic seasonal cycle of rainfall and cold SST bias over the Indian Ocean in AOGCM. They show that precipitable water-rainfall relationship is overestimated in the model, i.e., for a given value of precipitable water, the rainfall estimated by the model is higher than observed. These suggest the need for a detailed study of the relationship between SST and rainfall over the tropical Oceans [2].

3.4 Projected precipitation and temperature change for 2021-2050 South Asian monsoon

Figure 6 shows the mean monsoon precipitation change (mm/day) projected by the 4 CMIP5 GCMs during 2021-2050 under the RCP4.5 scenario relative to the 1979-2005 base period. It is worth mentioning that the models simulate a JJAS precipitation increase of the order of 0.5-2.0mm/day over equatorial Indian Ocean. On the other hand, precipitation is likely to increase all over India except for a few regions, as is also noticed in the study by Chaturvedi et al(2012) [6] for these short term projections. All-India mean monsoon precipitation is projected to increase by 3.7-6.6% relative to the 1979-2005 historical simulations, when the computation is done solely over the Indian landmass. Also, the existing rainfall maximum trend over the west coast of the country and adjoining Arabian Sea is likely to intensify as predicted by most of the models, especially NCAR, CCCMA and CNRM. All these results are testimony to an intensification of summer monsoon precipitation over India.

Figure 7 shows the spatial pattern of mean summer monsoon warming (°C) projected by the 4 CMIP5 GCMs during 2021-2050 under the RCP4.5 scenario relative to the 1961-1990 base period. The most significant aspect is the greater warming scenario projected over the northern parts of India compared to the rest of the country, especially over J&K and Himalayan areas by the NCAR and CNRM models. As a whole, all-India mean monsoon temperature increases by 1.06-2.04°C as per the GCM simulations. Also, worth mentioning is a 2.0-5.0°C warming over Afghanistan, Iran and parts of Arabian Desert in western Asia, as predicted by the CCCMA, GFDL and NCAR models.

4. Discussions and conclusions

Climate change is recognized as the biggest challenge that the planet faces[11]. Climate scientists use simulations from a range of coupled models to account for the merits and demerits of individual GCMs instead of branding climate models as ‘bad’ or ‘good’ model [12]. In the present study, an effort has been made to illustrate the fidelity of the state-of-the-art CGCMs under CMIP5 in simulating South Asian summer monsoon climatology. This exercise is needed as the consideration of model reliability in simulating present day climate provides confidence to decision makers to incorporate these precipitation and temperature projections while formulating policies for future climate change impacts assessment. The following major conclusions are drawn from this study:

1) There exists large bias in the spatial pattern of CMIP5 GCM simulated rainfall compared to the observed (GPCP) rainfall, especially marked by an overestimated precipitation of the order of 2-5mm/day over equatorial Indian Ocean.
2) A single model fails to realistically simulate all the major features of Indian monsoon rainfall

distribution, viz, maximum over Bay of Bengal and adjoining northeast India and west coast, minimum over NW India and another maximum over the southeast equatorial Indian Ocean. This proves that, use of a single metric to evaluate a model in simulating climatology is difficult and for Indian rainfall, it is even more challenging because of multiple patterns; viz., seasonality [13], periodicity [14], inter-annual variability [15], and association with SST [16].

3) In spite of widespread biases prevalent in spatial distribution of rainfall, most of the models simulate the observed trend of annual cycle of Indian rainfall reasonably well marked by a July-peak in precipitation.
4) The GCMs exhibit a cold bias in simulation of surface temperatures over north Indian Ocean implying a need for better understanding and incorporation of the observed SST-rainfall relationship.
5) This paper provides temperature and precipitationprojections for India based on the 4 GCMs under consideration for the RCP4.5 scenario over the period 2021-2050. Mean All-India summer monsoon warming is projected to be in the range of 1.06-2.04°C. On the other hand, All-India precipitation is projected to increase by 3.7-6.6% relative to the base period 1979-2005 base period, while much larger variability is seen in the spatial distribution of precipitation.
6) CMIP5 simulations and RCP scenario-based projections of future climate change should be used by policy makers in order to develop an effective adaptation plan and also for framing subsequent water resources planning and management policies.

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Tables and Figures:

Table 1: *List of CMIP5 GCMs used in this study with their modelling organization, spatial resolution and model designation respectively*

Modelling organization	**GCM**	**Spatial Resolution**	**Model Designation**
National Center for Atmospheric Research (USA)	CCSM4	0.942°X 1.25°	NCAR
Canadian Centre for Climate Modelling and Analysis (Canada)	CanESM2	2.79° × 2.8125°	CCCMA
Centre National de Recherches Meteorologiques/ Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CM5	1.4008° × 1.4063°	CNRM
NOAA Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM3	2.0° × 2.5°	GFDL

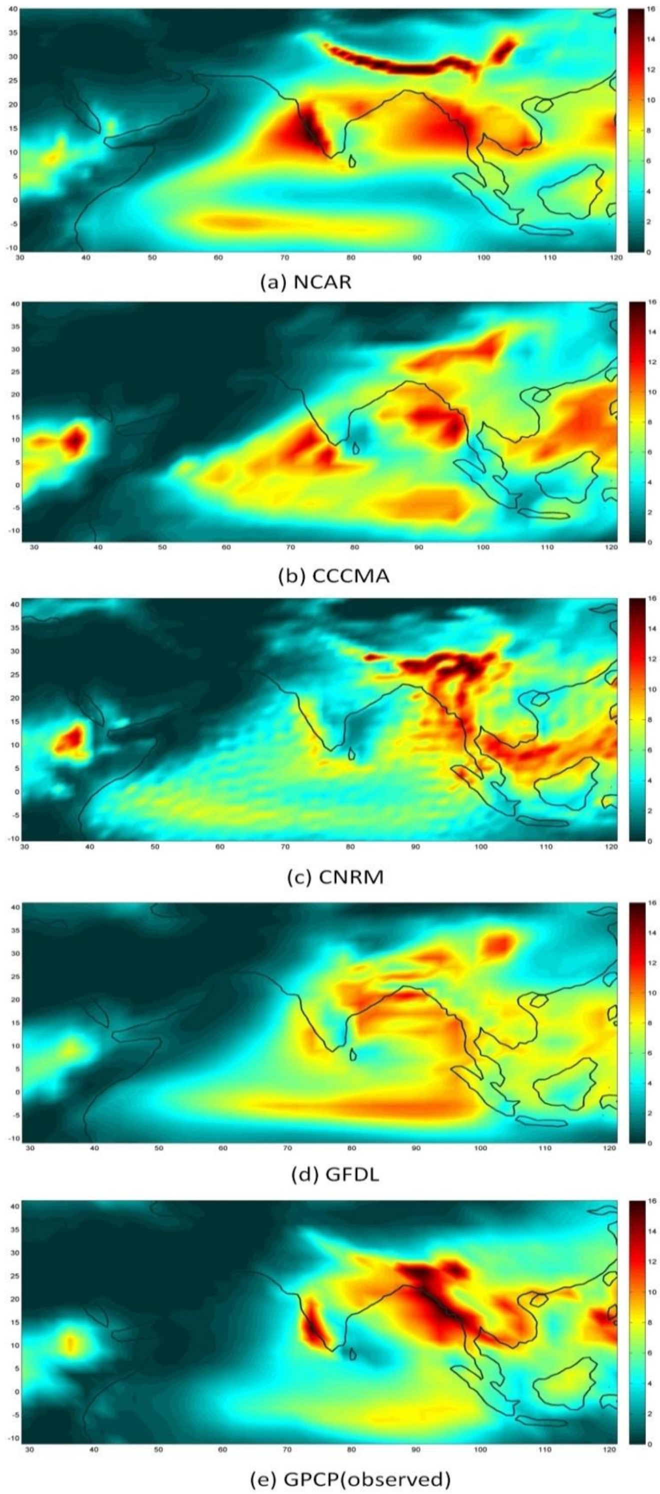


Figure 1(a)-1(d): *South Asian summer monsoon seasonal (JJAS) rainfall (mm/day) simulated by the 4 CMIP5 GCMs for 1979-2005.****Figure 1(e)*** *represents the observed GPCP rainfall climatology.*

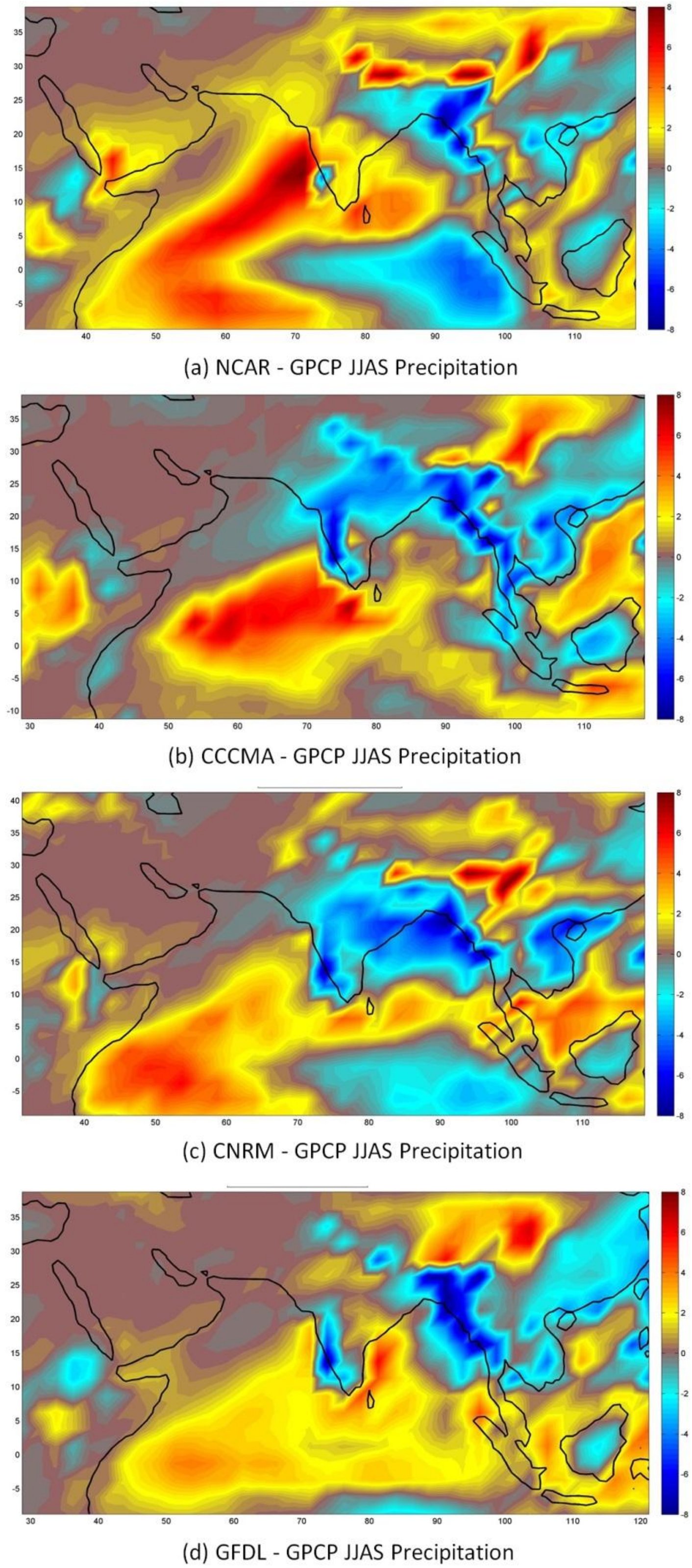
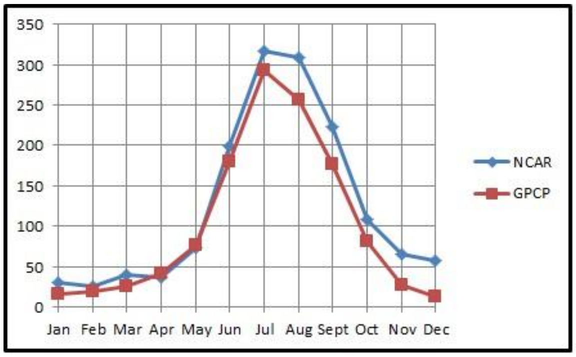
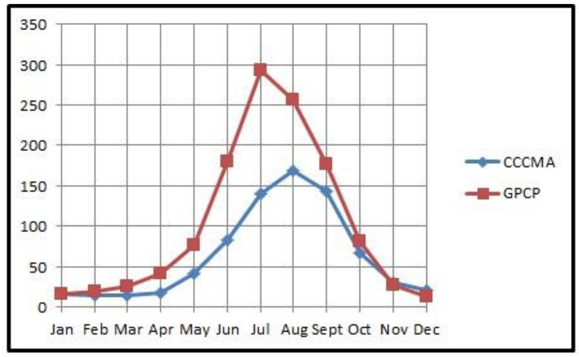


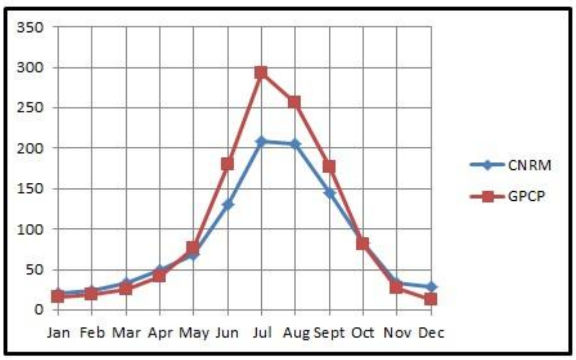
Figure 2(a)-2(d): *The spatial distribution of the biases between the GCM simulated and observed (GPCP) mean seasonal (JJAS) rainfall in mm/day over the period 1979-2005 for the 4 CMIP5 GCMs used in this study.*



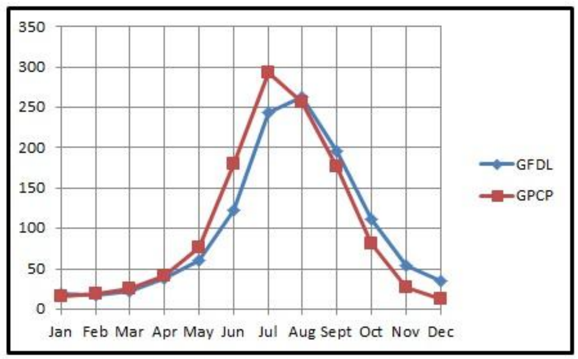
(a) NCAR vs. GPCP



(b) CCCMA vs. GPCP



(c) CNRM vs. GPCP



(d) GFDL vs. GPCP

Figure 3(a)-3(d): *Seasonality plots highlighting the annual cycle of the observed (GPCP) and GCM simulated monsoon rainfall (mm/month) over India.*

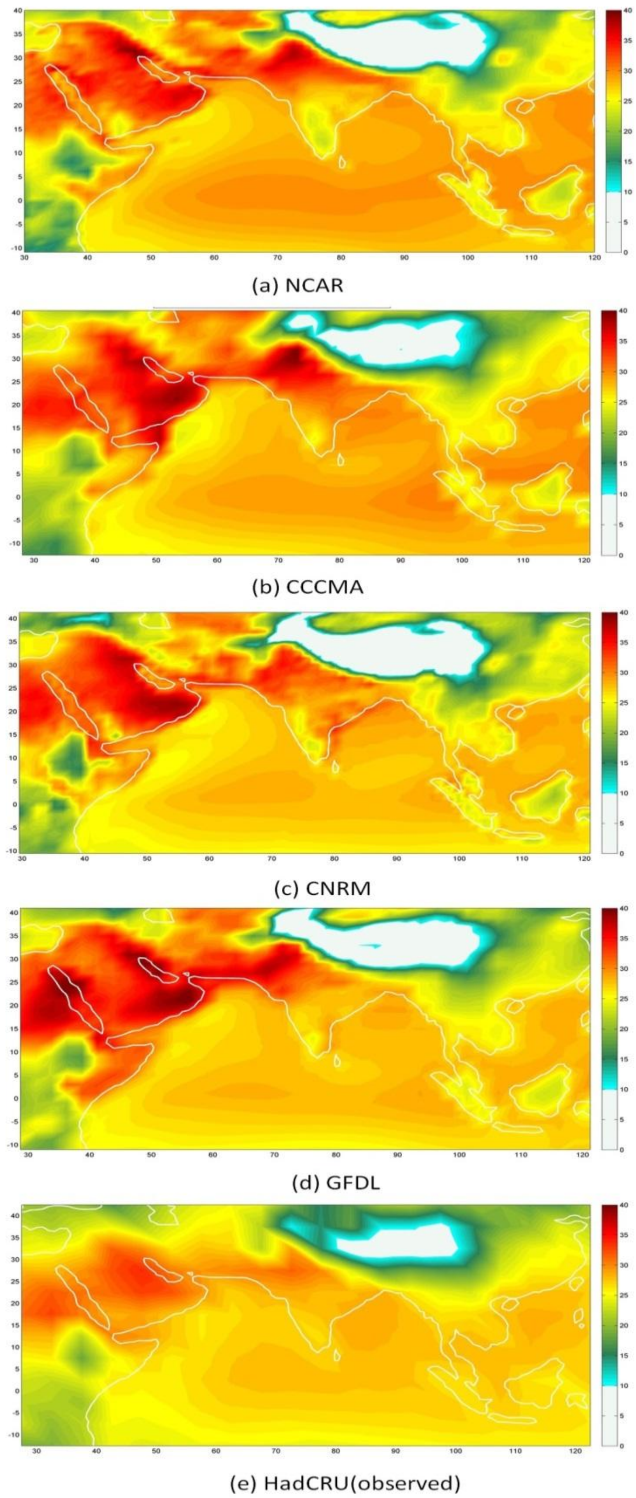


Figure 4(a)-4(d): *The spatial distribution of South Asian summer monsoon (JJAS) surface temperature (°C) as simulated by the 4 CMIP5 GCMs for the period 1961-1990.* ***Figure 4(e)*** *represents the observed HadCRU surface temperature climatology.*

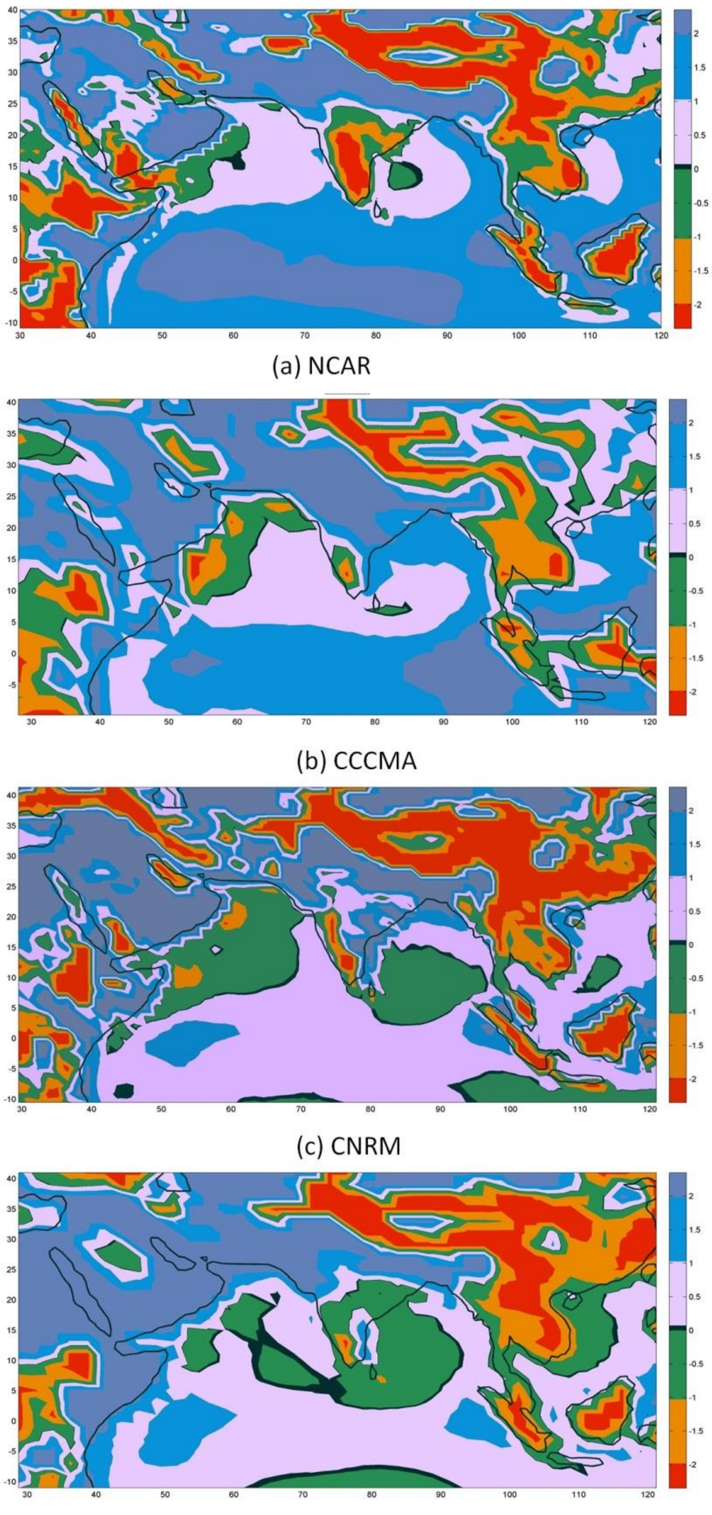
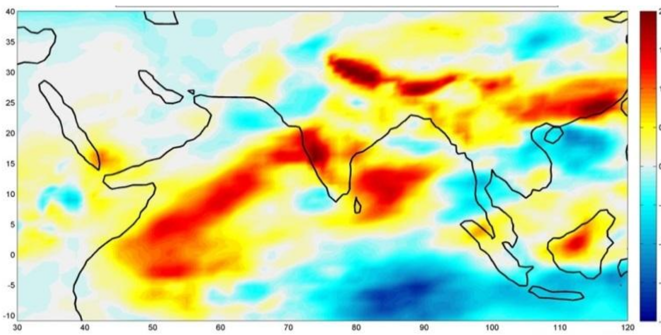
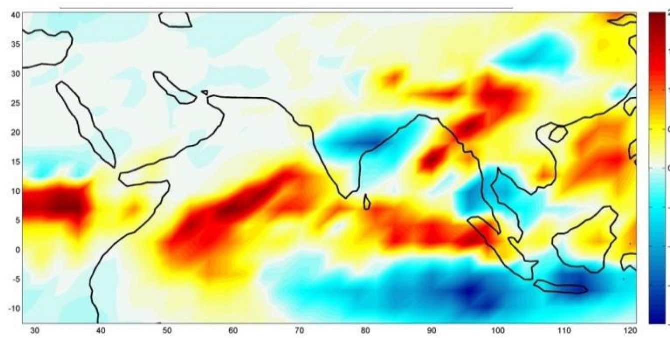


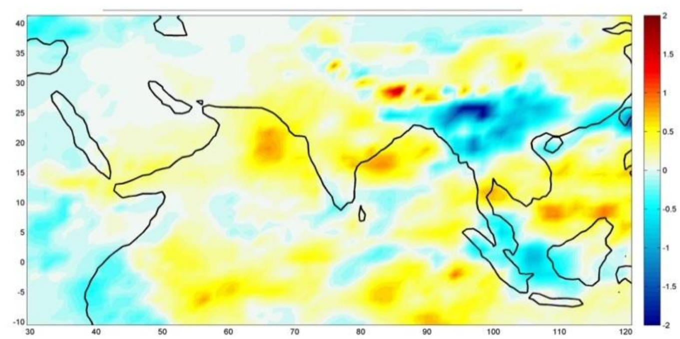
Figure 5:*The spatial distribution of the biases between the GCM simulated and observed (HadCRU) summer monsoon surface temperatures in °C over the period 1961-1990 for the 4 CMIP5 GCMs used in this study; viz. (a) NCAR, (b) CCCMA, (c) CNRM and (d) GFDL.*



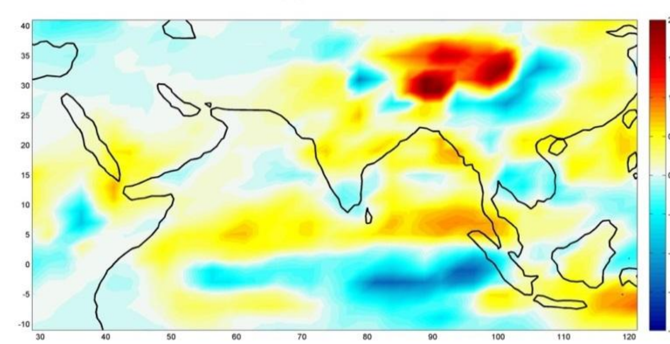
(a) NCAR



(b) CCCMA



(c) CNRM



(d) GFDL

Figure 6: *The spatial distribution of the South Asian summer monsoon precipitation change (mm/day) projected for 2021-2050 relative to the 1979-2005 base period by the 4 CMIP5 GCMs; viz. (a) NCAR, (b) CCCMA, (c) CNRM and (d) GFDL.*

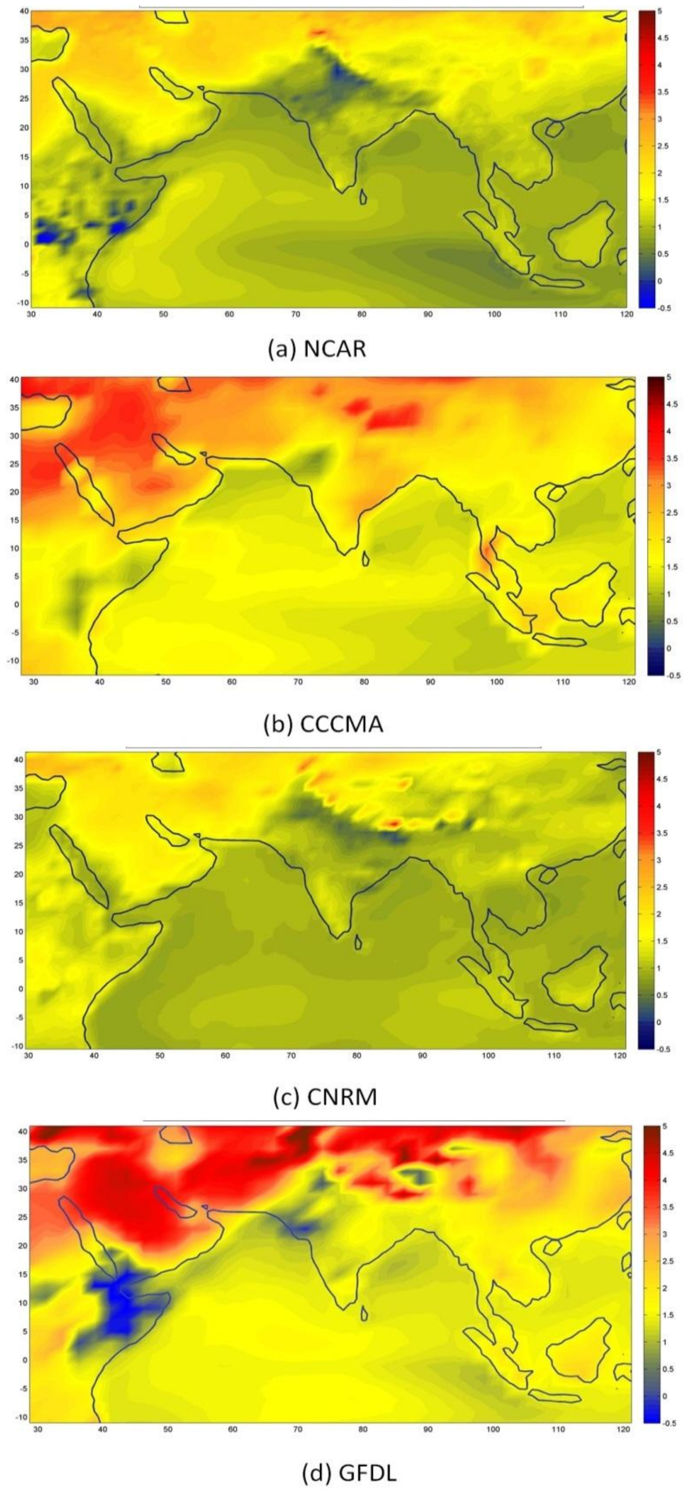


Figure 7: *The spatial distribution of the South Asian summer monsoon temperature increase (°C) projected for 2021-2050 relative to the 1961-1990 base period by the 4 CMIP5 GCMs; viz. (a) NCAR, (b) CCCMA, (c) CNRM and (d) GFDL.*