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Coupled model simulations of twentieth century climate of the Indian summer monsoon

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In this review article, we have examined the skill of the state-of-the-art coupled ocean-atmosphere models in simulating the twentieth century mean climate of the Indian monsoon. Assessment of the skill and systematic biases of the climate models is very important for interpreting and assessing the future climate change projections over the Indian region from these models.

For this purpose, we have considered 10 ocean-atmosphere coupled models, which participated in the Intergovernmental Panel for Climate Change (IPCC) AR4 report. These models were identified using the thresholds of pattern correlation and root mean square error in the model simulation of summer monsoon rainfall over the Indian region. The analysis shows that there are large biases in the mean monsoon rainfall simulated by the coupled models as compared to the observations. The models simulate excess rainfall over the equatorial Indian Ocean, while over the continental tropical convergence zone (CTCZ), models simulate less rainfall compared to observations. The models showed serious problems in simulating the northward seasonal migration of the Inter-tropical convergence zone (ITCZ) into the Indian landmass. They have also shown systematic cold bias in simulation of sea surface temperatures (SST) over the equatorial Indian and Pacific Oceans. At the same time, the rainfall simulation in the models is found to be very sensitive to the SST variations. At a given SST, these models predict more rainfall than observed. While the models simulate the low level monsoon circulation reasonably well, there are systematic biases in the strength of monsoon flow over the Indian region.

Most of the coupled models simulate the observed El Niño/Southern Oscillation (ENSO) Indian monsoon relationship reasonably well. However, the models have shown serious problems in simulating the observed simultaneous relationships between the monsoon rainfall and the Equatorial Indian Ocean Oscillation (EQUINOO). This could be related to overestimation of rainfall over the Equatorial Indian Ocean and errors in simulating the seasonal cycle of rainfall over both the Eastern and Western Equatorial Indian Oceans.

These results show that considerable improvements are still needed for these coupled climate models in simulations of the climate of the Indian monsoon.

1. Introduction

The Indian monsoon is one of the most dominant tropical circulation systems in the general circulation of the atmosphere. The country receives more than 80% of the annual rainfall during a short span of four months (June to September) of the southwest monsoon season. Variability in the onset, withdrawal and quantum of rainfall during the monsoon season has profound impacts on water resources, power generation, agriculture, economics and ecosystems in the country.

Keywords. Indian monsoon; climate change; coupled model; ENSO.

The El Niño/Southern Oscillation (ENSO) and the equatorial Indian Ocean climate anomalies are the primary sources of inter-annual variability of the Indian summer monsoon. An improved capability to predict the Indian monsoon seasonal rainfall variability would be of profound significance to many sectors. Apart from the challenges of coping with patterns of climate variability, there is also concern about how future climate change due to increase in greenhouse gases may influence the Indian monsoon. The increasing human activities due to industrial revolution have led to unprecedented changes in the composition of the earth's atmosphere and thus the earth's delicate climate system. There is now unequivocal evidence that the earth's surface has warmed during the past 100 years, which is mainly attributed to the anthropogenic activity. Changes in many components in the climate system, like precipitation, snow cover, sea ice, extreme weather events, etc., also have been observed. These changes, however, showed significant regional variations. Among the regional manifestations of global warming, the Indian summer monsoon also could be susceptible.

The only way to understand the impact of global warming on the Indian monsoon and to assess future monsoon climate is to use climate models based on carefully constructed scenarios of emission of greenhouse gases. Previous studies (Lal and Bhaskaran 1992; Meehl and Washington 1993; Lal *et al* 1994, 1998; Rupa Kumar and Ashrit 2001; May 2002, 2004; Kripalani *et al* 2005; Rupa Kumar *et al* 2006; Rajendran and Kitoh 2008) examined the possible impact of the global warming on Indian summer monsoon using the output of different climate models. However, there are uncertainties in the regional climate projections due to the inaccuracies of the global climate models. The confidence in regional climate projections will depend on how well the models are able to simulate the 20th century monsoon climate. We can give considerable confidence in quantitative estimates of future climate change if the models showed ability to simulate the important aspects of current climate. The ability of the models to represent important climate features increases our confidence that they represent the essential physical processes important for the simulation of future climate change. Assessment of the future climate change should take into account the model skill and biases in the simulations of the present day climate. Therefore, it is important to assess how well the climate models simulate the 20th century monsoon circulation and rainfall and to assess the model biases.

Unprecedented levels of evaluation of the climate models have taken place over the last decade in the form of multi-model inter-comparisons. The global model inter-comparison activities began in late 1980s and continued with the Atmospheric Model Inter-comparison Project (AMIP) (Gadgil and Sajini 1998; Gates *et al* 1999). Several other climate model evaluations have been also conducted as part of specific projects, e.g., CMIP (Coupled Model Inter-comparison Project: Meehl *et al* 2000, 2007; Covey *et al* 2003; Achuta Rao *et al* 2004), and CLIVAR GCM Inter-comparison Project (Kang *et al* 2002; Kucharski *et al* 2008). Starting in the mid 1990s, a World Climate Research Programme (WCRP) committee (CLIVAR) working group on Coupled Models (WGCM) organized the first global coupled climate model inter-comparison exercise whereby modeling groups performed control runs and idealized 1% per year CO_2 increase experiments (Meehl 1997). Subsequently, there were several additional phases of the coupled model inter-comparison project (CMIP), termed as CMIP2 and CMIP2+ (Meehl *et al* 2000, 2005; Covey *et al* 2003).

There are several studies analyzing the skill of climate models (both AGCMC and coupled models) in simulating the mean Indian monsoon and its variability. Studies on the simulation and prediction of the monsoon (Gadgil and Sajini 1998; Kang *et al* 2002; Wang *et al* 2004) have suggested that there are significant problems in the representation of the mean monsoon climate and its variation on different time scales. The analysis by Gadgil and Sajini (1998) of 20 atmospheric GCMs organized under AMIP showed that atmospheric models have not evolved to a stage where they can simulate the year-to-year variation of the Indian monsoon realistically. One of the problems in using atmospheric models for prediction is that the sea surface temperature (SST) has to be prescribed for the period of prediction. The AMIP simulations were made with the SST specified from observations and are therefore expected to have better skill than predictions made with predicted SST. Out of the 20 models, only one model could predict the large rainfall deficit of the drought year, 1979. The study by Wang *et al* (2005) indicated that the state-of-the-art AGCMs when forced by observed SST are unable to simulate properly Asian–Pacific summer monsoon rainfall. In their analysis, over parts of Western Pacific, the correlation between SST and rainfall is negative while over the Indian region it is insignificant. All AGCMs yield positive SST-rainfall correlations in the summer monsoon. Their study suggested that the coupled ocean-atmosphere processes are crucial in the monsoon regions where atmospheric feedback on SST is critical. We reconsider this question in section 7.

The analysis by Gadgil *et al* (2005) showed that the problems in simulating the year to year rainfall variations persisted with the coupled atmosphere ocean general circulation models also. This exercise was done by analyzing the model forecast results from the 'Development of a European Multimodel Ensemble System for seasonal to interannual prediction' (DEMETER) project. The correlation between the simulated and observed rainfall for the 43-year period was poor. The pattern correlation suggests that positive correlations are observed only over the central parts of India, but they are statistically not significant. The model simulation showed the anomaly of the correct sign in four out of the 8 drought years. In 1997, a major El Niño year, the model suggested deficient monsoon, but the observed rainfall was above normal. In section 8.1, we re-assess the ability of coupled models to predict monsoons on the seasonal scale using the 'ENSEMBLES' forecasts.

For the fourth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC AR4), climate modeling groups have performed a well coordinated set of 20th and 21st century climate change experiments, including the projections for the 22nd century. For this purpose, climate modeling groups have used the state-of-the-art coupled ocean-atmosphere models. One of the aims of this exercise was to assess the ability of the coupled climate models to produce realistic projections of future climate change. This project differed from previous model intercomparisons in that a more complete set of experiments was performed, including unforced control simulations. It also differed in that, for each experiment, multiple simulations were performed by some individual models to make it easier to separate climate change signals from internal variability within the climate system.

A few recent studies have already reported the results of IPCC AR4 coupled models on south Asian monsoon and its future climate. Kripalani *et al* (2007) have examined the future climate scenario over south Asia under the doubling CO_2 scenario using six coupled models. Out of the 22 models considered, they found six models generate realistic 20th century monsoon climate. Projections reveal a significant increase in mean monsoon rainfall of 8% and a possible extension of the monsoon period. They attributed the projected increase in rainfall to the projected intensification of the heat low over northwest India, the trough of low pressure over the Indo-Gangetic plains and the land-ocean pressure gradient. They also found the El Niño/Southern Oscillation (ENSO)-monsoon relationship to be weakened in the future climate. Annamalai *et al* (2007) studied the relationship of South Asian monsoon with ENSO in the IPCC AR4 models. They have also found that six out of 18 models have reasonably realistic representation of the present day monsoon precipitation climatology. The study revealed that the ENSO-monsoon relationship will not weaken as the global climate warms up. The strength of the relationship in the model runs waxes and wanes to some degree on decadal timescales. The overall magnitude and timescale for this decadal modulation in most of the models is similar to the observations. Nanjundiah *et al* (2005) have addressed the impact of increase in CO_2 on the simulation of Tropical Biennial Oscillations (TBO) in 12 coupled models. TBO is defined as the tendency of the Asian monsoon to alternate in strength between low rainfall and high rainfall monsoon in consecutive years, which is caused due to large-scale coupled land-ocean-atmosphere interactions in the Indo-Pacific region. In the global warming scenario, the Indian and Australian precipitation showed an increase in TBO as the primary mode. This could be related to changes over the Niño 3.4 region through Walker circulation. Dai (2006) analyzed the precipitation characteristics of 18 IPCC AR4 coupled models and compared this with observations. Although most models reproduce the observed broad patterns of precipitation amount, models without flux corrections still showed an unrealistic double-ITCZ pattern over the tropical Pacific. This is related to westward expansion of the cold tongue of sea surface temperature (SST) that is observed only over the equatorial east Pacific but extends to the central Pacific in the models.

In the future climate change scenario, the largest impact on society will likely come from changes in precipitation patterns and variability. It is a big challenge for coupled global climate models (CGCMs) to realistically simulate the regional patterns, temporal variations and correct combination of frequency and intensity of precipitation (Trenberth *et al* 2003; Meehl *et al* 2005). The precipitation process in the atmosphere is quite complex due to cloud microphysics, cumulus convection, planetary boundary layer processes and large-scale circulations. It is known that most climate models tend to precipitate too frequently at reduced intensity, even though precipitation amount is reasonable (Dai and Trenberth 2004; Sun *et al* 2005). Sun *et al* (2005) showed that over land, most current coupled climate models overestimate the frequency of light precipitation (1–10 mm/day) and underestimate the intensity of heavy precipitation (>10 mm/day).

In this review paper, we examine the 20th century climate of the Indian summer monsoon simulated by seventeen IPCC AR4 models and discuss the systematic biases in the simulations of rainfall, sea surface temperatures (SST) and atmospheric circulation. Important aspects of the SST-rainfall relationship simulated by the climate models also have been critically examined. In section 2, the data used for this study and the methodology used are discussed. Observed rainfall and wind circulation climatology is discussed in section 3 and the results are discussed in sections 4–8.

2. Data and methodology

The WCRP/CLIVAR WGCM organized an international project to run a co-ordinated set of 20th and 21st-century climate simulations, as well as several climate change commitment experiments, for assessment in the IPCC AR4 (Meehl *et al* 2007). The IPCC climate model data were collected, archived and made available to the international climate science community by the Program for Climate Model Diagnosis and Inter-comparison (PCMDI) at the Lawrence Livermore National Laboratory, USA. This is the first time such a large set of climate change simulations had been made openly available for detailed analysis. The details of the IPCC AR4 coupled climate models considered in this study, their resolutions, along with key references are listed in table 1. Each model is identified by an abbreviated acronym (table 1). The major components of the coupled models such as atmosphere, ocean, sea ice, land and vegetation are interactive, while the interaction of other components such as atmospheric chemistry, bio-geochemistry, and aerosols varies from model to model. Most of these models do not use surface flux corrections at the ocean-atmosphere interface except the CCCMA, INM and MRI models. The new generation of non-flux adjusted control runs is nearly as stable as the flux-adjusted models. This is a significant advance compared to the previous generation of models, most of which employed flux corrections (Covey *et al* 2003) in order to maintain a stable climate in their control runs.

Some modeling groups submitted data to PCMDI from more than one model version. The two GFDL models (GFDL 2.0 and GFDL 2.1) differ in their dynamical core (having different numerical schemes for atmospheric advection), cloud scheme and land model. The atmosphere and oceans component models in GISS–AOM differ from those of GISS-EH and GISS-ER models. These latter two models only differ in the choice of ocean model. The Japanese group (JAMSTEC) models (MIHRES and MIMRES) employ the same physics, but are configured at different horizontal and vertical resolutions. From NCAR, there are two models, the Parallel Climate Model (PCM) and the Community Climate System Model Version (CCSM3). The UK Met office simulations include HadCM3 as well as their latest coupled model, HadGEM1. MHIRES model has the highest atmospheric resolution 1.125 lat. × 1.125 long, which was unthinkable some 5–10 years ago. Most of the models have the resolutions of 200–300 km in grid size. Ocean general circulation models often have higher horizontal resolutions than the atmospheric GCM. Some of the model groups have made many ensemble runs for the 20th century climate simulations as shown in table 1. The CCSM3 and GISS-ER models have a maximum realization of 9 ensembles each. Five models have made only one realization each.

In this paper, we have analyzed the data of monthly precipitation flux, wind circulation at 850 hPa and sea surface temperature (SST) available for the 17 models under the 20th century climate simulations (20 c^{3}m) scenario. The 17 models are listed in table 1. The total precipitation consists of convection and large-scale or stratiform precipitation. Model details and the data are available at http: //www-pcmdi.llnl.gov/ipcc/about_ipcc.php. The twentieth-century climate simulations started from a condition of the late nineteenth century (mainly in terms of atmospheric contents of trace gases and solar irradiance) by branching out from a pre-industrial control run. Historical time series of atmospheric CO_2 and other greenhouse gases, sulfate aerosol direct effects and volcanic and solar forcing were generally included in these model simulations, although specific treatments of these forcings vary among the models.

For validating the model simulations, we have used the Global Precipitation Climatology Project (GPCP) rainfall data (Adler *et al* 2003). The GPCP project was initiated under the WCRP to evaluate and provide global gridded data sets of monthly precipitation, based on all suitable observational techniques. The data set is ideally used for verification of climate model simulations. For SSTs, we have used the SST climatology based on the NOAA OI.v2 reanalysis using the method of Reynolds and Smith (1994). We have used the NCEP/NCAR monthly reanalysis data (Kalney *et al* 1996) for analyzing the observed circulation climatology.

For further detailed analysis, we have considered the 10 best coupled models out of 17 models listed in table 1. For this purpose, we have considered pattern correlations and root mean square errors (RMSE) between the observed rainfall climatology and simulated rainfall climatology over the Indian region including the oceanic area (70.0°–90.0°E, 5.0°–27.5°N). Figure 1 shows the pattern correlations and RMSE of the 17 models considered here. There is a good relationship between the pattern correlation and RMSE. Models with high pattern correlation have low RMSE. GFDL 2.0 model

Table 1. Climate models, resolutions, number of ensemble runs for 20 c^{3}m and reference in the IPCC AR4 experiments. Abbreviated acronyms are used in the text to identify each model.

No.	Modeling group	Model identification	AGCM resolution	OCGM resolution	Number of realization	Reference
1	National Centre for Atmospheric Research, USA	CCSM3			9	Collins *et al* (2006)
2	Canadian Centre for Climate Modeling and Analysis, Canada	CCCMA	T47 L31	192 × 96 L29	1	Flato *et al* (2000)
3	Meteo-France/Centre National De Recherches Meteorologiques, France	CNRM	T42 L45	180 × 170 L33	1	Salas-Melia *et al* (2005)
4	Max Planck Institute for Meteorology, Germany	MPI	T65 L32	1 × 1 L42	4	Junclaus *et al* (2006)
5	Geophysical Fluid Dynamics Laboratory (GFDL) USA	GFDL 2.0	N45 L24	1 × 0.33 L50	3	Delworth *et al* (2006)
6	Geophysical Fluid Dynamics Laboratory (GFDL) USA	GFDL 2.1	N45 L24	1 × 0.33 L50	3	Delworth *et al* (2006)
7	NASA/Goddard Institute for Space Studies, USA	GISS-AOM	90 × 60 L12	90 × 60 L16	2	Russel *et al* (1995)
8	NASA/Goddard Institute for Space Studies, USA	GISS-EH	72 × 46 L17	2 × 2 cos(lat) L16	5	Schmidt *et al* (2006)
9	NASA/Goddard Institute for Space Studies, USA	GISS-ER	72 × 46 L17	72 × 46 L13	9	Schmidt *et al* (2006)
10	Institute for Numerical Mathematics, Russia	INM	4 × 5 L21	2 × 2.5 L33	1	Diansky and Volodon (2002)
11	Institut Pierre Siomn Laplace	IPSL	96 × 72 L19	2 × 2 L31	2	Marti *et al* (2005)
12	Center for Climate System Research/ National Institute for Environmental Studies and Frontier Research Center for Global Change (JAMSTEC), Japan	MIHRES	T106 L56	T106 L48	1	K-1 Model developers (2004)
13	Center for Climate System Research/ National Institute for Environmental Studies and Frontier Research Center for Global Change (JAMSTEC), Japan	MIMRES	T42 L20	256 × 192 L44	3	K-1 Model developers (2004)
14	Meteorological Research Institute, Japan	MRI	T42 L30	2 × 0.5–2.5 L23	5	Yukimoto *et al* (2001)
15	National Center for Atmospheric Research, USA	PCM	T42 L18	384 × 288 L32	4	Washington *et al* (2000)
16	Hadley Centre for Climate Prediction and Research/ Meteorological Office	UKMO HadCM3	2.5 × 3.75	1.25 × 1.25 L20	2	Jones *et al* (2004)
17	Hadley Centre for Climate Prediction and Research/Meteorological Office	UKMO HadGEM1	N96 L38	1 × 0.33–1 L40	1	Jones *et al* (2006)

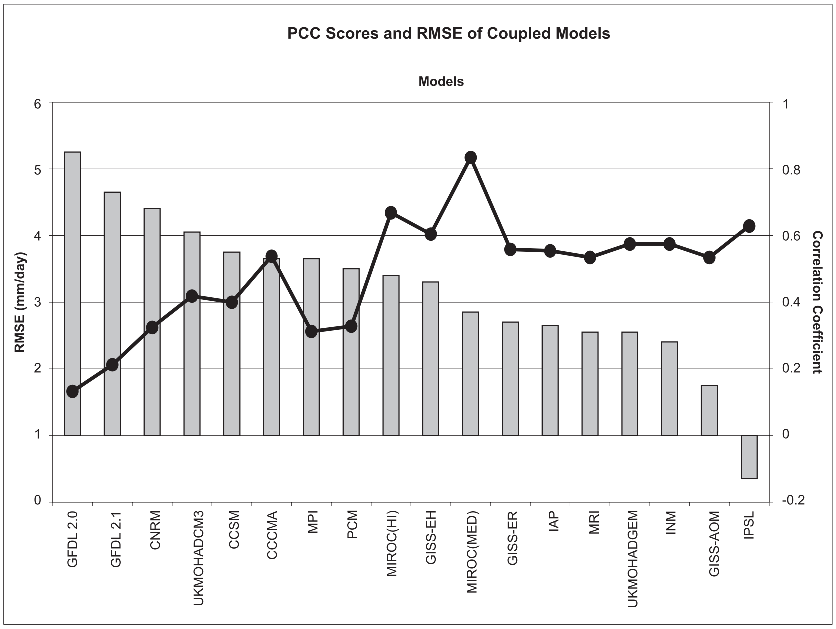


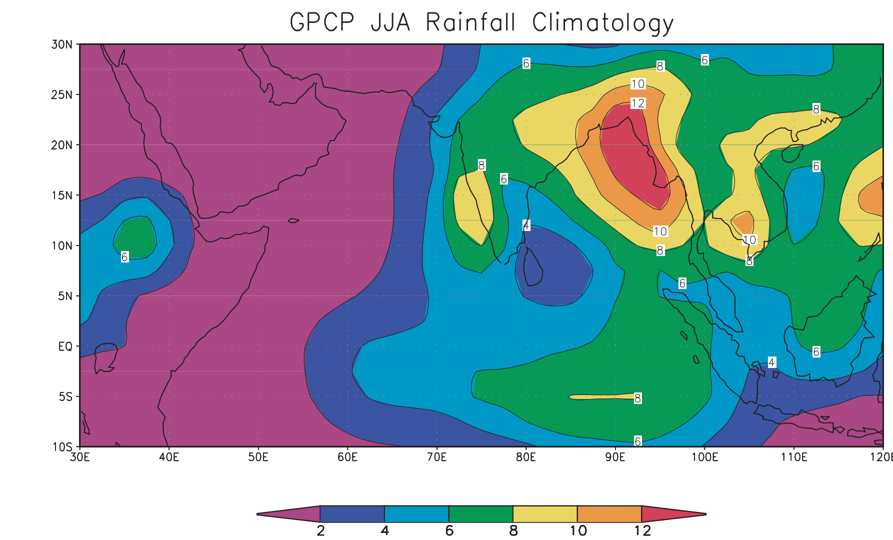
Figure 1. Pattern correlations and root mean square error (RMSE) of the rainfall (JJA) (mm/day) of 17 IPCC AR4 models with observed GPCP rainfall over the region 70.0°–87.5°E, 5.0°–27.5°N.

has the highest pattern correlation and the lowest RMSE. The other version of the GFDL (GFDL 2.1) model ranks the second. IPSL has negative correlation and RMSE more than 4 mm/day. Interestingly, the later version of the UK Met office (UKMOHadGEM1) model has lower (higher) pattern correlation (RMSE) compared to the earlier version (UKMOHadCM3). Out of the 3 coupled models with flux corrections, only CCCMA model has higher pattern correlation and lower RMSE. Other two models (MRI and INM) have low values of pattern correlation over the Indian region. We have considered the first 10 models with pattern correlation more than 0.4 for further analysis. These models are GFDL 2.0, GFDL 2.1, CNRM, UKMOHadCM3, CCSM, CCCMA, MPI, PCM, MIHRES and GISS-EH. The analysis of Kripalani *et al* (2007) showed that CCCMA, MPI, CNRM, MIHRES and UKMOHadCM3 models are among the seven best models considered to simulate inter-annual monsoon variability well. The models CCCMA, MPI, CNRM, MIHRES and UKMOHadCM3 also simulated the biennial oscillation (TBO) of monsoon rainfall reasonably well. Annamalai *et al* (2007) analyzed the IPCC AR4 models and found that six models (GFDL 2.0, GFDL 2.1, MPI, MRI, UKMOHadCM3 and PCM) showed a higher pattern correlation and lower root mean square difference compared to the observed rainfall. However, they have considered a larger area of south Asian monsoon for calculating the pattern correlation compared to the area considered in this study.

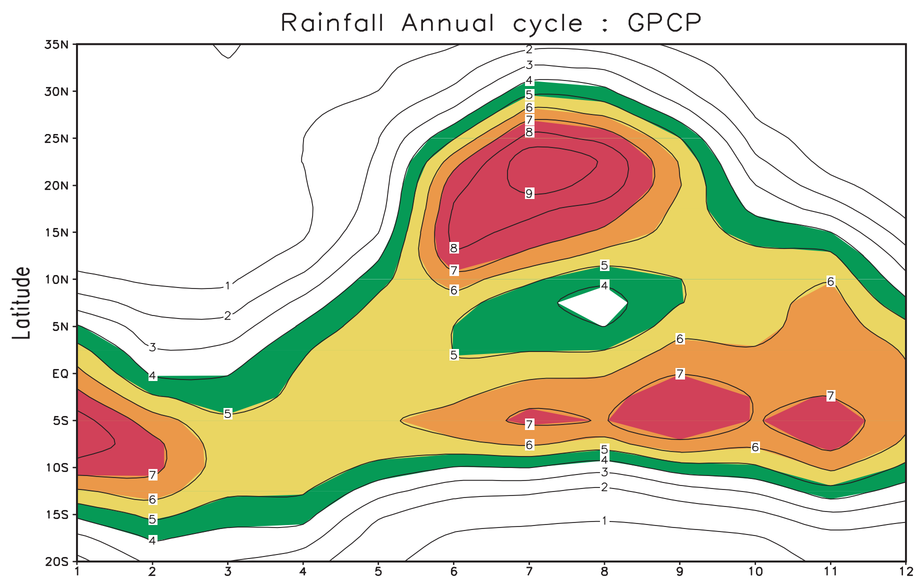
3. Observed mean precipitation and atmospheric circulation

The large-scale rainfall over the Indian region is associated with the tropical convergence zone (TCZ), which is characterized by intense convergence in the boundary layer, cyclonic vorticity above the boundary layer and organized deep moist convection. This TCZ is called the Continental TCZ (CTCZ) to distinguish it from the more common ITCZ. The CTCZ is a part of the planetary scale TCZ stretching from the Indian region to the tropical Pacific. The variation of the large-scale rainfall over the Indian region during the summer monsoon is linked to the space-time variation of the CTCZ (Sikka and Gadgil 1980). During the onset phase of summer monsoon, a TCZ appears intermittently over the equatorial Indian Ocean. During the onset phase, the TCZ over the equatorial Indian Ocean propagates northward in one or more spells. The CTCZ gets established over the core monsoon zone in July at the end of the onset phase of the summer monsoon. Thus, a major transition from a heat trough to a moist convective regime characterizing a TCZ occurs. Throughout the peak monsoon months of July and August, the CTCZ fluctuates primarily over this core monsoon zone.

Figure 2(a) shows the observed (GPCP) rainfall climatology during the summer monsoon season (June to August) over the south Asian region. Important features of the observed climatology are the rainfall maximum over the north Bay of Bengal



(a)



(b)

Figure 2. **(a)** Summer monsoon mean seasonal (JJA) rainfall (mm/day). **(b)** Month-latitude variation of seasonal mean (JJA) monsoon rainfall (mm/day) averaged over longitudes 65°E and 87.5°E.

and adjoining northeast India and along the west coast of India and low rainfall over northwest and southeast India. Another important feature is the rainfall maximum over southeast equatorial Indian Ocean, which is observed both on seasonal and sub-seasonal time scales. Latitude variation of mean rainfall averaged over the longitudes 70°–90°E for each month is shown in figure 2(b). It shows clearly the northward seasonal migration of inter-tropical convergence zone (ITCZ) in response to the seasonal variation of the latitude of maximum insolation. This northward migration is a unique feature observed over the south Asian region. During the monsoon season of June to September, maximum rainfall is observed between the latitudes 20°N and 25°N. Over the equatorial Indian Ocean, maximum rainfall is observed almost throughout the year, except during the spring season. During the peak monsoon season, maximum rainfall is observed over the monsoon zone (CTCZ) and also over the south equatorial Indian Ocean.

The observed mean atmospheric circulation over the south Asian region at 850 and 200 hPa levels during the JJA season is shown in figure 3. The most important features of the circulation pattern at 850 hPa are the monsoon westerlies and the low level jet stream passing across the equator into the Indian sub-continent. The northward horizontal

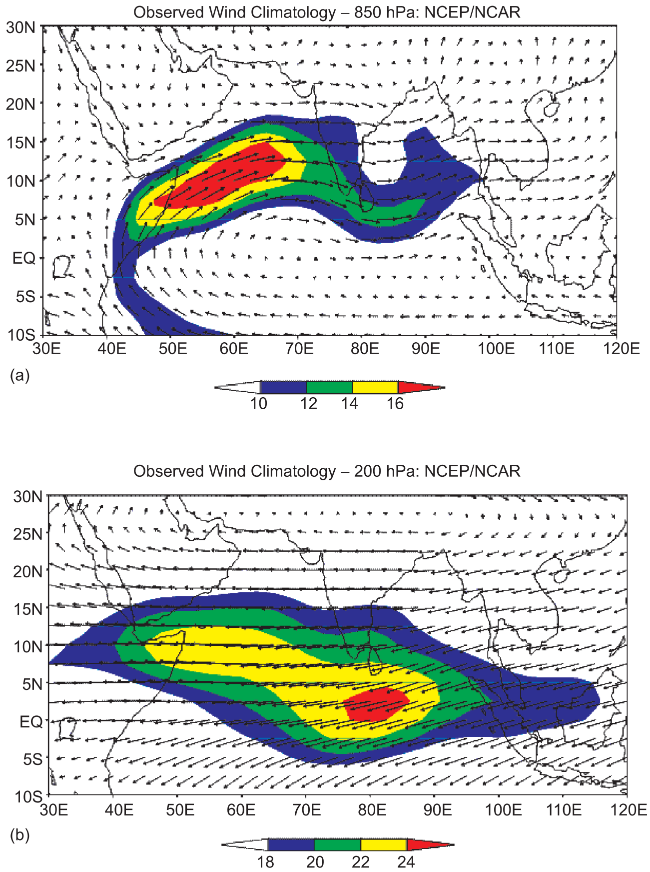


Figure 3. Observed climatology of summer monsoon circulation **(a)** 850 hPa mean wind and **(b)** 200 hPa mean wind over the Indian region. Wind speeds are in ms^{-1}.

wind shear is also noted. At 200 hPa level, the most important feature is the presence of the tropical easterly jet (TEJ) over the lower latitudes.

4. Coupled model simulations of twentieth century monsoon rainfall

4.1 *Mean monsoon seasonal rainfall*

The spatial pattern of the mean monsoon seasonal rainfall for the period JJA, simulated by the 10 IPCC AR4 models is shown in figure 4 and the differences between the simulated and observed (GPCP) rainfall are shown in figure 5. There are large differences between the observed and model simulated rainfall. The observed rainfall maximum over north Bay of Bengal was reasonably simulated by at least five models (UKMOHadCM3, CCSM3, CCCMA, MPI and PCM). In the GFDL 2.0 model, the Bay of Bengal rainfall maximum is shifted slightly eastwards. The other rainfall maximum along the west coast was reasonably well simulated by the GFDL models, CNRM, UKMOHadCM3, CCSM3 and MIHRES. In the MPI model, the rainfall maximum is shifted slightly northwards. The most important aspect of all the models is the over-estimated rainfall simulation over the equatorial Indian Ocean. The difference plots (figure 5) show that the differences over the equatorial Indian Ocean are of the order of 3–4 mm/day, which is equivalent to 90–120 mm. 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 ITCZ with the northward migration of solar insolation. As discussed in the previous section, this northward migration of ITCZ is a unique feature observed over the south Asian region. Since the models do not simulate the northward migration of ITCZ realistically, the rainfall over the continental tropical convergence zone (CTCZ) (monsoon trough zone) is also not simulated realistically. Over the CTCZ region, model simulated rainfall is appreciably less than the observed rainfall.

The seasonal migration of the ITCZ precipitation is a challenging problem of long standing. ITCZ precipitation is a result of complex nonlinear interaction among dynamical, thermodynamic, and physical processes. The seasonal migration of the ITCZ onto the heated continent in the boreal summer is the most important feature of the seasonal variation over this region. The Asian region is also more complex, because of the presence of warm oceans equatorward of heated continents. Most general circulation models are unable to reproduce the seasonal migration of the ITCZ precipitation (Hack *et al* 1998; Gates *et al* 1999; Wu *et al* 2003). Gadgil and Sajini (1998) examined the AMIP-I models for their skill in simulating the seasonal migration of the primary rain-belt. They found that in several atmospheric models, this rain-belt remains over the equatorial oceans in all the seasons. They concluded that the models which simulated the northward migration of rain-belt also simulated the interannual variation of the Indian monsoon reasonably well. This inference also supports the suggestion by Sperber and Palmer (1996) that a good rainfall climatology and proper simulation of the interannual variation are associated.

Using 20-year GCM simulations with observed SSTs, Wu *et al* (2003) identified that the secondary meridional circulation induced by convective momentum transport is the missing dynamical mechanism that causes the common failure in GCMs in simulating the seasonal migration of ITCZ precipitation across the equator. Lin (2007) addressed the issue of double-ITCZ problem in the 20th century simulation of the IPCC AR4 coupled models. The study revealed that most of the current state-of-the-art coupled models have

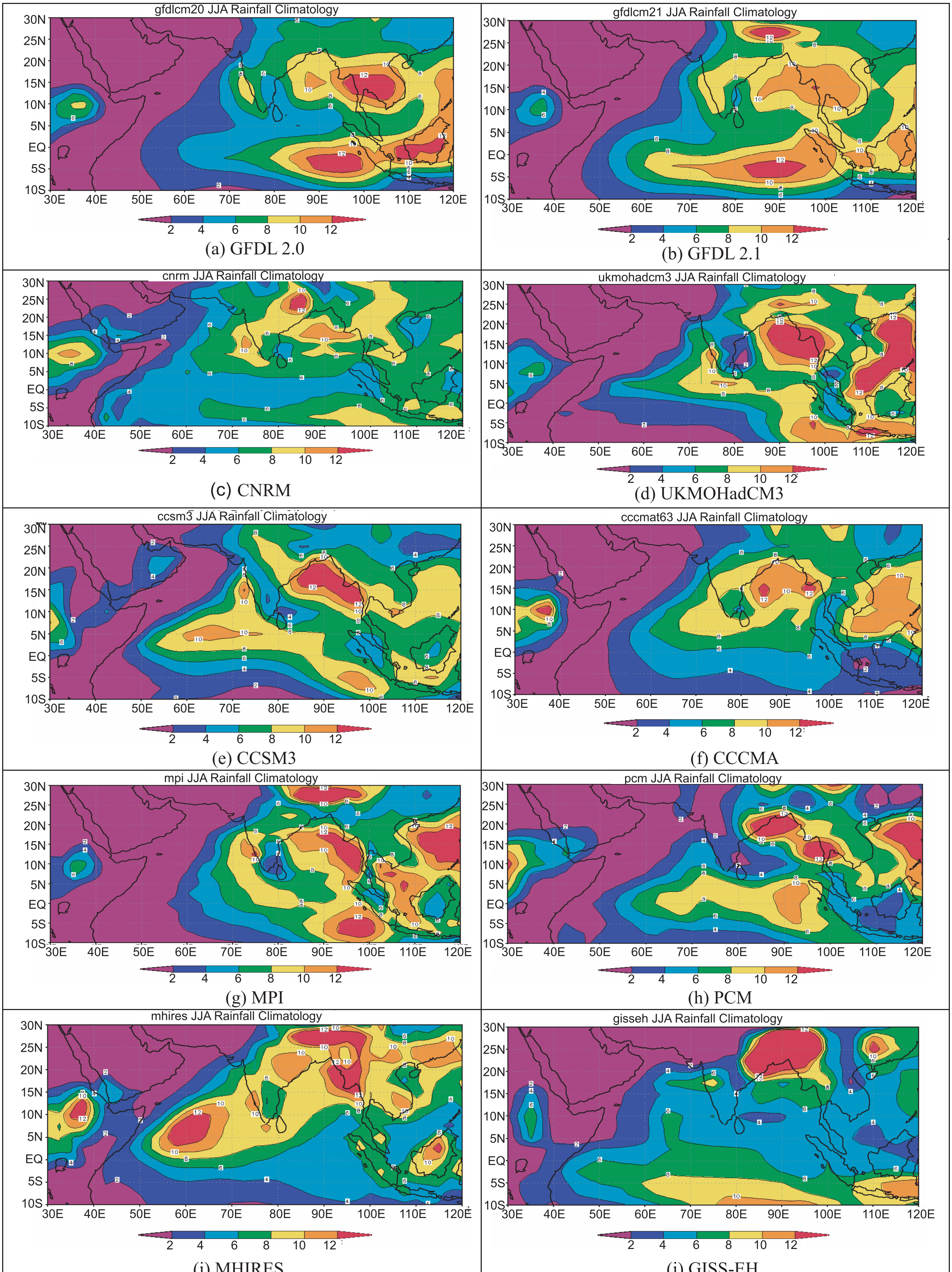


Figure 4. Monsoon seasonal (JJA) rainfall (mm/day) from the IPCC AR4 coupled models.

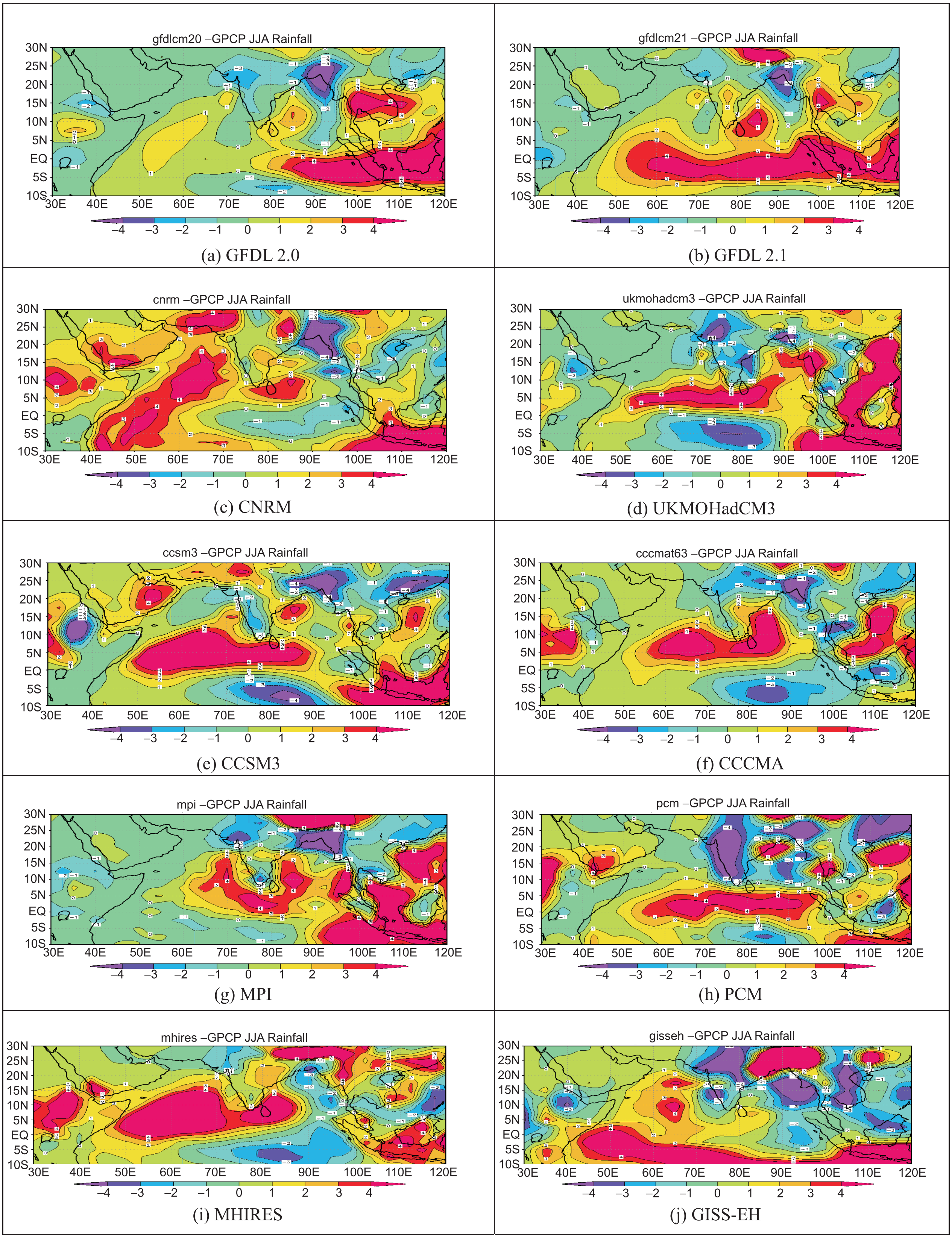


Figure 5. The difference between the model simulated and observed (GPCP) mean seasonal (JJA) rainfall in mm/day.

some degree of the double ITCZ problem, which is characterized by excessive precipitation over much of the tropics including the equatorial Indian Ocean. The excessive precipitation over the tropics usually causes overly strong trade winds, excessive latent heat flux, insufficient shortwave flux and thus leading to significant cold SST bias in much of the tropical oceans. The study found this problem with the atmospheric models also, which suggests that the excessive precipitation over the equatorial Indian Ocean is an intrinsic error of the atmospheric models.

4.2 *Annual cycle of rainfall over the Indian region*

The monthly variation of mean rainfall averaged over the Indian region (5.0° –27.5°N, 70.0°–90.0°E) for all the 10 models are shown in figure 6 along with the observed rainfall. Even though there are large differences in the spatial distribution of rainfall as discussed above, all the models capture the annual cycle of monsoon rainfall averaged over the Indian region reasonably well. However, the PCM model does not show a sharp peak during the monsoon season. While the CNRM and MIHRES models overestimate the observed rainfall during the monsoon season, GFDL 2.0, UKMOHadCM3, MPI and GISS-EH models underestimate the observed rainfall.

The time-latitude variation of rainfall averaged over the longitudes 70°–90°E for all the 10 models is shown in figure 7. This variation needs to be compared with the observed time-latitude variation of observed rainfall shown in figure 2(b). In the observed pattern, the maximum rainfall is observed between 20°N and 25°N, which is of the order of 7 mm/day. However, only CNRM and GISS-EH models showed rainfall maximum above 20°N. Other models are not able to capture the mean rainfall over the continental tropical convergence zone (CTCZ) very well. These maps clearly show the excessive rainfall over the equatorial Indian Ocean, discussed earlier. In the PCM model, there is hardly any monsoon season over India, as the rainfall maximum is always confined below 10°N.

Figure 8 shows the latitude variation of seasonal (JJA) observed rainfall and the mean of simulated rainfall by all the ten models considered here. It clearly shows the model bias in the equatorial region and also over the monsoon zone region. The models overestimate the rainfall over the equatorial Indian Ocean and underestimate rainfall over the monsoon zone.

5. Coupled model simulations of mean monsoon circulation

The mean atmospheric circulation pattern at 850 hPa simulated by five climate models (GFDL 2.0, GFDL 2.1, CNRM, CCCMA and UKMO-HadCM3) is shown in figure 9. All the models, simulated the wind circulation at 850 hPa realistically, even though there are biases in the strength of monsoon westerlies over the Indian region. All the models simulate the cross equatorial monsoon flow, lower level jet stream and north-south horizontal wind shear and convergence zone over the CTCZ, reasonably well. In the CCCMA model, the strength of the cross equatorial monsoon flow over the Arabian sea is more than observed. The GFDL 2.1 model simulates stronger monsoon flow over the Arabian sea, compared to the GFDL 2.0 model. Therefore, the models considered here, simulated the mean monsoon circulation at 850 hPa reasonably well with some biases in the wind speed.

6. Coupled model simulations of sea surface temperatures (SST)

In this section, we examine the SST simulations of the coupled models in the 20th century climate. Since SST and rainfall is strongly coupled in the tropics, unrealistic simulation of SST distribution may cause unrealistic rainfall distribution. Figure 10(a) shows the observed SST climatology for the JJA season. The most important aspect of the SST distribution during the JJA season is the warm pool region over the west Pacific with SSTs more than 28.0°C, cold SST tongue along the east coast of Africa (over the equatorial west Indian Ocean) and along the west coast of south America (over the east Pacific Ocean). Another important aspect is the strong SST east-west gradient across the equatorial Pacific Ocean and also north-south gradient over the southern hemisphere.

Figures 10(b) to 10(f) show the spatial distribution of the differences of the model simulated SST compared to the observed SST (NOAA OI SST) during the JJA season for five different models. The most conspicuous aspect is the significant cold bias over the tropics, especially over the equatorial Pacific Ocean. Over the Indian Ocean, all the models except the UKMOHadCM3 model simulate colder SSTs compared to the observed SST. Some models underestimate SSTs over the Indian Ocean almost by 2.0°C. The colder bias in the equatorial Pacific may be due to the more westward extension of cold tongue towards the central equatorial Pacific. However, the systematic cold tongue bias over the equatorial Pacific is not seen in the CCCMA model, which has adopted flux correction methods. Dai (2006) suggested that the models without flux corrections may have errors in heat, water and momentum exchanges and associated positive feedbacks may amplify SST and rainfall biases in the tropics and contribute to the double-ITCZ problem. In the UKMOHadCM3, GFDL 2.0 and 2.1 and CCSM3 models, the SST

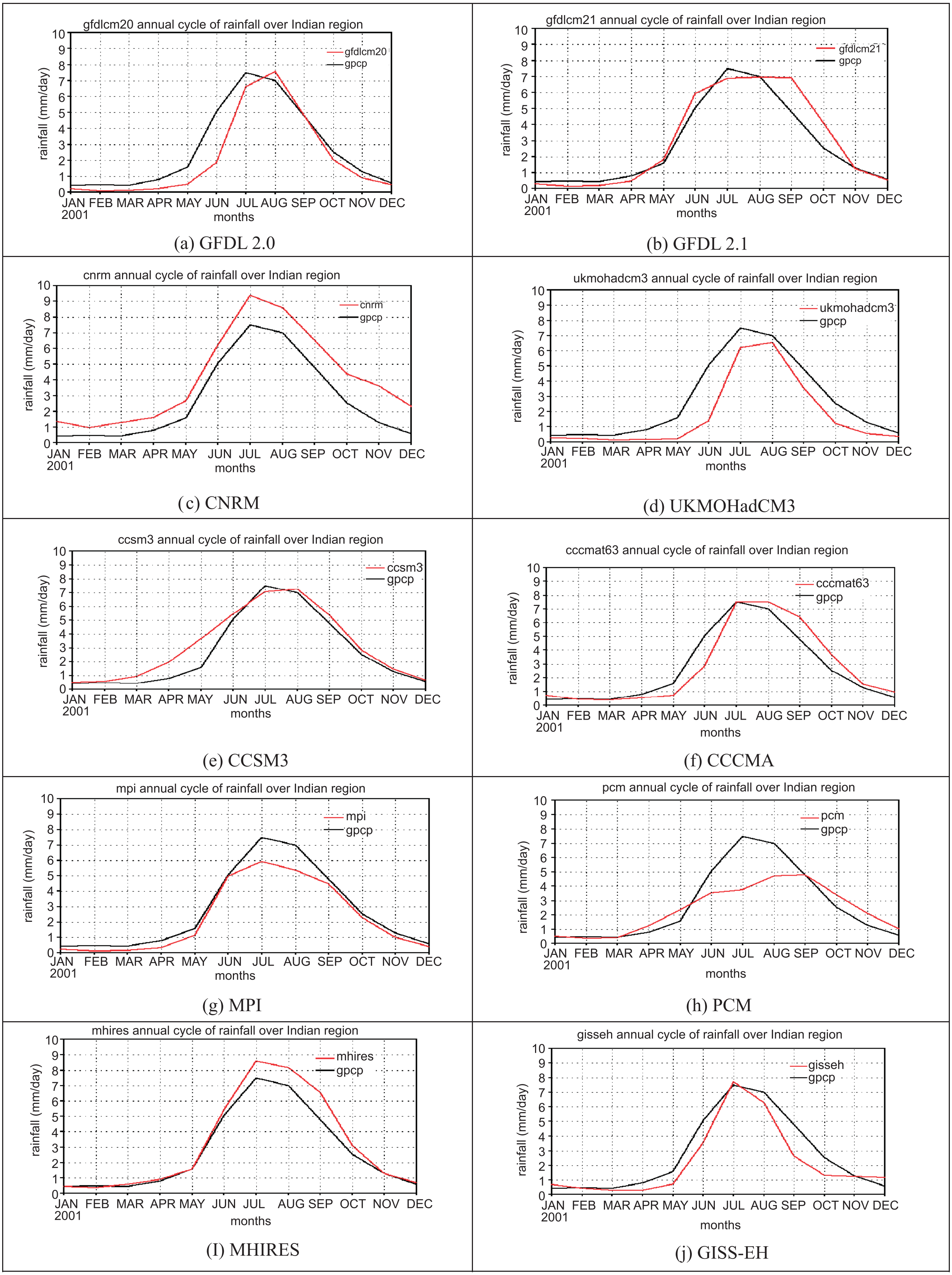


Figure 6. Annual cycle of the observed and model rainfall (mm/day) averaged over the area 5°–27.5°N, 70.0°–87.5°E.

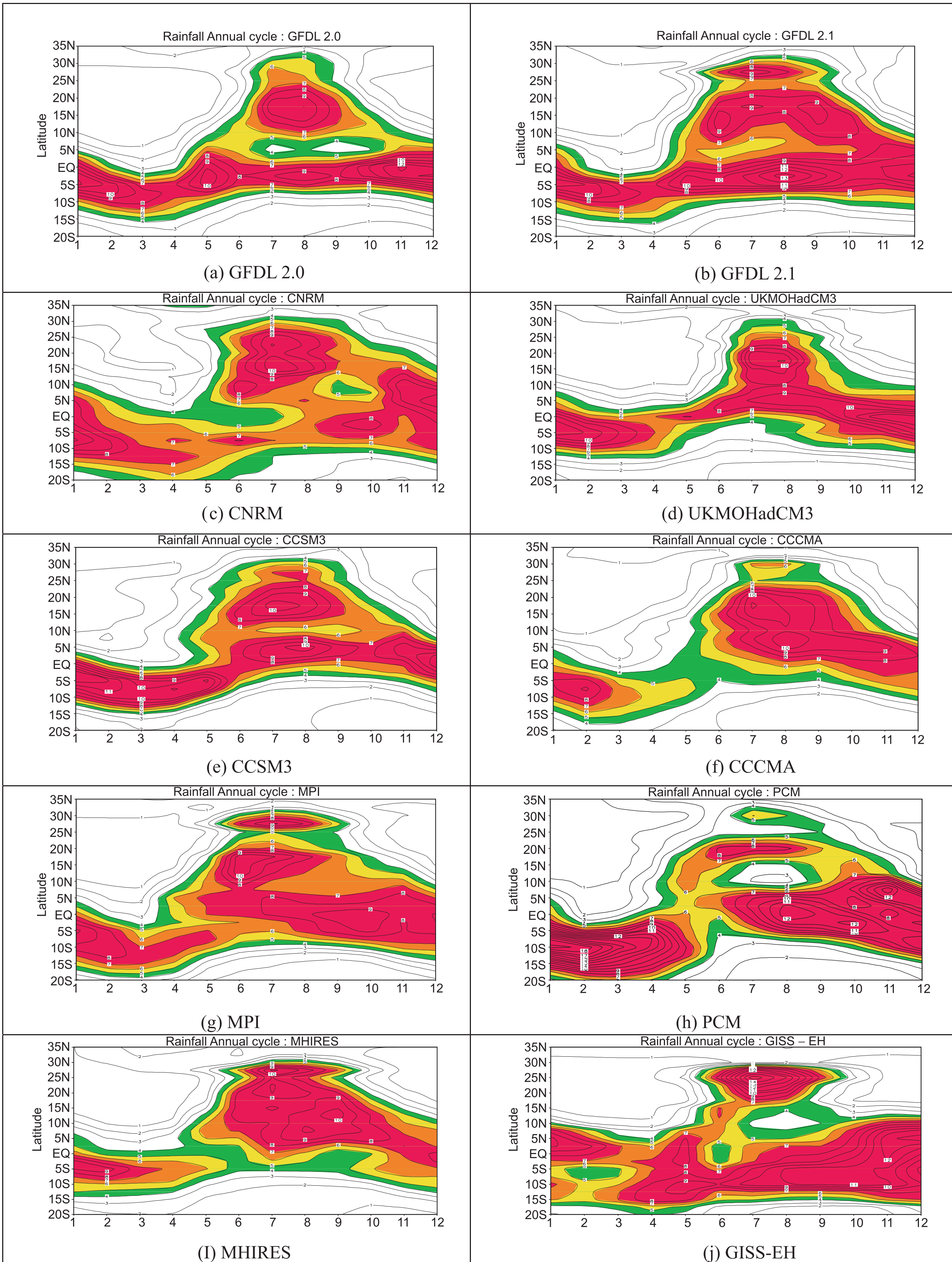


Figure 7. Latitude-month variation of coupled model simulated rainfall (mm/day) averaged over the longitudes 70°–90°E.

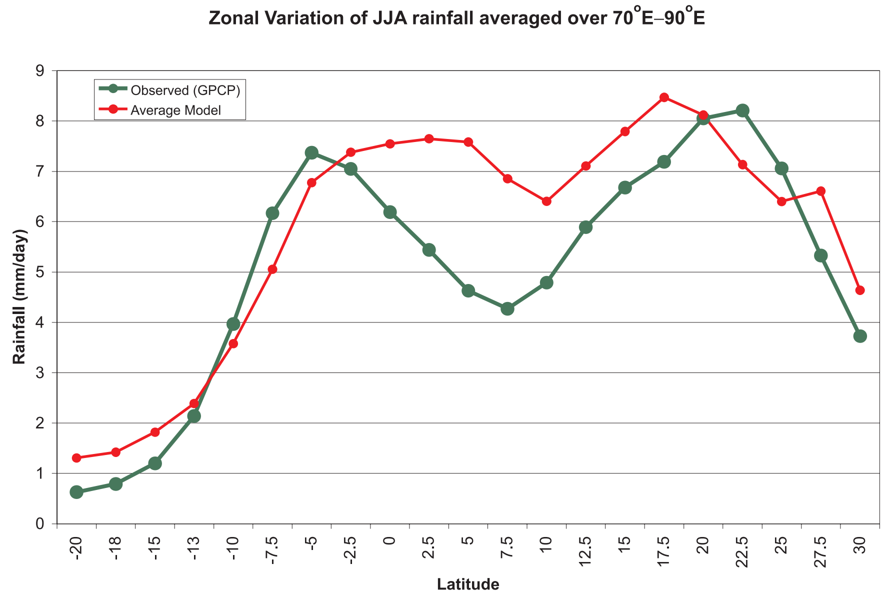


Figure 8. Zonal variation of observed and model (mean of all the 10 models) rainfall (mm/day) during June to August.

cold tongue does not extend to the coast of south America as in the observations. This may be due to weak ocean upwelling and biases in marine stratus clouds in the model (Lin 2007). In these models, positive SST biases are also seen along the west equatorial Indian Ocean, again may be due to weak ocean upwelling.

Figure 11(a) shows the frequency of SST values at every 1.0°C bins simulated by the 10 models against the observed SST frequency over the equatorial Indian Ocean. Figure 11(b) shows the same, but for the equatorial Pacific Ocean. Over the equatorial Indian Ocean, observed SST frequency peaks around 28.0–29.0°C, while over the equatorial Pacific Ocean, the peak frequency is between 27.0° and 28.0°C. The large negative bias in the simulated SSTs is clearly visible in these frequency bar charts. Over the Indian Ocean, the bias is more common in the 29.0–30.0°C interval. Among the models, the CNRM model has the largest negative SST bias. As mentioned earlier, the UKMOHadCM3 model has shown a positive bias. In spite of large negative SST biases in the models, at majority of the grid points over the equatorial Indian and Pacific Oceans, the model SST values are more than 27.0°C, close to the threshold SST value for initiating convection.

As we have seen in the previous sections, 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), 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). The excessive precipitation over the tropics usually causes strong trade winds, excessive latent heat flux, reduced short wave flux at the surface, leading to cold SST biases.

Nanjundiah *et al* (2007) 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 their model, i.e., for a given value of precipitable water, the rainfall estimated by the model is higher than observed. Lower SSTs lead to lower precipitable water over the Indian region. Thus, there is a compensation of errors, *viz*, lower SSTs reduce precipitable water while overestimation of rainfall leads to a more realistic simulation of rainfall. They further show that in their AGCM simulation, where the SST is specified, the rainfall is overestimated. A detailed study is therefore required to further examine this important link between SST and rainfall over the tropical Oceans. In the next section, we discuss the important issue of SST-rainfall relationship.

7. SST-rainfall relationship in the coupled models

The SST-rainfall relationship over the tropics is very complex. Observations suggested that the propensity for convection increases with SST and around 27.5°C, the mode shifts with the maximum frequency implying occurrence of organized deep convection. Gadgil *et al* (1984) concluded that over the Indian Ocean, 27.5°C is the threshold for deep convection. However, they noted that SST being above the threshold is necessary but not sufficient condition for organized deep convection. This means, tropical convection is known to depend on other factors like large-scale convergence, SST gradient, etc. The study by Wang *et al* (2004) suggests that the deficiencies in simulating the southeast Asia and west-north Pacific (WNP) monsoon rainfall results from the failure to simulate correctly the relationship between the local rainfall and SST anomalies over the tropical WNP, the south China Sea, and the Bay of Bengal. Over these warm oceans, the observed summer rainfall anomalies are negatively correlated with local SST anomalies, whereas in nearly all the models, rainfall anomalies

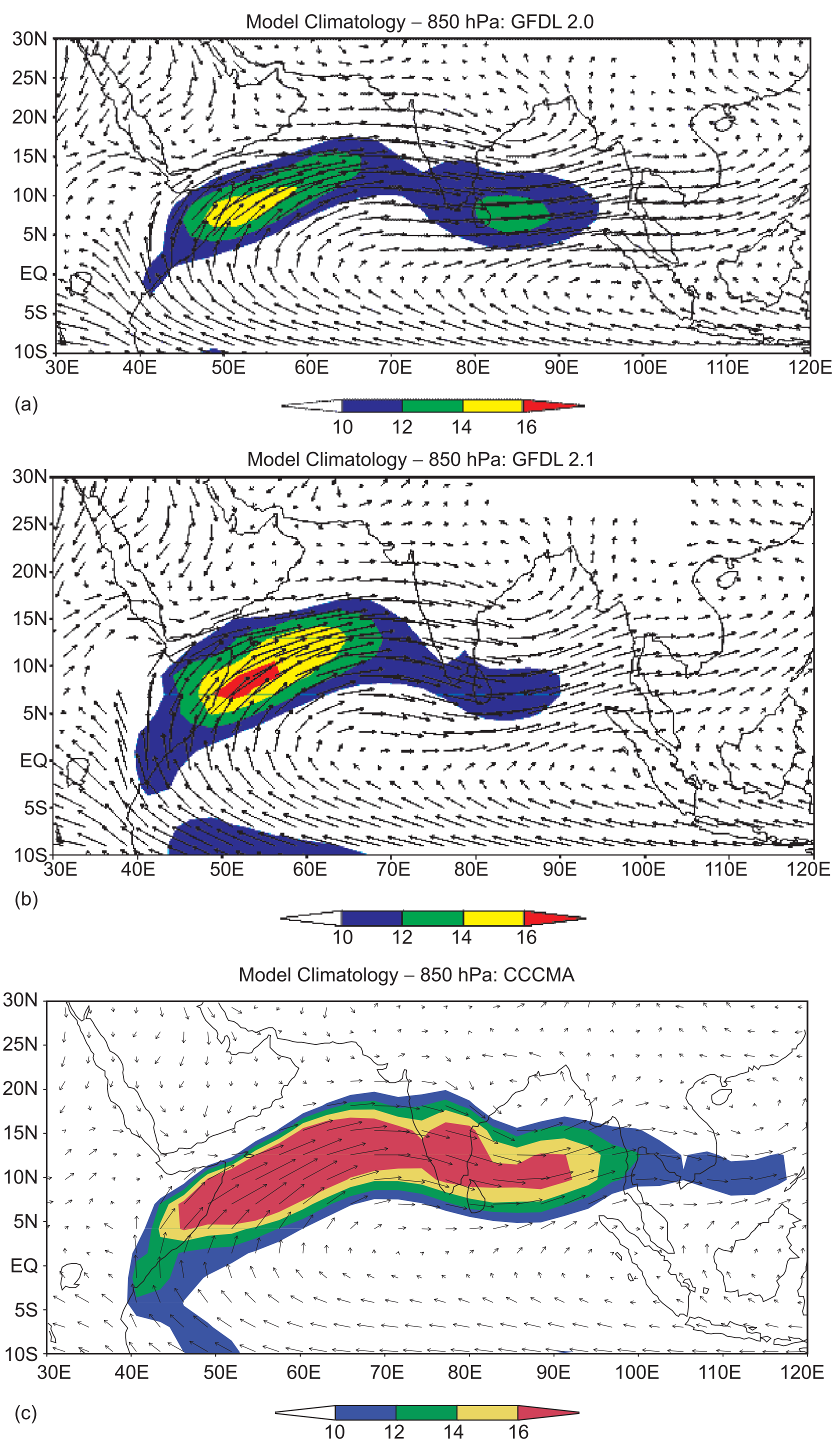


Figure 9. (*Continued*)

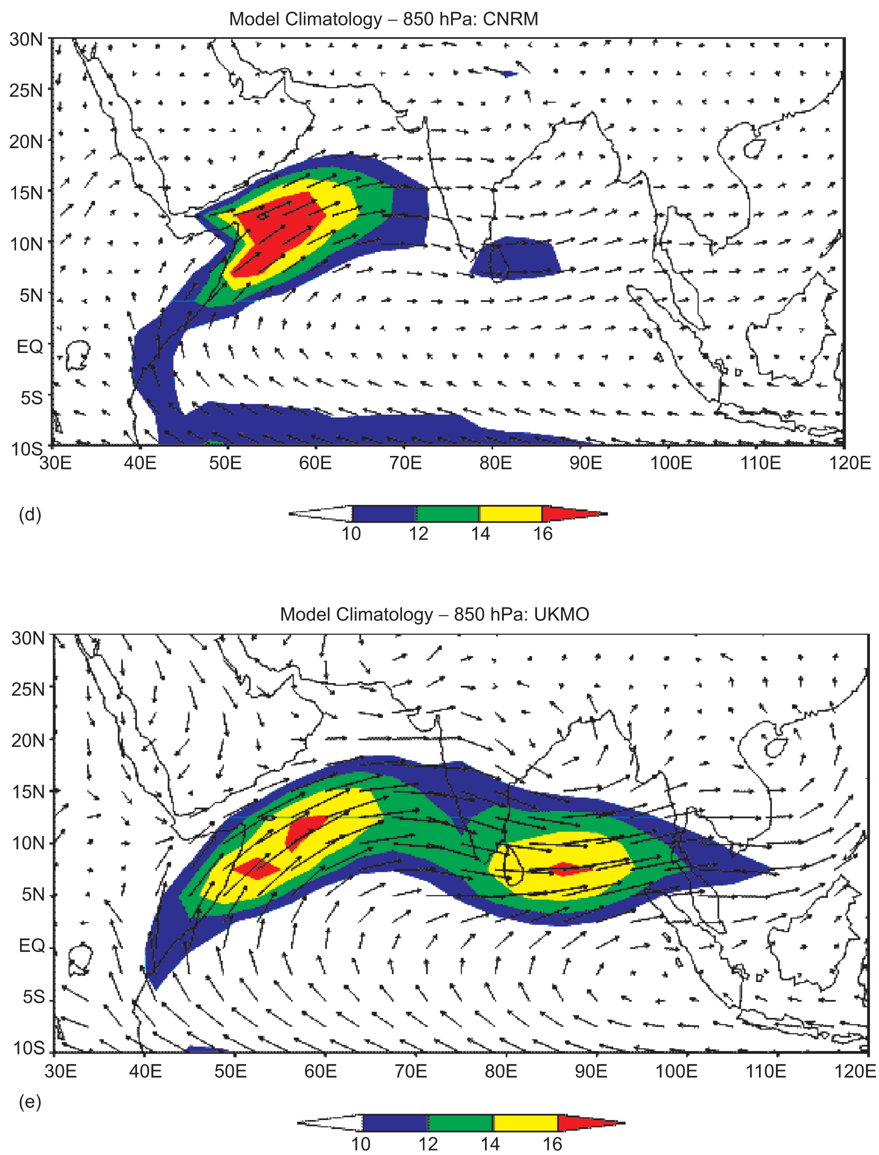
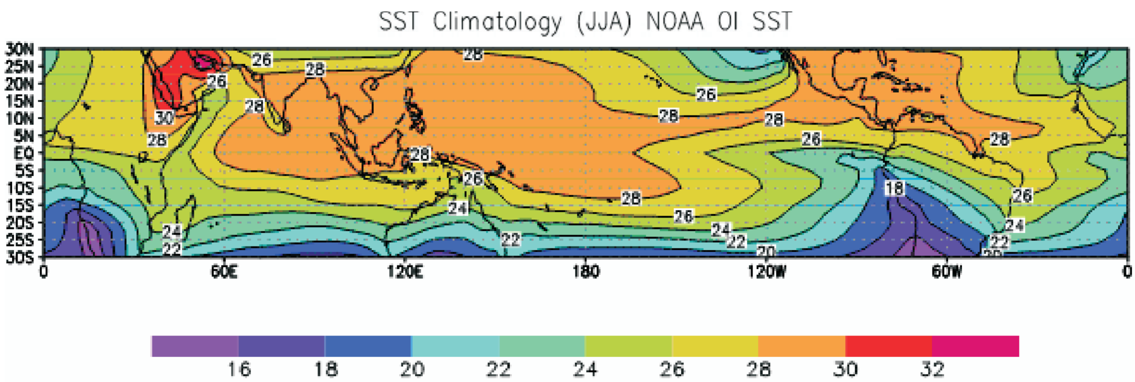


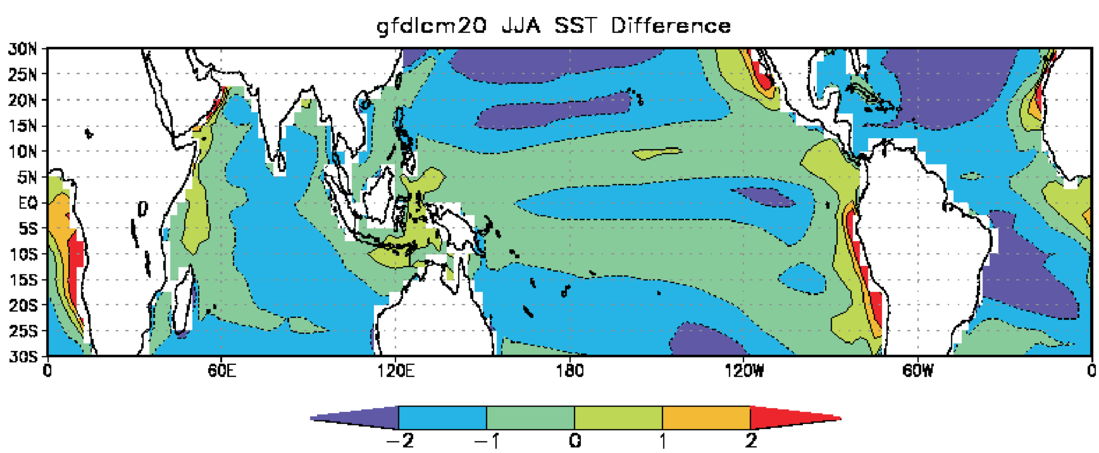
Figure 9. Simulated mean circulation at 850 hPa for the JJA season by the coupled models **(a)** GFDL 2.0 **(b)** GFDL 2.1 and **(c)** CCCMA **(d)** CNRM and **(e)** UKMOHadCM3. Wind speed $>10\,\mathrm{ms}^{-1}$ is shaded.

are positively correlated with local SST anomalies. They concluded by stating that this problem is attributed to the experimental design in which the atmosphere is forced to respond passively to the specified SSTs, while in nature the SSTs result in part from the atmospheric forcing. The study by Wang *et al* (2005) suggested that an AGCM, coupled with an ocean model, simulates realistic SST-rainfall relationships. Their study suggested that the coupled ocean-atmosphere processes are crucial in the monsoon regions where atmospheric feedback on SST is critical. Graham and Barnett (1987) have also studied the relationship between SST and convection. Their analysis shows that there exists a threshold of about 27.5°C above which the magnitude of convection is controlled not by SST. They conclude "... This suggests that where the SSTs are above Tc, remotely forced changes in vertical motion or stability or both play an important role in regulating convection." If we examine the regions where Wang *et al* (2004, 2005) find negative correlations (in the deep tropics), these are the regions where the SSTs are above the threshold temperature. Additionally, the correlations especially over the Indian Ocean region are insignificant. Hence it is not clear whether SST-rainfall relationship over the Indo-Pacific region is the cause of this problem. We examine the SST-rainfall relationship in coupled models to find out whether the nonlinear behaviour of rainfall-SST relationship is reproduced by coupled climate models.

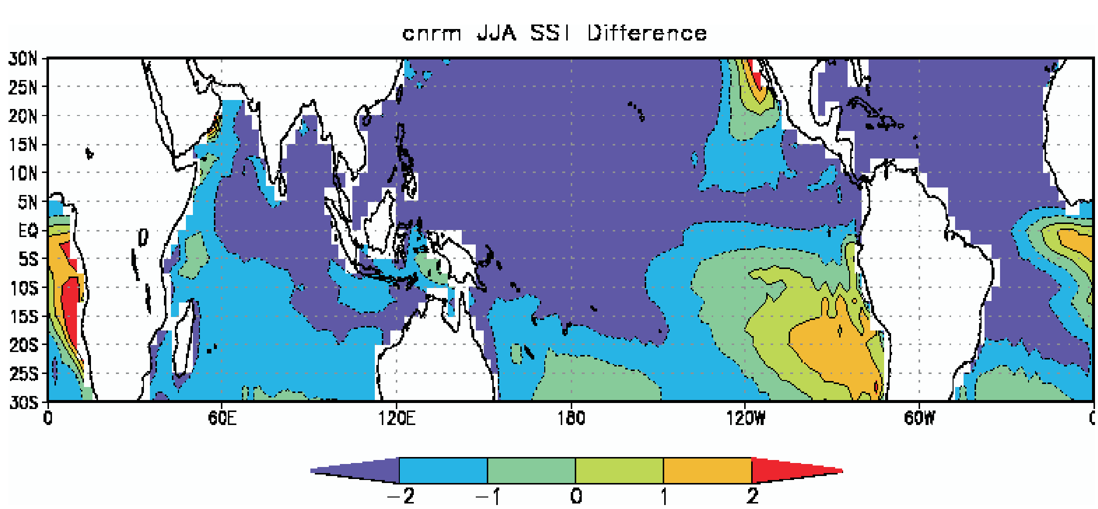
This rainfall-SST relationship may however differ from region to region. In order to see the regional variations of this relationship, we have considered 4 regions for examining the relationship. The regions considered are North Bay of Bengal, Arabian Sea, east equatorial Indian Ocean (EEIO) and west equatorial Indian Ocean (WEIO). The results of rainfall-SST relationship are shown in figure 12. The observed relationship between GPCP rainfall and NOAA OI SST is also shown as a thick black line.



(a) SST OI Climatology for JJA period

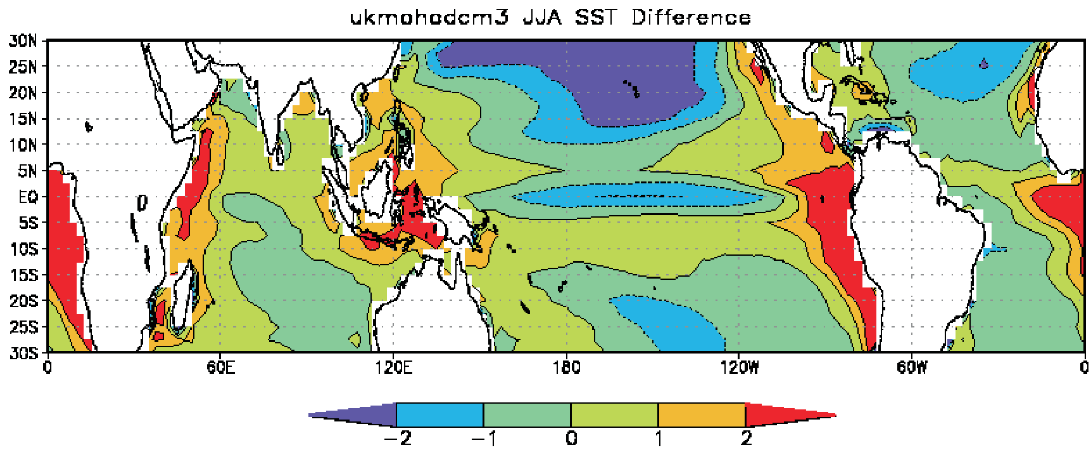


(b) GFDL 2.0

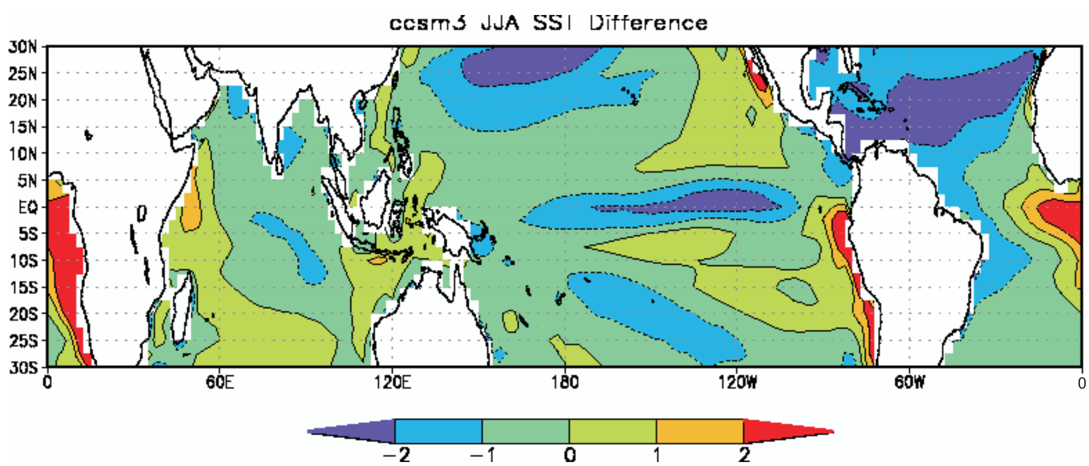


(c) CNRM

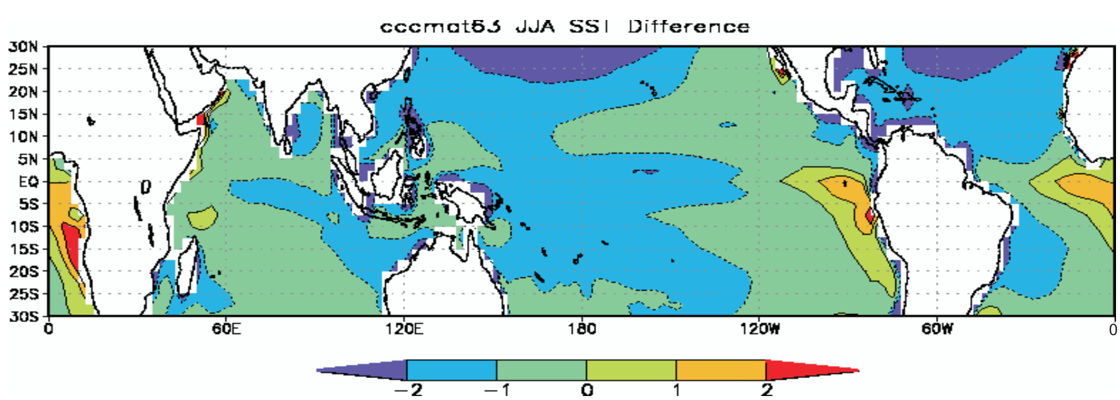
Figure 10. (*Continued*)



(d) UKMOHadCM3



(e) CCSM3



(f) CCCMA

Figure 10. **(a)** Observed SST (°C) climatology based on NOAA OI SST data for the JJA season. Figures **(b)** to **(f)** show the difference of SST (°C) simulated by the coupled models from the observed SST data.

Over the Indian monsoon region, maximum convection is observed over the north Bay of Bengal, where the SSTs are more than 28.0°C. Convection over the north Bay of Bengal plays an important role in monsoon circulation. In the observed relationship, rainfall peaks around 29.0°C, and it decreases with increasing SSTs. Interestingly, most of the models simulate the observed relationship correctly. The PCM model has not shown any skill in simulating the observed relationship, in which rainfall monotonically increases with increasing SSTs. The CNRM model also has not shown

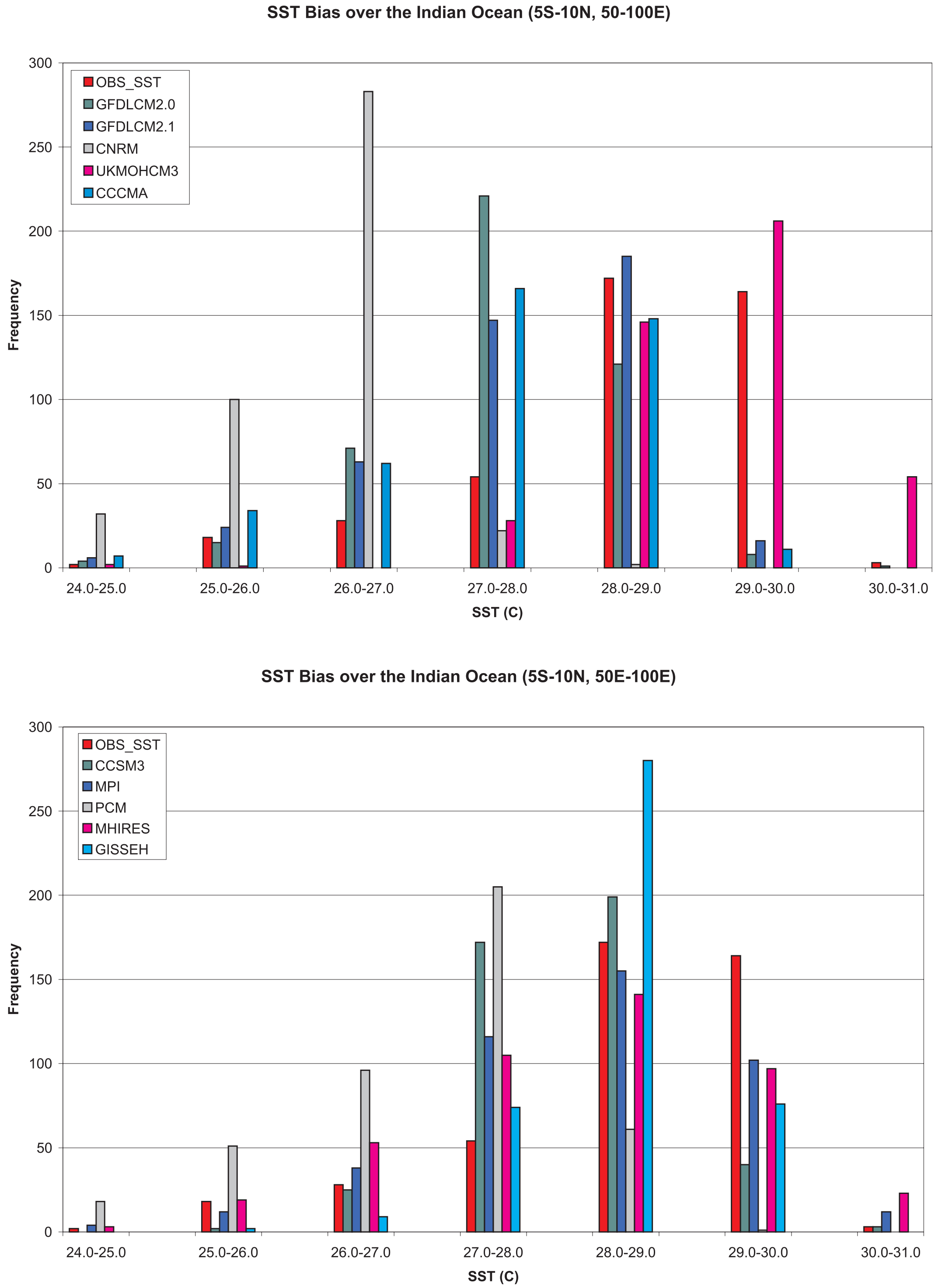


Figure 11(a). Frequency distribution of simulated SST (°C) by the coupled models and observed over the equatorial Indian Ocean (5°S–10°N, 50°–100°E).

realistic simulation. Over the Arabian Sea, the observed relationship shows an increase in rainfall with SSTs up to 29.0°C and thereafter does not change till 30.5°C. The peak is however not sharp but broadened. However, in most of the models, rainfall peaks at a lower SST (around 28.0°C), compared to the observed. As in the case of Bay of Bengal, CNRM and PCM models do not simulate the observed relationship very well. A common feature observed among the models is the higher sensitivity of rainfall to SSTs. At a given SST, these models predict more rainfall compared to the observations.

The equatorial Indian Ocean plays an important role in modulating the Indian monsoon circulation and rainfall. After the discovery of Indian

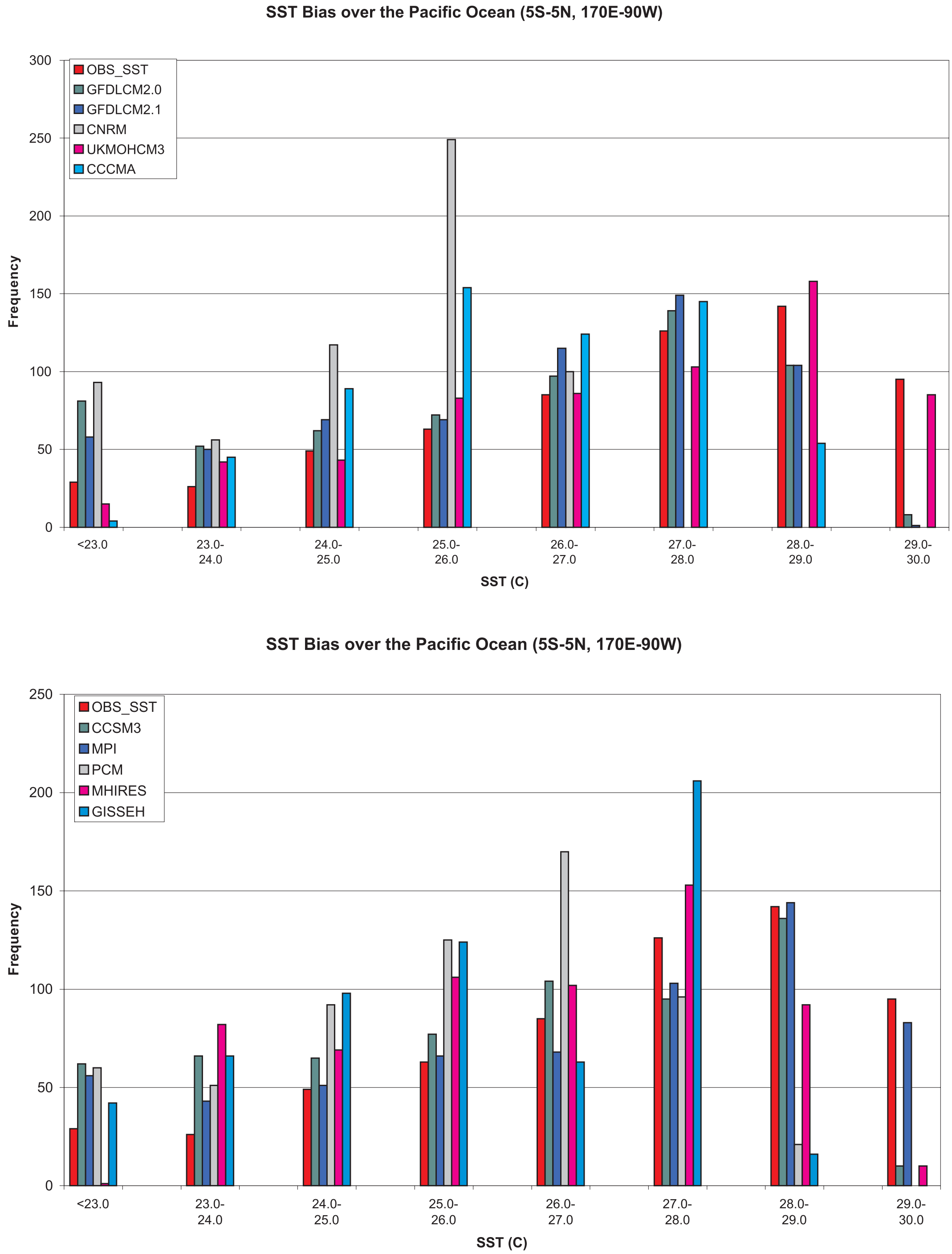


Figure 11(b). Frequency distribution of simulated SST (°C) by the coupled models and observed over the equatorial Pacific Ocean (5°S–5°N, 170°E–90°W).

Ocean Dipole (IOD) (Saji *et al* 1999; Webster *et al* 1999), there is a keen interest in exploring the Indian Ocean dynamics and its relationship with Indian monsoon circulation. Gadgil *et al* (2004) have shown an interesting relationship between the equatorial oscillation in the Indian Ocean and Indian monsoon rainfall. They have concluded that all the extremes of Indian monsoon (both droughts and excess monsoons) can be explained in terms of either El Niño/southern oscillation (ENSO) or the equatorial Indian Ocean oscillation (EQUINOO) or both. Figures 12(c) and (d) show the SST-rainfall relationships for the eastern and western Indian Ocean, respectively. The important role of east Indian Ocean is also highlighted by Wang *et al* (2005). Over the east equatorial Indian Ocean, rainfall increases monotonically up to 28.0°C, and any further increase in SSTs does not have any influence on rainfall. Most of the models simulate well the monotonic increase in rainfall with SSTs and the observed relationship. However, these models are more sensitive to SSTs compared to observations. The CNRM and GISS-EH models, however, do not simulate the relationship very well. As shown by Gadgil *et al* (2004), convection over the west coast of India and northwestern parts of India has a link with the convection over the west equatorial Indian Ocean. In the observed relationship, as in the EEIO, rainfall increases monotonically with SSTs up to 28.5°C. Further increase in SSTs does not have any influence on rainfall. Most of the models simulate well this relationship, however, with greater sensitivity compared to observations. The PCM model has shown serious problem in simulating the observed relationship. This model is too sensitive to SSTs and with increasing SSTs, rainfall increases more sharply and at

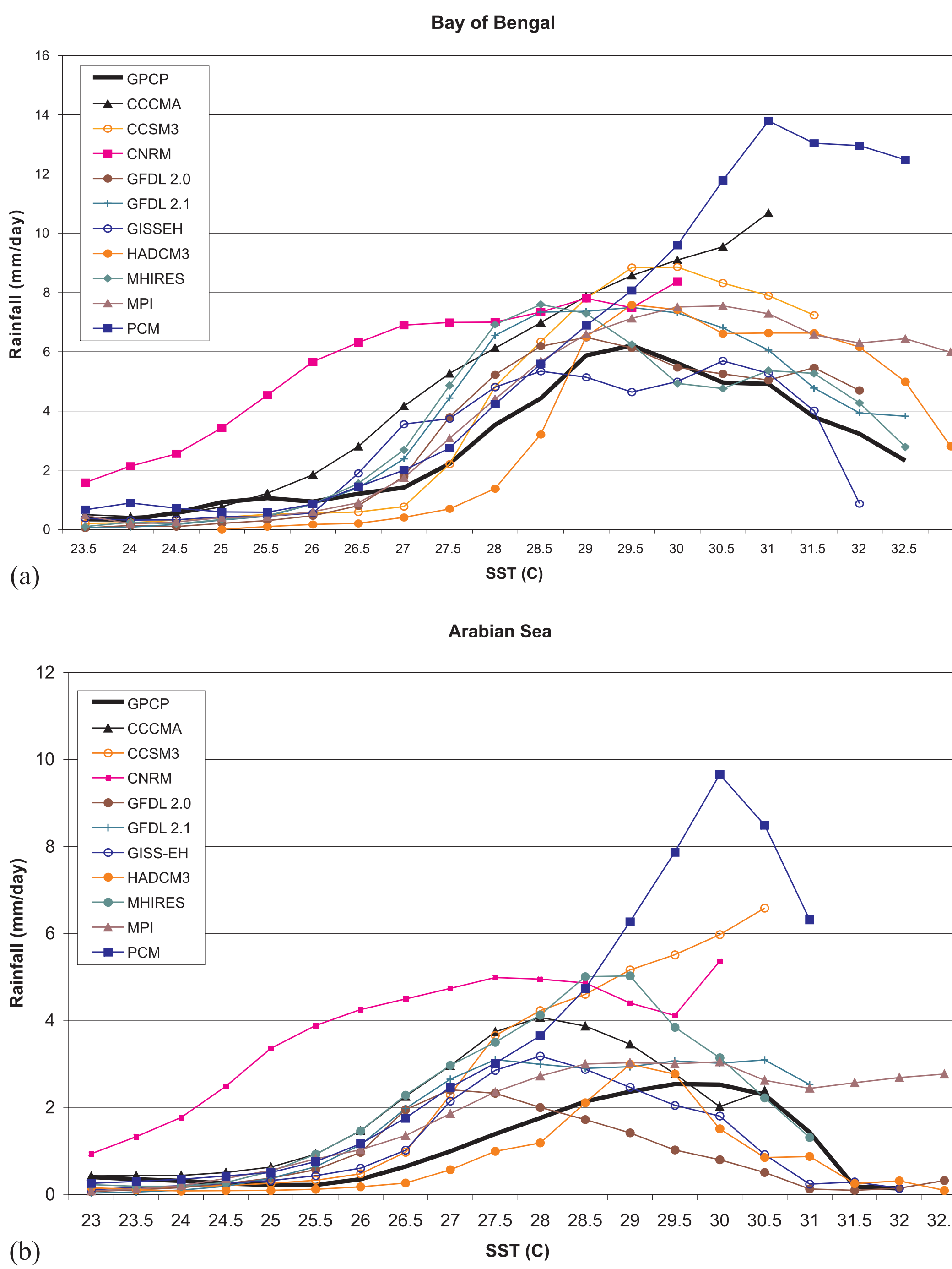
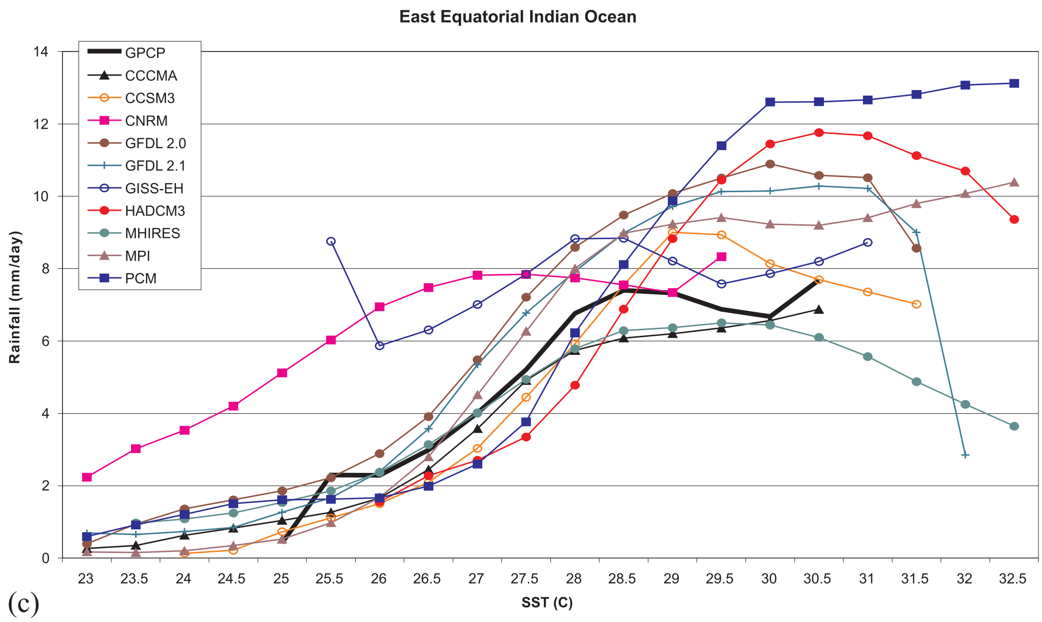
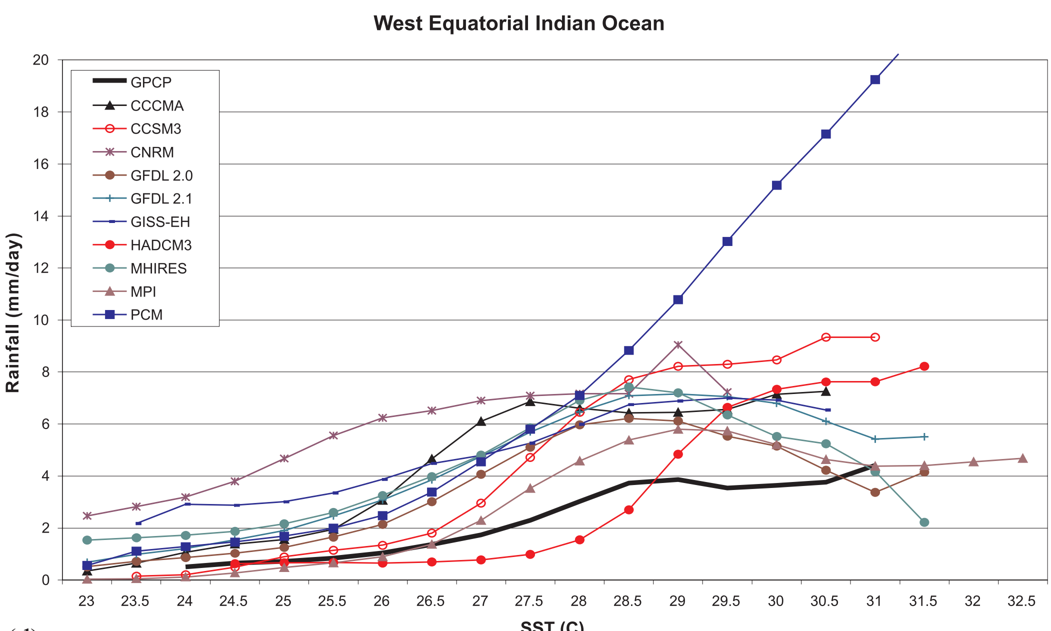


Figure 12. (*Continued*)



(c)



(d)

Figure 12. SST–Rainfall relationship in the observed data (GPCP) and IPCC AR4 coupled models over **(a)** Bay of Bengal **(b)** Arabian Sea **(c)** East equatorial Indian Ocean (EEIO) and **(d)** West Equatorial Indian Ocean (WEIO).

SSTs more than 30.0°C, rainfall of 20 mm/day is simulated.

8. Interannual variability of Indian monsoon in coupled models

The year to year variations of Indian summer monsoon has a large impact on the agricultural production and economy of the country. A major advance in our understanding of the interannual variation of the Indian monsoon occurred in the eighties with the discovery of a strong link with El Niño/southern oscillation (ENSO), which involves oscillation between a warm phase, El Niño, characterized by abnormal warming of surface ocean waters of the central and eastern Pacific and enhanced convection in the atmosphere above. There is an increased propensity of drought during El Niño and of excess rainfall during La Nina. To study the relationship of the Indian summer monsoon with ENSO, we normally use an ENSO index based on the SST anomaly of the Niño 3.4 region (120–170°W, 5°S–5°N), since magnitude of the

Table 2. Correlations between Indian monsoon rainfall and ENSO and EQUINOO.

	ENSO			EQUINOO		
Model	July	June–August	June–Sept.	July	July–August	June–Sept.
Observed	−0.32	−0.4	−0.53	−0.4	−0.4	−0.39
CNRM	−0.17	−0.47	−0.52	−0.03	0.13	0.33
CCSM3	−0.34	−0.37	−0.36	−0.01	0.06	0.05
GFDLCM2.0	−0.33	−0.35	−0.38	0.16	0.15	0.32
GFDLCM2.1	−0.25	−0.43	−0.51	0.1	0.04	0.2
MPI	−0.19	−0.45	−0.51	0.11	0.34	0.45
PCM	−0.23	−0.32	−0.36	0	0.22	0.07
CCCMA	0.02	−0.08	−0.09	0.03	0.35	0.27
UKMOHADCM3	−0.22	−0.31	−0.38	−0.15	0.07	0.2
MHIRES	−0.01	−0.15	−0.21	−0.10	−0.20	−0.22
GISS-EH	0.06	0.04	0.04	−0.04	−0.08	−0.11

correlation coefficient of ISMR with the convection over the central Pacific is higher than that with convection over the central Pacific.

The intriguing monsoon seasons of 1997 and 2002 triggered studies which suggested a link to the events over the equatorial Indian Ocean and studies relating the impact of El Niño on the monsoon to the pattern of SST anomalies over the Pacific and to the nature of the evolution of the El Niño in the seasons preceding the summer monsoon. Gadgil *et al* (2004) showed that in addition to ENSO, the phase of the equatorial Indian Ocean Oscillation (EQUINOO), which is considered to be the atmospheric component of the Indian Ocean dipole/zonal mode (Saji *et al* 1999) makes a significant contribution to the interannual variation of ISMR. The results of Ihara *et al* (2007) showed that the association of ISMR with ENSO and EQUINOO over 1881–1998 are consistent with those of Gadgil *et al* (2004). They further showed that there is a strong relationship between the extremes of ISMR and a complex index of ENSO and EQUINOO with all the droughts characterized by low values and excess monsoon by high values. Gadgil *et al* (2004) used an index of the EQUINOO based on anomaly of surface zonal wind over the equatorial Indian Ocean (60°–90°E, 2.5°S–2.5°N). Thus, ENSO and EQUINOO are considered to be two major critical modes of Indian summer monsoon variability. However, winter and spring snow cover over Eurasia and north Atlantic winter and summer circulation patterns also are shown to influence the Indian summer monsoon variability.

To examine how the coupled climate models simulate the observed teleconnection patterns with ENSO and EQUINOO, we have calculated the correlation coefficients between the monsoon rainfall over India and the indices representing the ENSO and EQUINOO. For ENSO, we have used the Niño 3.4 SST index and for EQUINOO, we have used zonal wind anomalies over the equatorial Indian Ocean at 925 hPa. The results for the ENSO and EQUINOO are shown in table 2.

In the observed relationship, Indian monsoon rainfall has statistically significant negative correlation with the ENSO index, suggesting a positive index (El Niño) is related to deficient monsoon rainfall. Among the coupled models considered, all the models except the GISS-EH and CCCMA showed the negative relationship between monsoon rainfall and ENSO index correctly, but with varying degree of magnitude. CNRM, GFDLCM 2.1 and MPI models showed the magnitude of the relationship (with JJAS rainfall) close to the observed magnitude of the correlation. Therefore, most of the coupled climate models simulate the ENSO-Indian monsoon relationship correctly.

In the observed relationship, Indian summer monsoon is also correlated negatively with EQUINOO, suggesting negative (positive) phase of EQUINOO is favourable for good (deficient) monsoon rainfall. The magnitude of the correlations is however smaller compared to the correlations with the ENSO index. However, as seen in table 2, none of the coupled models simulate the relationship between Indian monsoon and EQUINOO correctly. The model correlations are either close to zero or positive. Thus, these models fail miserably to simulate the simultaneous relationship between EQUINOO and Indian monsoon rainfall.

The absence of linkage between convection over the equatorial Indian Ocean and the Indian monsoon rainfall made us look at the question of seasonal cycle of rainfall over this region. We have already seen that the seasonal cycle of rainfall over the Indian region is reasonably well simulated by most coupled models. However, we have also seen that most models overestimate the rainfall over

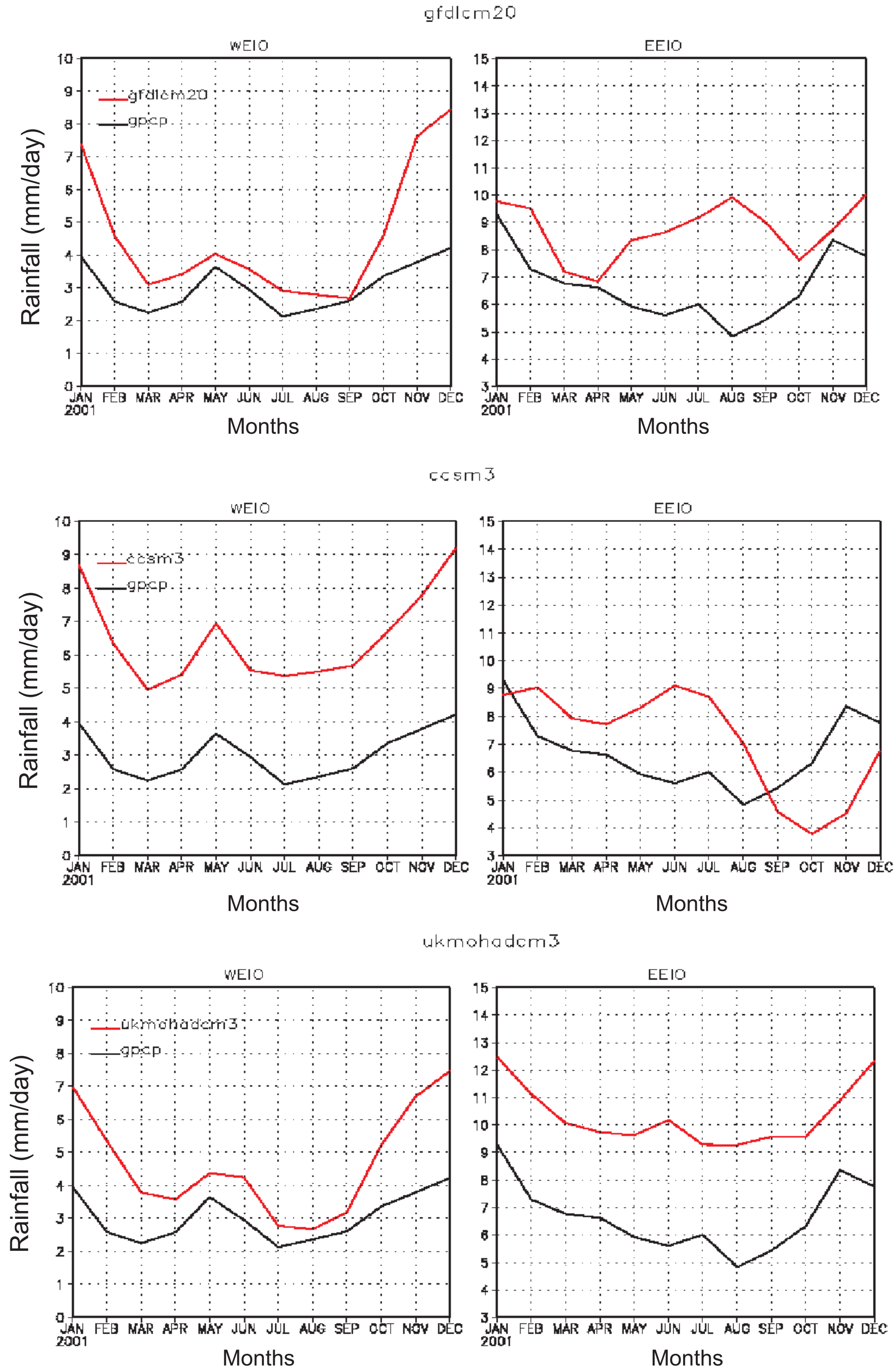


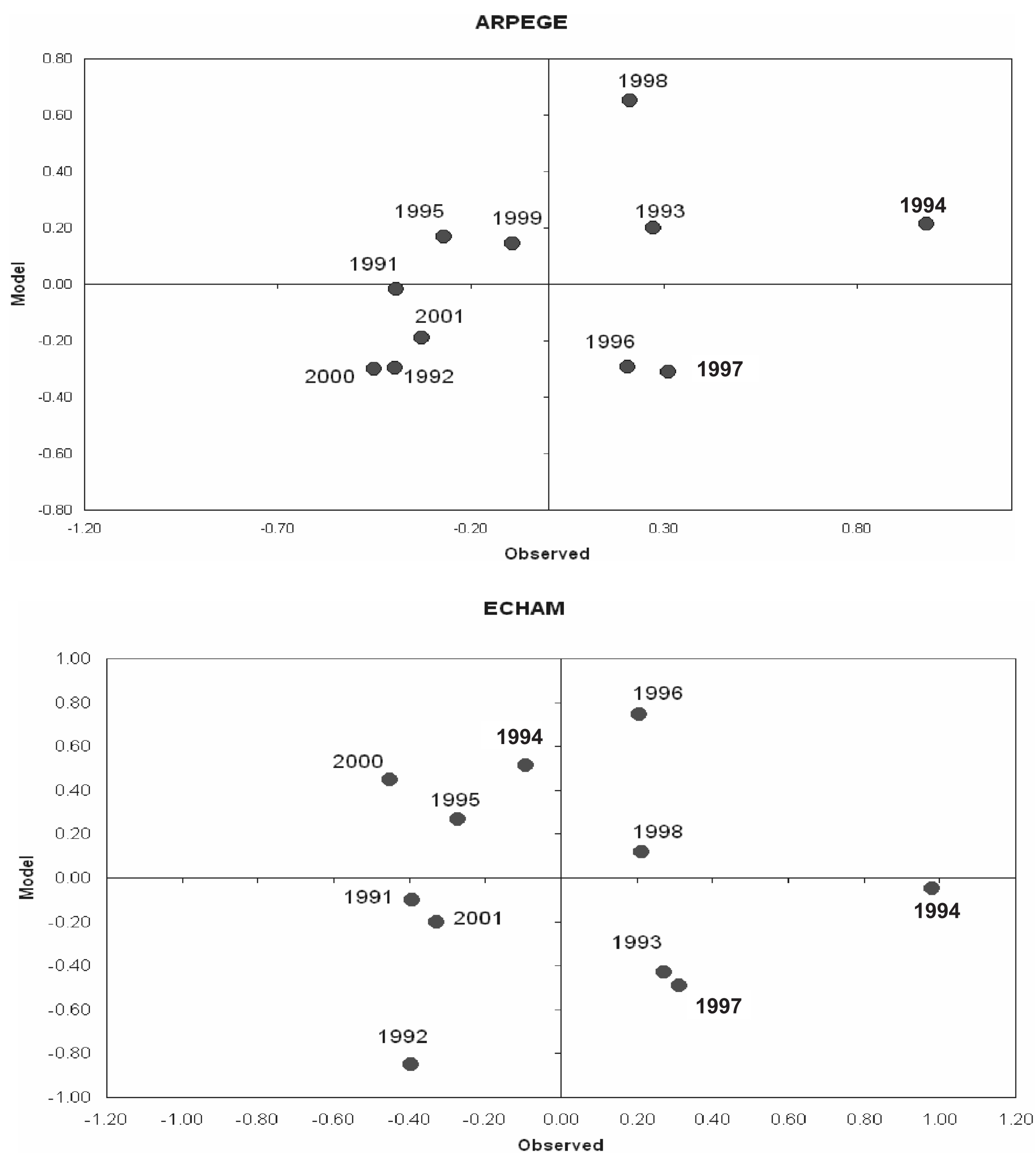
Figure 13. Seasonal cycle of rainfall over (left) west equatorial Indian Ocean, (right) east equatorial Indian Ocean. Top figure is for GFDL 2.0, middle for CCSM3 and bottom for UKMOHadCM3. Black curves are for observations (GPCP) and red curves are for the respective models.

equatorial Indian region during JJAS. We therefore analysed the seasonal cycle of rainfall over western equatorial Indian Ocean (WEIO) and eastern equatorial Indian Ocean (EEIO). We show the seasonal cycle for a few models in figure 13. We note that the seasonal cycle over WEIO is reasonably well simulated by most models. However, the same does not appear to be true over EEIO where most models fail to simulate the period of low convection during the JJAS season. In contrast, most models simulate a peak in rainfall during this period. This is indeed intriguing as one finds that the SST over these regions is generally underestimated by most models. Since this appears to be a systematic problem with almost all the models it perhaps points to a major flaw in the modeling of cloud and convection and needs to be looked into.

Annamalai *et al* (2007) have examined the IPCC AR4 simulations on the ENSO-Indian monsoon relationship. They found that all the six models (they have examined) capture the inverse relationship during boreal summer, but the timing of the maximum magnitude of correlation is correctly reproduced only by the GFDLCM 2.1. In the other models, the maximum correlation occurs too early. They found that the models that best capture the ENSO-monsoon teleconnection are those that correctly simulate the timing and location of SST and diabatic heating anomalies in the equatorial Pacific, and the resultant anomalous Walker circulation with considerable descent anomalies over the Indian region during El Niño events.

8.1 *Prediction of Indian summer monsoon in Ensembles project*

The simulation of interannual variation of the Indian monsoon rainfall with climate models remains a challenging problem. The analysis of atmospheric model intercomparison project (AMIP) (Gadgil and Sajini 1998) showed that while almost all models simulated the correct sign of the ISMR anomaly in 1988, a vast majority of the models failed to capture the anomaly for the excess monsoon season of 1994 (during which the ENSO was unfavourable). None of the models participating in the CLIVAR/Monsoon GCM intercomparison project could simulate realistically the observed response of the Indian monsoon to the 1997 ENSO event (Kang *et al* 2002).



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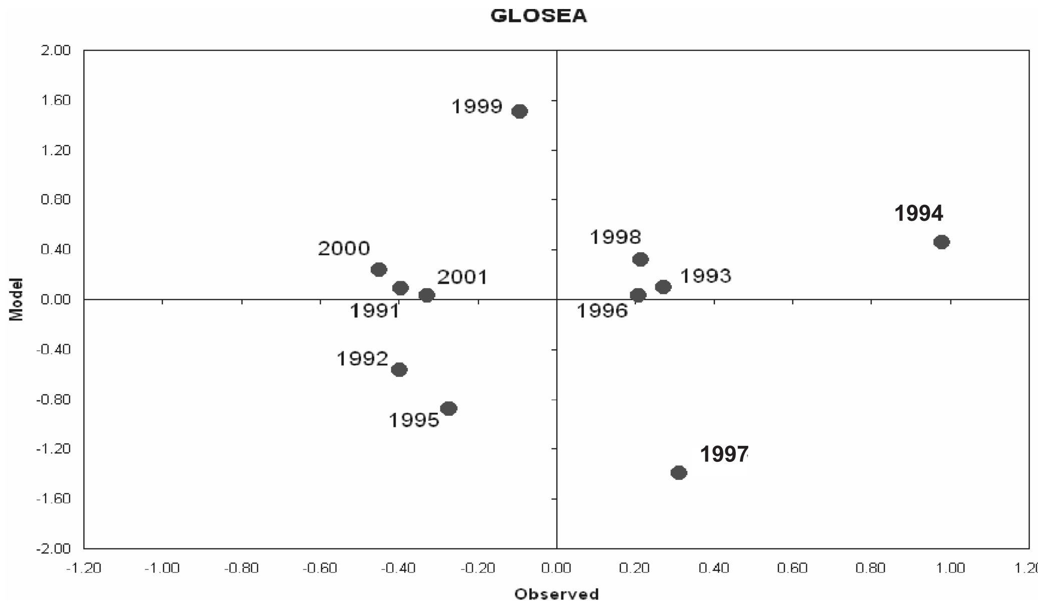

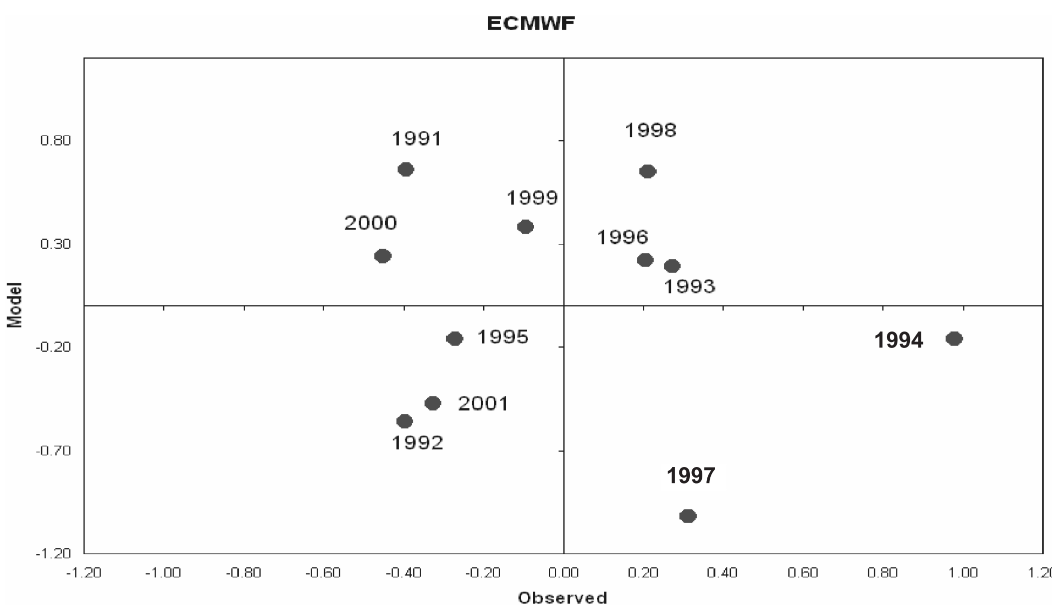

Figure 14. Scatter plot between the observed rainfall anomaly over the Indian region and ENSEMBLES model rainfall anomaly. Period 1991–2001. **(a)** ARPEGE **(b)** ECHAM **(c)** UK MET office and **(d)** ECMWF models.

Wang *et al* (2004) suggested that the models experience unusual difficulties in simulating the Indian monsoon of 1997. Both in 1994 and 1997, Indian monsoon rainfall was above normal in spite of unfavourable ENSO. Gadgil *et al* (2004) suggested that this could be due to favourable conditions over the equatorial Indian Ocean.

The skill of coupled models GCMs in predicting monsoons on the seasonal scale has been examined using the results of the latest coupled climate model experiments being conducted by the modeling groups in Europe. The Ensembles project is supported by the European Commission's 6th Framework Programme as a 5 year Integrated Project from 2004–2009 under the Thematic Sub-Priority 'Global Change and Ecosystems'. More details of this project are available at http://ensembles-eu.metoffice.com/index.html. One of the objectives of the ENSEMBLES project is to develop an ensemble prediction system based on the principal state-of-the-art, high resolution, global and regional Earth System models. For the present study, we have considered four coupled models for detailed analysis. The models considered are ARPAGE (Meteo-France), ECHAM

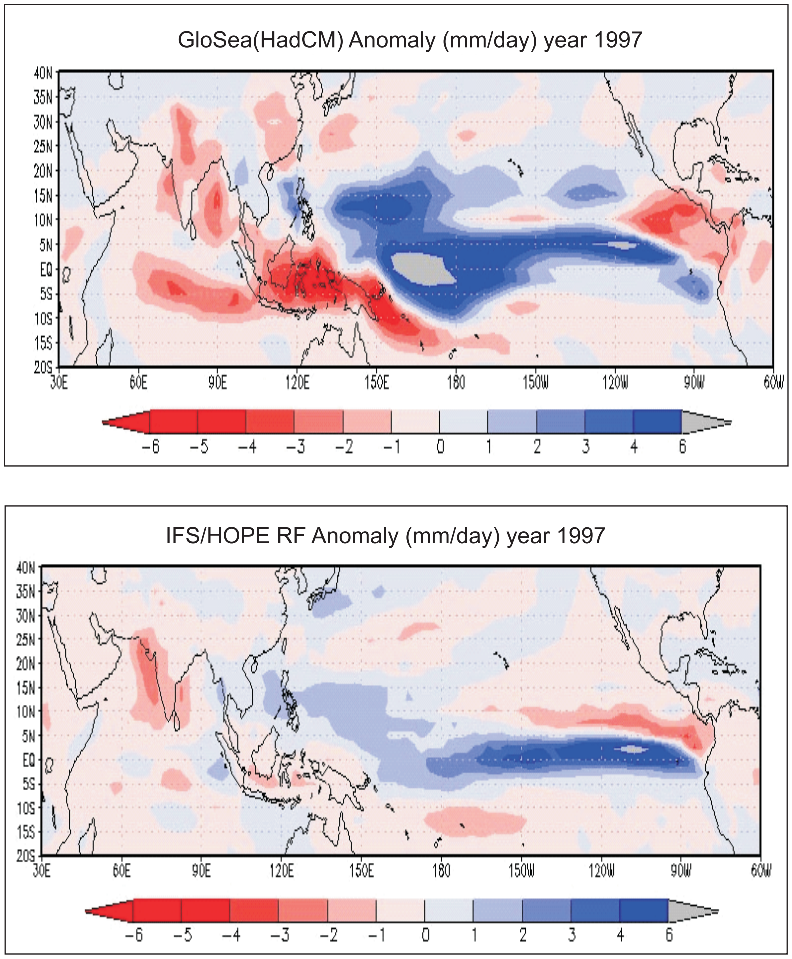

Figure 15. Model rainfall anomaly (mm/day) during June–September 1997 **(a)** UK MET Office and **(b)** ECMWF models in the ENSEMBLES project.

(Max Planck Institute, Germany), UK Met office and ECMWF coupled models.

The scatter plot between the observed rainfall anomaly over the Indian region and model derived rainfall anomaly for the period 1991–2001 is shown in figure 14 for the four models considered here. The scatter plot shows none of these four models could simulate the observed rainfall in 1997 correctly. All the models simulated deficient rainfall over the Indian region in 1997, while the observed rainfall in 1997 was slightly above normal. In case of the other good monsoon year of 1994, ARPAGE and UK Met Office models simulated above normal rainfall, however, not high as observed. The other two models simulated deficient rainfall in 1994.

The spatial plots of rainfall anomaly during the June–September of 1997 in respect of the UK Met office and ECMWF models are shown in figure 15. The models respond well to the positive SST anomaly over the equatorial Pacific Ocean due to the presence of the severe ENSO event in 1997. Over the Pacific Ocean, both the models simulated excess rainfall as expected. However, over the Indian region, both the models simulated deficient rainfall, possibly in response to the positive SST anomalies over the Niño 3.4 region. Thus, while the state-of-the-art coupled models simulate the ENSO-Indian monsoon relationship reasonably well, they have serious problems in simulating the influence of the Indian Ocean on the Indian summer monsoon.

9. Conclusions and discussions

In the present study, we have considered 17 IPCC AR4 models for analyzing the skill and biases of these models in simulating the 20th century monsoon climate. This exercise is required so that future climate projections made by these models can be interpreted and assessed properly. Out of the 17 models considered, we have identified 10 best models for further analysis using the pattern correlation and root mean square error of rainfall simulation. For detailed analysis, model simulated precipitation, sea surface temperature and atmospheric circulations were considered. The 10 best models considered in the present study are GFDL 2.0, GFDL 2.1, CNRM, CCCMA, CCSM3, UKMOHadCM3, MHIRES, GISS-EH, MPI and PCM. From the present study, the following conclusions can be drawn:

- There are large differences in the spatial pattern of model simulated rainfall, compared to observed rainfall. In all the 10 models, rainfall over the equatorial Indian Ocean is much more than the observed, while over the CTCZ region, models simulate less precipitation compared to observations.
- Not a single model could simulate realistically 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 southeast India and another maximum over the southeast equatorial Indian Ocean.
- Even though there are large differences (biases) in the simulated spatial rainfall pattern, all the models reproduce the observed feature of annual cycle of rainfall averaged over the Indian region (5°–27.5°N, 70°–90°E).
- Very few models simulate the northward migration of the ITCZ associated with the northward migration of solar insolation. However, in none of the models, the maximum rainfall zone moves north of 20°N, while in the observed rainfall pattern, maximum rainfall is observed north of 20°N, over the CTCZ region. The results show that considerable improvements in precipitation simulations are still desirable for these coupled climate models.
- The models simulate the large-scale monsoon circulation pattern at 850 hPa over the Indian region reasonably well, but with biases in wind speed.
- All the models showed systematic cold bias in the simulation of sea surface temperatures over the Tropics. Over the north Indian Ocean, the negative biases are of the order of 1°–2°C.
- The models also showed problems in simulating the observed SST-rainfall relationship. While most of the models simulate the general pattern of the relationship over Bay of Bengal and the equatorial Indian Ocean, the models have problems over the Arabian Sea.
- All the models showed higher sensitivity in simulating rainfall at a given SST, compared to the observed pattern. At a given SST, the models simulate more rainfall compared to the observed.
- While the state-of-the-art coupled models simulate the ENSO-Indian monsoon relationship reasonably well, they have serious problems in simulating the influence of the Indian Ocean on Indian monsoon. It appears that most models have problems in simulating even the seasonal cycle of rainfall over the Equatorial Indian Ocean.

We have found that some models have a reasonable simulation of the mean pattern of Indian summer monsoon and its seasonal cycle. However, there are systematic biases in the models, simulated precipitation over the equatorial Indian Ocean is much more than observed. On the interannual scale, most models are able to simulate the linkage with central Pacific region, i.e., the El-Niño monsoon teleconnection is reasonably well simulated by the models. However, almost all the models fail to simulate the linkage between Indian monsoon and the equatorial Indian Ocean. The rainfall over the equatorial Indian Ocean is overestimated. This could be related to the higher sensitivity of rainfall to SST in the climate models. Thus, it appears that more work needs to be done to improve the cloud convection schemes, which would improve rainfall simulation and thus the simulation of variability of monsoons on various scales.

Another problem could be air-sea interaction over the Indian Ocean. This issue was discussed in a recent study by Bollasina and Nigam (2008). They have analyzed the IPCC-AR4 coupled simulations of the Indian Ocean SST, evaporation and precipitation during the south Asian summer monsoon. Their analysis also showed the presence of large systematic biases in the simulated precipitation, evaporation and SST over the Indian Ocean, often exceeding 50% of the climatological values. Many of the biases are common to all models. They found that models exhibited problems in realistic representation of atmosphere-ocean interactions. Models overestimated local air-sea coupling in the Indian basin, as reflected by their large precipitation-SST correlations. However, these are at variance with the observations, which show insignificant correlations. The Indian monsoon rainfall-SST links are also misrepresented. The study found that in overall, coupled models are deficient in portraying local and non-local air-sea interactions in the Indian Ocean.

This problem of the climate models in air-sea coupling could be a serious issue in interpreting the future projections of monsoon rainfall in response to warming of the Pacific and Indian Oceans. The models may not provide durable insights on regional climate feedbacks over the Indian Ocean and thus may not provide reliable projections of regional rainfall variability and change. Therefore, we need to understand the coupled physical processes over the Indian Ocean more critically. However, this would be a challenging task, given the complexity of dynamical and thermo-dynamical coupled physical processes in the Indian Ocean during boreal summer. Moreover, we need to address this issue with sub-seasonal time scale as these feedback processes occur on sub-seasonal time scale.

The problem of the models in realistic representation of air-sea interaction could also constrain the model capability in realistic simulation of the intra-seasonal oscillations (ISO) over the Indian region. Model physics, model resolution and air-sea coupling are possible important factors for ISO simulations. The previous GCM sensitivity studies of ISO simulation focused on the role of air-sea coupling, and found that air-sea coupling significantly improves the ISO signals. Unfortunately, the subseasonal variability of Asian summer monsoon has not been well simulated in general circulation models used for weather and climate predictions. Waliser *et al* (2003) found that the model ISO patterns are typically less coherent, lack sufficient eastward propagation, and have smaller zonal and meridional spatial scales than the observed patterns. A recent study by Lin *et al* (2008) analyzed the sub-seasonal variability associated with Asian summer monsoon simulated by the IPCC AR4 coupled models. The results show that current state-of-the-art climate models still have difficulties and display a wider range of skill in simulating the subseasonal variability associated with Asian summer monsoon. This problem of the models in simulating the northward propagation of ISO may be also responsible for the poor skill of the models in reproducing the seasonal migration of the ITCZ and the systematic biases in the spatial distribution of simulated rainfall.

Another problem could be the model problems in simulating the cloud distribution and its effect on atmospheric radiation. A bias in cloud distribution can affect the simulation of surface energy budget and thus surface temperatures. For example, Wild (2008) suggested that considerable differences in the simulated global mean radiation budgets are also found in the IPCC-AR4 models, particularly in the atmosphere and at the surface. The majority of the IPCC-AR4 models still show a tendency to overestimate the shortwave and underestimate the longwave downward radiation, each by 6 $\mathrm{W\,m^{-2}}$ on average, a long standing problem in many GCMs. Deficiencies in clear-sky radiative transfer calculations are major contributors to the excessive surface insolation in many of the models. Therefore, more vigorous validation of the model simulations of the surface energy budget, including the role of clouds may be desirable with multi-platform observations including satellites.

In the model validation process, several important issues are involved. For example, present climate is not an independent dataset since it has already been used for the model development. Similarly, good model performance evaluated from the present climate does not necessarily guarantee reliable prediction of future climate. Despite these difficulties and limitations, model agreement with observations of today's climate is the only way to assign model confidence with the underlying assumption that a model that accurately describes present climate will make a better projection of the future. Reichler and Kim (2008) discussed the issue of how well coupled models do simulate today's climate. They objectively determined the ability of three generations of models to simulate present-day mean climate. They found that current models are certainly not perfect, but they are much more realistic than their predecessors. This is mostly related to the enormous progress in model development, especially physical parameterizations and higher resolution climate models. There is a hope that these models will improve in performance in simulating mean Indian monsoon.

However, we need to make some inferences on future monsoon climate projections using the current coupled model results, in spite of biases and errors associated with the present day climate simulations. In the present analysis, we have seen that no single model can be considered the best and it may be important to utilize results from a range of coupled models, especially for the regional climate projections. Tebaldi *et al* (2005) proposed a Bayesian statistical model that combines information from a multi-model ensemble of atmosphere-ocean general circulation models and observations to determine probability distributions of future temperature change on a regional scale. Thus, uncertainty in projections of regional climate change is quantified. In this approach, the posterior distributions derived from the statistical assumptions incorporate the criteria of bias and convergence in the relative weights implicitly assigned to the ensemble members.

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