Chapter 5

Simulation of Indian monsoon droughts from state-of-art climate models

5.1 Introduction

This chapter provides an assessment of the state-of-art climate models in simulating monsoon droughts over India. In the wake of the severe socio-economic impacts associated with monsoon droughts in past, there has always been a compelling necessity for accurate predictions of seasonal monsoon rainfall over India [e.g., Blanford, 1884; Walker, 1923, 1924; Normand, 1953; Jagannathan, 1960; Gowariker et al., 1991; Krishna Kumar et al., 1995; Sikka, 2003; Gadgil et al., 2002; Rajeevan et al., 2004; Delsole and Shukla, 2002; Sahai et al., 2003]. Despite advances in seasonal forecasting techniques, the skill in the seasonal predictions of the Indian monsoon rainfall both by statistical models and dynamical models has been poor [Gadgil et al., 2005; Krisha Kumar et al., 2005; Delsole and Shukla, 2002; Kang and Shukla, 2005].
These studies indicate that the statistical/empirical based predictions generally fail to capture the monsoon rainfall extremes (i.e., droughts and excess rainfall seasons); while dynamically-based GCM predictions have large errors in simulating the year-to-year monsoon rainfall variations.

The low seasonal predictability of the state-of-art GCMs over the Indian monsoon region is partly due to the fact that a majority of the models face a major challenge even in simulating the mean rainfall distribution over the Indian and East Asian monsoon regions [e.g., Gadgil and Sajani, 1998; Kang et al., 2002a]. Furthermore, the effects of atmospheric internal dynamics on the precipitation variability are non-negligible over the Indian monsoon region and compare with the level of variability from the slowly varying external boundary forcing [e.g., Palmer and Anderson, 1994; Sperber and Palmer, 1996; Brankovic et al., 1997; Sugi et al., 1997; Goswami, 1998; Brankovic and Palmer, 2000; Wang et al., 2004; Kang et al., 2002b]. It is now recognized that the strong sensitivity of the simulated Indian monsoon rainfall variations to atmospheric initial conditions tends to limit the seasonal predictability over the region.

Recent studies have suggested that ocean-atmosphere coupled models may have better skills than the atmosphere-alone GCMs in forecasting the Indian monsoon rainfall [e.g., Krishna Kumar et al., 2005; Wang et al., 2005]. The predictions systems designed with atmospheric models (AGCM) are driven with a specified ocean surface temperature. Such a configuration pre-supposes the Indian monsoon variability to be a consequence of solely the atmosphere reacting to the ocean. However since the Indian monsoon involves a fully coupled ocean-land-atmosphere system, it is expected that the sea surface temperature (SST) field evolves through interactions with the atmospheric circulation. Wang et al., (2004) have suggested that the lack of skill of AGCMs
in simulating the interannual variability over Southeast Asia and west North Pacific results from the failure of the models to simulate correctly the relationship between the local summer rainfall and the SST anomalies in the Philippine Sea, the South China Sea and the Bay of Bengal. In contrast to the design of AGCM experiments, the coupled model simulations take into account SST variations that result from atmospheric forcing. It has been suggested that this interactive ocean-atmosphere coupling improves the skill of the Indian monsoon predictions [Krishna Kumar et al., 2005; Wang et al., 2005; Kang and Shukla, 2005].

The analyses of Krishna Kumar et al., (2005) were based on the theoretical assumption that the coupled models have perfect skill in forecasting the Indian summer monsoon rainfall. Since coupled model predictions also involve growth of model forecast errors, the perfect forecast skill may not be achievable in actual practice. Therefore, it is not clear if coupled models can actually perform substantially better than the AGCMs in capturing the interannual variability of the Indian summer monsoon rainfall. In order to understand this problem, we have examined an ensemble of hindcast monsoon simulations conducted using an AGCM; as well as hindcasts generated by the DEMETER coupled modeling system. The DEMETER project (Development of a European Multi-model Ensemble System for Seasonal to Interannual Prediction) is a multi-model ensemble prediction system involving a number of state-of-art global coupled ocean-atmosphere models run a single supercomputer, to produce a series of six-month multi-model ensemble hindcasts. The details will be discussed subsequently in section 5.3.
5.2 Atmospheric GCM simulation of interannual variability (IAV) of monsoon rainfall

5.2.1 Description of the SPIM experiments

In this section, we shall first examine the interannual variability of the Indian summer monsoon rainfall simulated by the Center for Ocean Land Atmosphere Studies (COLA) AGCM for the period (1985-2004). These runs were conducted as part of the Seasonal Prediction of Indian Monsoon (SPIM) project (see http://www.climvar.org/organization/aamp/presentations/India%20Rajeevan.pdf). The SPIM project was launched to assess the skills of the AGCMs, currently used in India, for generating monthly / seasonal predictions. All the AGCMs were ported and run on a single computational platform at the Centre for Development of Advanced Computing (CDAC), Bangalore. The COLA T300L18 AGCM (please see Chapter 4 for more details) was one of the six models that participated in the SPIM project. The SPIM simulations consist of hindcasts for 20 summer monsoon seasons (1985-2004). The hindcast methodology consists of 5-member ensemble runs starting from the initial conditions of 26-30 April of each year; wherein observed SSTs are specified as lower boundary condition. The assessment of all the models that participated in the SPIM project is currently underway through a joint effort involving various modeling groups in the country. However, at present, we confine our analysis to the performance of the COLA AGCM – which was supported in the SPIM project from Indian Institute of Tropical Meteorology, Pune, India.

5.2.2 Mean monsoon rainfall distribution

Here, we shall examine the simulation of the mean summer monsoon rainfall in
Figure 5.1: Climatological rainfall (mm day$^{-1}$) and 850 hPa winds (m s$^{-1}$) for June-September (JJAS) monsoon season (a) GCM (b) CMAP rainfall and NCEP reanalysis winds. The climatological fields in the GCM are computed from the 20-year simulation. For the CMAP/NCEP data, the climatology is based on the period (1979-2004).
the COLA AGCM. Figure 5.1a shows the climatological mean monsoon rainfall for the June-September (JJAS) season simulated by the AGCM; and the corresponding observed rainfall from CMAP is shown in Figure 5.1b. Superposed on the rainfall maps are the mean winds at 850 hPa in the model simulation (Figure 5.1a) and NCEP reanalysis (Figure 5.1b). Although the simulated wind-field essentially captures the salient large-scale features of the low-level monsoon cross-equatorial flow; it can be seen that the simulated monsoon rainfall over India differs considerably from the CMAP rainfall distribution. It can be noticed that the simulated rainfall maxima over Bay of Bengal is located more southward as compared to the CMAP rainfall; while the west coast rainfall maximum is located more to the west over the Arabian Sea in the AGCM simulation. There are also differences between the simulated and observed rainfall distribution over the equatorial Indian and Pacific Oceans.

Gadgil and Sajani [1998] examined the simulation of summer monsoon precipitation by 30 different AGCMs that participated in the Atmospheric Model Intercomparison Project (AMIP). The AMIP runs were carried out by forcing models with observed monthly SST and sea-ice distribution over a 10-year (1979-1988) period - starting from the atmospheric initial state of 1 January 1979 [see Gates et al., 1992]. Gadgil and Sajani [1998] noted that the models fall into two distinct classes on the basis of the seasonal variation of the major rain-belt over the Asia West Pacific sector - the first class (class I) comprising models with a realistic simulation of the seasonal migration of the major rain-belt over the continent in the boreal summer; and the second (class II) comprising models with a smaller amplitude of seasonal migration than observed. Based on their study, the COLA model simulation was placed in the class II category. However, it must be mentioned that the version of COLA model (T30L18 v1.11) used in SPIM is different from the COLA (R40L18)
model that was used in AMIP. Although the SPIM-version has a coarser resolution than the AMIP-version, the monsoon rainfall to the west of India is better simulated by the former (Figure 5.1a) as compared to the latter [see Fig.9, Gadgil and Sajani, 1998]. This appears to be largely related to the different moist convection schemes used in the two versions. The convection scheme used in the R40L18 version of AMIP was based on Kuo [1965]; while the T30L18 v1.11 version uses the Relaxed Arakawa Schubert (RAS) scheme [Moorthi and Suarez, 1992]. In fact, in the 2nd phase of the AMIP project (AMIP-II), the R40L18 model employed the RAS convection scheme which led to a marked improvement in the simulation of the mean monsoon precipitation over India and adjoining region [see Kang et al., 2002]. In noting the above, the main point is that accurate simulation of the mean rainfall distribution over the Indian and East Asian monsoon regions still remains a challenging issue for many state-of-art AGCMs [Gadgil and Sajani, 1998; Kang et al., 2002, Kang and Shukla, 2005].

5.2.3 Observed and simulated monsoon droughts during (1985-2004)

Here, we discuss the simulated interannual variability of monsoon rainfall in the COLA AGCM and also examine spatial maps of precipitation anomalies associated with the 5 monsoon droughts (1985, 1986, 1987, 2002 and 2004) over India that occurred during the 20-year (1985-2004) period. Figure 5.2 shows the interannual variations of the summer monsoon rainfall over the Indian region for the period (1985-2004) both from the AGCM simulation and observations. The rainfall anomalies for the AGCM simulation, averaged over the Indian region (70°E - 90°E; 12°N - 32°N), are shown by blue bars. Note that the AGCM runs are 5-member ensemble realizations for each of the 20 years.
Interannual variations of the Indian summer monsoon rainfall

The red bars in Figure 5.2 indicate the CMAP rainfall anomalies averaged over the same region. The black bars in Figure 5.2 correspond to the observed All India Summer Monsoon Rainfall (AISMR) index. The details of the CMAP and AISMR rainfall data are given in the figure caption. Note the high correlation (0.87) between the CMAP and AISMR indices. On the other hand, the correlation between the observed and simulated monsoon rainfall variations is low.

It can be noticed that from Figure 5.2 that the negative rainfall
departures associated with the monsoon droughts of (1985, 1986 and 1987) are not captured by AGCM. On the other hand, it is interesting to note that the monsoon droughts of 2002 and 2004 are brought out in a majority of the ensemble members. Further, it is also seen that the 4 consecutive deficient monsoons during (1999-2002) are consistently captured in the AGCM simulation; although the magnitudes of the simulated rainfall anomalies are larger than the observed anomalies. It is not clear as to why the simulation skills of the AGCM are better during certain periods (eg., 1999-2002) than during other periods (eg., 1985-1987). Likewise, it is intriguing to note that the excess monsoon rainfall during 1988 is consistently captured in the AGCM by all the ensemble members; while on the other hand all the 5-members consistently failed to capture the excess monsoon of 1994. Grimm et al., [2006] have suggested that the possibility of secular variations in the model forecast skills. It is not obvious if the SPIM simulations of the Indian monsoon are subject to such variations introduced through the specification of SST forcing over the 20-year period. Furthermore, the AGCM simulated monsoon precipitation exhibits strong member-to-member variations even in the presence of anomalous SST conditions. For example, the 1987 monsoon drought was accompanied by El Nino conditions in the Pacific [eg., Krishnamurti et al., 1989; Palmer et al., 1992; Sperber and Palmer, 1996; Fennessy and Shukla, 1994; Krishnan and Fennessy, 1996; Mujumdar and Krishnan, 2001]. Despite the presence of the anomalous SST boundary forcing, it is surprising to note that the AGCM simulation for 1987 shows significant member-to-member variations (note that 3 members have positive anomalies; while one member has negative departure and the other is close to zero).

The spatial maps of the observed and simulated rainfall anomalies for the 5 monsoon droughts (1985, 1986, 1987, 2002 and 2004) are shown in Figure
Figure 5.3: Spatial distribution of JJAS summer monsoon rainfall anomalies (mm day$^{-1}$) for the droughts of (1985, 1986, 1987, 2002 and 2004). The panels (a, d, g, j, m, p) are based on the CMAP data; the panels (b, e, h, k, n, q) are from the GCM; and the panels (c, f, i, l, o, r) are for the high resolution ($1^\circ \times 1^\circ$) gridded daily data from IMD - version 2 [Rajeevan et al., 2006].
Figure 5.3: Continued…
5.3. Also included in Figure 5.3 are maps of rainfall anomaly, over the Indian landmass, from the India Meteorological Department. It can be noticed from the CMAP rainfall that there are significant variations in the rainfall anomalies over the Indo-Pacific region from one drought year to another. Even under El Nino conditions, there are significant differences in the precipitation patterns from one drought case to another. For example, both 1987 and 2002 show enhanced precipitation over the equatorial central Pacific; however the rainfall anomalies over the tropical Indian Ocean are quite different in the two years. The AGCM simulated precipitation anomalies during (1985, 1986, 1987) exhibit significant mismatch with the CMAP anomalies particularly over the Indian subcontinent. Figure 5.3p shows the rainfall anomaly composite, based on the 5 drought years, for the CMAP data. The corresponding anomaly composites for the GCM and IMD rainfall are shown in Figure 5.3q and Figure 5.3r respectively. It can be seen that the GCM broadly captures the enhanced precipitation over the equatorial central Pacific; while the rainfall reduction over the Indian region is not clearly brought out. This essentially indicates that the AGCM might be able to reproduce the ENSO related precipitation anomalies over the tropical Pacific; while the teleconnections over the Indian monsoon region are not realistic in the AGCM simulation. Recent studies have shown that in addition to the ENSO-induced impacts on the monsoon, it will be necessary to take into account the effects of convection changes over the tropical Indian Ocean on the monsoon rainfall variation [eg., Gadgil et al., 2003, 2005; Krishnan et al., 2003, 2006; Ashok et al., 2004]. In view of the above complexities, it is clear that issues related to the interannual variability of the Indian monsoon rainfall will confront the scientific and modeling community during the years to come [Gadgil et al., 2005].
5.3 DEMETER coupled model simulations of the IAV of monsoon rainfall and drought events

In the previous section, it was seen that the AGCM simulated IAV of the Indian monsoon rainfall showed poor correlation with the observed IAV. Although, we had described the results for one particular AGCM (ie., COLA model) from the SPIM project, it is known that most of the AGCMs, that participated in the AMIP, had comparable hindcast skills in reproducing the observed IAV [see, Kang et al., 2002; Wang et al., 2004; Gadgil et al., 2005]. Several studies have suggested that this problem arises primarily from the AMIP-type of experimental design (ie., known as 2-tier approach) in which the atmosphere is forced to respond passively to the specified SSTs [eg., Krishna Kumar et al., 2005; Wang et al., 2005; Kang and Shukla, 2005]. In reality, the SST and rainfall in the monsoon ocean region interact with each other. Therefore, their anomalies tend to be negatively correlated, because the SST anomalies are, to a large extent, a response to monsoon forcing. In a region of an enhanced monsoon, the increased rainfall and cloudiness will tend to reduce the downward solar radiation into the ocean mixed layer, meanwhile, the increased rainfall enhances the monsoon westerly winds, which further enhance the surface evaporative cooling and the entrainment cooling of the mixed layer. Furthermore, it was suggested that coupling of the ocean and atmospheric GCMs can lead to improved simulation of the IAV of monsoon rainfall [Krishna Kumar et al., 2005; Wang et al., 2005]. Here, we have examined the simulation of the monsoon IAV by a suite of coupled ocean-atmosphere models from the DEMETER ensemble prediction system.
Table 5.1: Details of seven coupled models used in DEMETER project (Development of a European Multi-model Ensemble System for Seasonal to Interannual Prediction). The modeling partners are: CERFACS (European Centre for Research and Advanced Training in Scientific Computation, France), ECMWF (European Centre for Medium-Range Weather Forecasts, International Organization), INGV (Istituto Nazionale de Geofisica e Vulcanologia, Italy), LODYC (Laboratoire d’Oceanographie Dynamique et de Climatologie, France), Meteo-France (Centre National de Recherches Meteorologiques, Meteo-France, France), MPI (Max-Planck Institut für Meteorologie, Germany) and Met Office (The Met Office, UK) [adapted from Palmer et al., 2004].

### 5.3.1 DEMETER ensemble prediction system

The DEMETER (Development of a European Multi-model Ensemble System for Seasonal to Interannual Prediction) system comprises seven global coupled ocean-atmosphere models which are run on a single supercomputer to produce a series of six-month multi-model ensemble hindcasts with common archiving and common diagnostic software [e.g. Palmer et al., 2004; Doblas-Reyes et al.,]
2005; Hagedorn et al., 2005]. Details about the atmospheric and oceanic components of the 7 coupled models used in the DEMETER project are given in Table 5.1. In this analysis, we shall examine the hindcasts from the coupled models datasets over a 22 year (1980-2001) period. During this period, all seven coupled models that participated in the DEMETER project generated hindcasts. The seasonal hindcasts in the DEMETER simulations were started from 1st February, 1st May, 1st August and 1st November initial conditions. Each hindcast is 6-month integration and comprises an ensemble of 9-members. Since, our primary interest is to investigate the IAV of the Indian summer monsoon; we have examined the DEMETER hindcasts that were initiated from the 1st May initial condition.

5.3.2 Coupled model simulations of mean and IAV of the Indian summer monsoon

Figure 5.4a shows the CMAP rainfall climatology for the June-September (JJAS) season and the corresponding maps from the 7 coupled models are shown in Figure 5.4 (b-h). The rainfall climatology for each model is based on the 22-year (1980-2001) simulation and is averaged over the 9-ensemble members. The distribution of the mean rainfall in most of the models shows the maximum precipitation over the Indian region; the secondary rainfall maximum over the equatorial Indian Ocean and the tropical west Pacific. The rainfall band over the equatorial Pacific is associated with the Inter Tropical Convergence Zone (ITCZ). Notice that the rainfall minima over the sub-tropical east Pacific in both the hemispheres, the sub-tropical Indian Ocean and the sub-tropical regions of Arabia and west-Asia are captured well in almost all of the models. While there are differences in the spatial distribution of the mean rainfall across the models; the large-scale structure of the tropical rainfall distribution is quite consistent among the 7 AGCMs. Further, it can be noticed that the simulated
Figure 5.4: Climatological rainfall (mm day$^{-1}$) from (a) CMAP (b) CERFACS (c) ECMWF (d) INGV (e) LODYC (f) Meteo-France (g) MPI (h) Met Office. The DEMETER (Development of a European Multi-model Ensemble System for Seasonal to Interannual Prediction) is a project on multi-model ensemble prediction from global coupled models.
Figure 5.5: Climatological winds (m s\(^{-1}\)) at 850 hPa from (a) NCEP (b-h) DEMETER models. The shaded regions have wind-speed exceeding 10 m s\(^{-1}\).
Figure 5.6: Time-series of the inter-annual variability of AISMR (black bars) and area averaged summer monsoon rainfall over the Indian region (70°E - 90°E; 12°N - 32°N) from CMAP (red bars) and DEMETER models (blue bars) (a) CERFACS (b) ECMWF (c) INGV (d) LODYC (e) Meteo-France (f) MPI (g) Met Office. The rainfall variations are expressed as percentage departures from normal.
mean low-level winds at 850 hPa by the DEMETER models (Figure 5.5) captures the salient large-scale circulation features (i.e., monsoon south-westerlies and the cross-equatorial flow; easterly trades over the tropical Pacific, the sub-tropical anti-cyclones, etc.).

The simulated interannual variability of the summer monsoon rainfall over the Indian region (70°E - 90°E; 12°N - 32°N) by the DEMETER models for the 22-year period (1980-2001) is shown by blue bars in Figure 5.6. The corresponding rainfall index based on the CMAP dataset (red) and the observed AISMR index (black) are also shown in Figure 5.6. It is seen that the DEMETER models show a modest improvement in capturing the observed IAV as compared the COLA AGCM simulations discussed earlier. Out of the 7 coupled models, the best 5 simulations had correlations in the range of 0.2 to 0.38 with the CMAP rainfall variations over the Indian region. Except for the marginal improvement, it is not evident from Figure 5.6 that the coupled models significantly out-perform the AGCMs in capturing the observed IAV of the Indian monsoon rainfall.

5.3.3 Observed and simulated large-scale anomalies during monsoon droughts

Figure 5.7a shows the CMAP rainfall anomaly composite based on the 4 monsoon droughts (1982, 1985, 1986, and 1987) during the 22-year period. The corresponding anomaly composites from the 7 coupled models are shown in Figure 5.7 (b-h). The striking feature in the CMAP anomaly composite is the increased rainfall over the equatorial central-eastern Pacific and decreased rainfall over the Indian sub-continent; Southeast Asia, Indonesia and equatorial west Pacific. A careful examination of Figure 5.7a shows increased rainfall over
Figure 5.7: Composite of seasonal (JJAS) rainfall anomaly (mm day\(^{-1}\)) (a) CMAP (b) CERFACS (c) ECMWF (d) INGV (e) LODYC (f) Meteo-France (g) MPI (h) Met Office. The anomaly composites are based on the 4 monsoon droughts during (1982, 1985, 1986 and 1987) – when the rainfall departures were less than \(-10\%\) of the normal.
the equatorial eastern Indian Ocean; but decreased rainfall over the western Indian Ocean. In the coupled model simulations, a qualitative increase in rainfall over the equatorial central Pacific can be seen in most of the models; although there are differences in the location and intensity of the Pacific rainfall anomaly. However, the simulation of the monsoon rainfall deficiency over the Indian region is not adequately captured in majority of models. It can be seen that the simulated regional rainfall anomalies over the Indian subcontinent vary considerably from one model to another.

Composite maps of low-level winds and SST anomalies from the DEMETER simulations, based on the 4 monsoon droughts, are shown in Figure 5.8 and Figure 5.9 respectively. The corresponding anomaly composites of winds from NCEP (Figure 5.8a) and observed SST (Figure 5.9a) are shown for comparison. Notice that a majority of the models broadly capture the weakening of the tropical Pacific trade winds (i.e., westerly anomalies) and the warm SST anomalies in the central-eastern equatorial Pacific; although there are differences in the location and amplitude of the anomalies across different models. On the other hand, notice that the simulation of SST and wind anomalies varies considerably among the different coupled models over the Indian Ocean region. In particular, it can be seen that the CERFACS, ECMWF, LODYC, Meteo-France, and Met-Office models show larger SST cooling, anomalous easterly winds and decreased rainfall over the equatorial eastern Indian Ocean (EEIO) as compared to the INGV and MPI models. The bias in the simulation of the ocean-atmosphere anomalies in the EEIO (Figures 5.7-5.9) by the CERFACS, ECMWF, LODYC, Meteo-France, and Met-Office models is associated with an enhanced easterly outflow from the EEIO which tends to increase the monsoon precipitation to the north of the equator [see Behera et al.,
Figure 5.8: Circulation anomaly (m s$^{-1}$) at 850 hPa from (a) NCEP (b-h) DEMETER models.
Figure 5.9: SST anomaly (°C) from (a) OISST (b-h) DEMETER models.
This may be a possible explanation why the CERFACS, ECMWF, LODYC, Meteo-France, and Met-Office models fail to produce the strong rainfall deficiency over the Indian subcontinent; as compared to the INGV and MPI models. Therefore, the above discussion suggests that biases in accurately representing the ocean-atmosphere coupling in the Indian Ocean environment can significantly limit the simulation of IAV of monsoon rainfall. Therefore, in addition to capturing the ENSO variability, it is also essential for coupled models to realistically depict the Indian Ocean variability in order to be able to improve the simulation of the IAV of monsoon rainfall. This point will be further taken up in the next section.

5.3.4 Regional aspects associated with the IAV of Indian monsoon rainfall

Significant advances in our current understanding of air-sea interactions in the tropical Indian Ocean environment have taken place during the last decade [eg., Yamagata et al., 2004; Annamalai and Murtugudde, 2004]. In particular, the discovery of the Indian Ocean Dipole (IOD) phenomenon and its effect on the regional climate variability has drawn considerable attention [eg., Saji et al., 1999; Webster et al., 1999; Behera et al., 1999; Murtugudde et al., 2000]. An IOD episode is characterized by cold SST anomalies in the southeastern part of the tropical Indian Ocean off the Coast of Sumatra; and warm SST anomalies in the west-central Indian Ocean. The zonal SST gradient during IOD events drives anomalous easterlies over the equatorial Indian Ocean; which increases upwelling and cooling in the southeastern tropical Indian Ocean and leads to rainfall reduction over the region. Generally, the ocean-atmosphere anomalies during IOD events evolve through the boreal summer and attain maximum amplitude during the autumn months. During the last 50 years, there have been
four major IOD events during 1961, 1994, 1997 [Meyers et al., 2007] and more recently during 2006 [Luo et al., 2006]. Studies have shown that positive IOD events favor stronger-than-normal monsoonal rains over the Indian subcontinent through enhanced supply of moisture from the south-eastern tropical Indian Ocean into the plains of north-central India [eg., Behera et al., 1999; Ashok et al., 2004]. Observed rainfall records over India (http://www.tropmet.res.in) provide corroborative evidence for anomalously wet summer monsoons during 1961 and 1994; while the monsoon precipitation was above-normal in 1997 and 2006 – despite 1997 being a very strong El Nino year. Based on model simulation experiments, Ashok et al., [2004] noted that the strengthening of monsoonal winds during an IOD episode can counteract and compensate the impact of an ongoing El Nino on the Indian monsoon. Slingo and Annamalai [2000] pointed out that the strong suppression of convection over the southeastern Indian Ocean and the Maritime Continent by the intense El Nino of 1997 in fact altered the local monsoon Hadley circulation in a manner as to favor above-normal precipitation over the Indian landmass. Here, we examine the simulation of the rainfall anomalies during the summer monsoon of 1997 by the DEMETER models; and contrast them with the CMAP rainfall anomalies (Figure 5.10). The increased rainfall over the central-eastern equatorial Pacific in the CMAP data is associated with the strong El Nino conditions which prevailed in 1997. In fact, the 1997 event was the strongest El Nino in the last century. A strong suppression of rainfall is seen over the equatorial west Pacific and eastern Indian Ocean; while above-normal precipitation is seen over northern India, Indo-China and Eastern China (Figure 5.10a). Increased precipitation is also seen over the western tropical Indian Ocean in the CMAP data (Figure 5.10a). While most of the coupled models, capture the increased precipitation over the equatorial eastern-central Pacific and the decreased rainfall over west Pacific; they fail to capture the sign of the
Figure 5.10: Seasonal (JJAS) rainfall anomaly (mm day$^{-1}$) for 1997 (a case of intense El Nino plus a positive IOD) (a) OISST (b) CERFACS (c) ECMWF (d) INGV (e) LODYC (f) Meteo-France (g) MPI (h) Met Office.
Figure 5.11: Same as 5.10 except for SST anomaly (°C) (a) OISST (b-h) DEMETER models.
rainfall anomaly over the Indian subcontinent. The model simulations mostly show large decrease of rainfall over the Indian landmass. In other words, the DEMETER coupled models basically depict the ENSO-related precipitation changes; while the competing regional effects associated with the IOD are not properly depicted in the GCM simulations.

The biases in the rainfall simulations are consistently reflected in the simulated SST during the 1997 IOD event by the DEMETER coupled models (Figure 5.11). Although the 1997 El Nino conditions in the Pacific (ie., positive SST anomalies in the equatorial eastern Pacific and negative anomalies in the western Pacific) are reasonably captured by a majority of models; the regional Indian Ocean SST anomalies associated with the IOD are not so robust in the simulation. For example, the CERFACS and Meteo-France coupled models show cooling in the south-eastern tropical Indian Ocean, the anomalous warming in the western Indian Ocean is not very clear. Gadgil et al., [2003, 2005] note that the IAV of the Indian summer monsoon rainfall is strongly determined by the pattern of rainfall / convection anomalies over the equatorial Indian Ocean – which they refer to as the Equatorial Indian Ocean Oscillation (EQUINOO) - the atmospheric component of the IOD. During years of normal or above-normal monsoon rainfall over India, the EQUINOO is associated with suppressed rainfall over the eastern equatorial Indian Ocean and increased rainfall over the western Indian Ocean. The EQUINOO anomalies in the eastern and western Indian Ocean are reversed for the years of monsoon droughts over India. Since the EQUINOO precipitation anomalies are closely linked to the IOD and the regional SST anomalies, it is important that reliable model simulations of the monsoon rainfall critically depend on the treatment of the coupled interactions in the Indian Ocean environment.
Progress in dynamical seasonal climate prediction over the past 25 years has been considered useful for some societal applications. However, such successes are limited to periods of large, persistent anomalies at the Earth’s surface and there is significant unrealized seasonal predictability [Shukla and Kinter 2006]. When the lower boundary forcing is weak, the skill of seasonal forecasts tends to be limited by internal variabilities [see Krishnamurti et al., 2006].

In order to be able to simulate the monsoon and its variability at sub-seasonal, interannual and decadal time-scales, the climate models must be able to resolve the cloud systems with embedded deep convection, and also be able to capture the mean rainfall and its variability in space and time [Shukla 2007]. The accuracy of simulating deep tropical convection and associated rainfall distribution still remains a major hurdle due to uncertainties in the parameterizations of sub-grid scale processes in GCMs (eg., moist convection, boundary-layer processes, cloud-radiation interactions). Additionally, the other major barrier in seasonal prediction is the difficulty with initializing coupled ocean-atmosphere-land models [Shukla and Kinter, 2006]. While atmospheric data assimilation has reached a mature stage in extracting large fraction of usable information from available observations [Simmons and Hollingsworth, 2002]; and ocean data assimilation has rapidly developed in recent decades [Derber and Rosati, 1989; Ji et al., 1995], assimilation of land surface observations has only recently been attempted globally [eg., Dirmeyer, 2000]. Soil moisture not only responds to precipitation variability, but also affects precipitation through evaporation. This two-way interaction has often been referred to as a positive feedback, since the water added to the land surface during a precipitation event leads to increased evaporation, and this in turn can lead to further rainfall [eg., Walker and Rowntree, 1977; Shukla and Mintz
1982; Rind, 1982, Yeh et al., 1984; Meehl and Washington, 1988, Delworth and Manabe 1989, Simmonds and Lynch, 1992; Meehl, 1994; Sud et al., 1995; Douville et al., 2001]. Although, the importance of using realistic initial state of soil wetness for seasonal prediction of the Asian and African monsoons has been pointed out by several studies [eg., Fennessy et al., 1994; Fennessy and Shukla, 1999, Douville and Chauvin, 2000; Douville et al., 2001], our limited understanding of initializing the land-surface conditions in models has been one of the major constraints for monsoon seasonal prediction [Shukla and Kinter, 2006].

As pointed out by Gadgil et al., (2005), there are no quick-fix solutions available to tackle the problem of seasonal prediction of the Indian summer monsoon rainfall. In a series of papers, T.N. Krishnamurti and his research group at FSU have demonstrated the feasibility of seasonal climate forecasts based on the multi-model super-ensemble methodology [eg., Krishnamurti et al., 1999, 2000a, 2000b, 2001, 2002, 2003a, 2003b, 2006; Stefanova and Krishnamurti (2002); Willford et al. (2003), Kumar et al., (2003), Yun et al., (2003) and Ross and Krishnamurti, 2003]. This is a very powerful method for producing a consensus forecast from a suite of multi-models and use of statistical algorithms. In this methodology, the super-ensemble reduces the errors considerably compared with those of the member models and of the ensemble-mean [Krishnamurti et al., 2006]. Given the various challenges in the seasonal prediction of Indian monsoon, the multi-model super-ensemble appears to be a tangible approach for foreshadowing the monsoon.

Furthermore, recent studies have demonstrated the potential for extended range prediction of monsoon break spells about 2-3 weeks in advance using statistical [eg., Webster and Hoyos, 2004; Goswami and Xavier, 2003]
and dynamical (GCM based) approaches [eg., Krishnamurti et al., 1990, 1992, Waliser et al., 2003a, 2003b]. Such improvements in extended range predictions on sub-seasonal time-scales could actually complement the seasonal monsoon forecasts. Likewise, it has been reported that improved representation of monsoon sub-seasonal variability in model simulations can be achieved through realistic treatment of air-sea interactions in the tropics [see Fu et al., 2003; Fu et al., 2007]. It is hoped that with the increasing observational network in the Indian Ocean region through special platforms like moorings, data buoys and ARGO floats (http://www.clivar.org/organization/indian/index.htm) and satellite observations over oceanic and land regions; together with developments in coupled modeling and data-assimilation will foster significant improvements in extended and seasonal range monsoon rainfall predictions in the coming years and provide better understanding of the ocean-atmosphere-land coupled system.