5

MULTISCALE MODELING AND SIMULATION

To advance the simulation of weather and climate and climate change projection, General Circulation Models (GCMs) need to represent atmospheric processes such as multiscale organization of organized convection and aerosol-cloud-radiation feedback.

Under CSIR-4PI Multiscale Modeling and Simulation Group (MMSG) we seek to develop an ultra-high resolution climate modeling framework to address multiscale processes of the atmosphere and analyze the data from observations and simulations in a data intensive paradigm of research.

Inside

- ***Earth System Model: New version of the coupled ocean-atmosphere climate model***
- ***Impact of increased GHG emissions for the state of Kerala***
- ***RCP8.5 scenario climate change projection for india using high resolution global climate model***
- ***Role of mean and variability of Indian summer monsoon rainfall in reliability of future projections in CMIP5 coupled models***
- ***Comparing statistically downscaled simulations of indian monsoon at different spatial resolutions***
- ***Implementation of regional climate model for climate change applications***
- ***Bivariate PDF analysis of latent heating over the tropics***
- ***Cyclonic events in megha-tropiques data***
- ***Rainfall and aerosol optical depth from an aerosol coupled GCM during the abnormal Indian summer monsoon of 2000***
- ***Characteristics of MODIS aerosol optical depth during 2002 drought monsoon***

5.1 Earth System Model: New version of the coupled ocean-atmosphere climate model

A large number of climate phenomena and climate variability are strongly dependent on the coupling between ocean and atmosphere and the feedbacks among various components of the climate system. A clear understanding of this coupling and feedbacks thus plays a pivotal role in predicting the global pattern of climate variables and their variability especially associated with the global warming. Hence, it is essential to incorporate the complex processes involving biological and chemical components of the climate system (e.g., the processes related to aerosols and GHGs, as well as the feedback processes between carbon cycle and climate change) as well, into the climate model. Such a climate model, viz. the Earth System Model (ESM) enables us to represent the important components of the climate system including terrestrial and oceanic material transport, as well as their interactions, reasonably well. A global coupled ocean-atmosphere general circulation model (GCM), developed by Meteorological Research Institute (MRI, Japan), coupled with an ESM module, is now installed and benchmarked. The coupling between ocean and atmosphere in this climate model involves exchange of Sea Surface Temperature (SST) from ocean to atmosphere and heat flux components, freshwater flux and horizontal momentum flux in return. Further improvement of this version, is being carried out so as to help in better understanding and predicting the changes in the climate system.

Two versions of the climate model (CGCM2.3 and CGCM3) are analyzed to assess the improvements/ drawbacks of the modified version. SSTs from the climatological simulation of the two versions are shown in Figure 5.1. It can be seen that the mean SST patterns from the simulations compare well with that from HadISST in capturing the large-scale aspects. However, it can be seen that the model

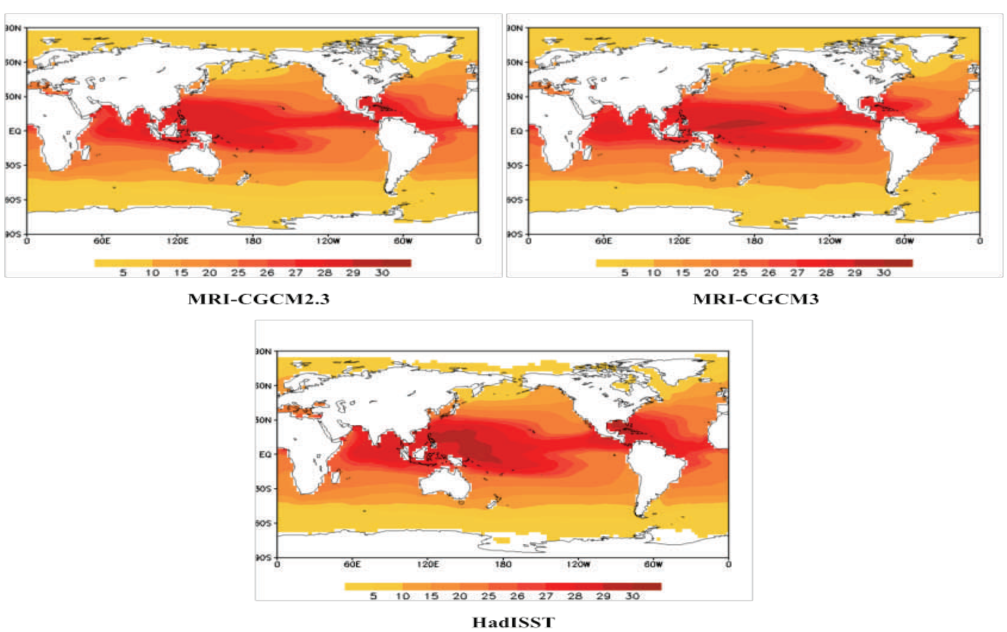


Figure 5.1 50 year climatological June to September mean SST from the simulations of CGCM2.3, CGCM3, and HadISST (1941-1990) observation.

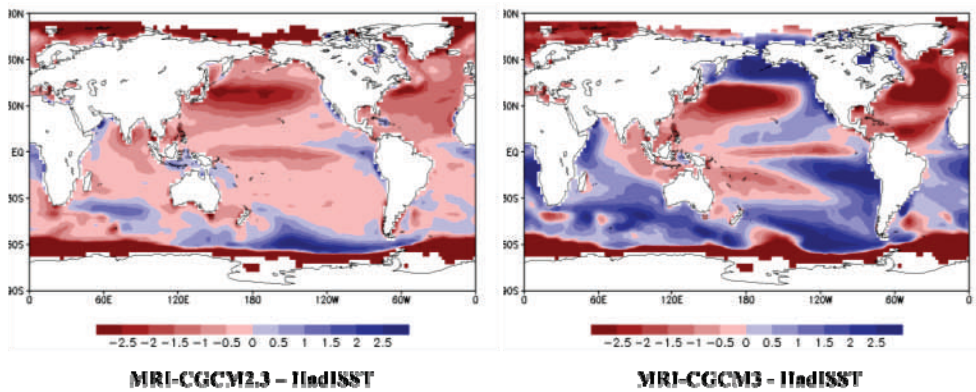


Figure 5.2 Difference between simulated (by CGCM2.3 and CGCM3) and observed climatological June to September mean SST over a period of 50 years (1941-1990).

climatology departs from the observed fields over some parts, which are referred to as the climate bias of the models. Such a bias can be a serious hindrance in using the model to study climate and climate change. Figure 5.2 shows the bias in simulating seasonal mean SST. A significant cold bias is seen over the northern Pacific, which is stronger in the newer version of CGCM3. This could be partly due to the exclusion of flux adjustment that was employed in the CGCM2.3.

This initiative taken at CSIR Fourth Paradigm Institute (CSIR-4PI) through an in-house collaborative project involving CSIR 4PI, Meteorological Research Institute (MRI), Japan Meteorological Agency (JMA), and Divecha Centre for Climate Change (DCCC) Indian Institute of Science, aims in developing a skillful Earth System Model based on the coupled ocean-atmosphere GCM for climate studies of Indian region. This effort is poised to employ modified sub-grid scale parameterization scheme suitable for Indian region in the climate model.

Stella Jes Varghese, Sajani Surendran, K Rajendran
Y Adachi (JMA***), A Kitoh*** (University of Tsukuba),
S Yukimoto and R Mizuta (MRI, Japan)

5.2 Impact of increased GHG emissions for the state of Kerala

There is strong evidence for the occurrence of climate change in the form of global warming. Over the last few decades, temperatures have risen nearly everywhere as is the case for India. These trends in temperature and summer monsoon rainfall have accelerated since the 1990s. According to climate scientists, the accumulation of CO_2 and other greenhouses gases (GHGs) in the atmosphere is the fundamental cause of recent global warming. In support, CO_2 emissions show a clear increase over the last two decades, regionally as well (Figure 5.3). The more GHGs there are in the atmosphere, the more heat is trapped and the higher the Earth's temperature becomes. Today the major cause of the increase in CO_2 emissions is human activity (anthropogenic). Anthropogenic GHG emissions also include methane (CH_4) and nitrous oxide (N_2O) and others such as hydrofluorocarbons that are released by various industrial processes. Global emissions of CO_2, similar to the emissions from India, continues to rise.

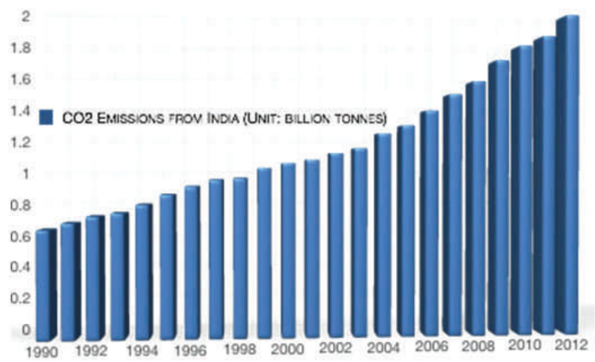


Figure 5.3 Simulated changes in CO_2 emissions from India since 1990 based on EDGAR data.

The major sources of anthropogenic GHGs in India show that the energy sector and especially electricity and heat are responsible for the majority of GHG emissions from India (Fig. 5.4). Direct agriculture activities (23%) are about as important as industry (15%) and transport (6%). Contribution from land-use changes consisting mainly of the harvesting of agriculture and forestry products and the clearance of natural vegetation for agriculture and constructions is also an important source.

Kerala, the southern state of India, is known for its green landscape, water bodies, rolling mountains and narrow valleys. With high rainfall, chains of backwater bodies, many rivers, reservoirs, lakes, ponds, springs and wells, the state is considered as the land of water. When the neighboring states are harnessing large quantum of surface and groundwater sources for irrigation, hydro power generation, domestic and industrial purposes, the scope for development of this precious resource is very limited in Kerala due to its unique characteristics. For the last three decades, Kerala is frequently facing dry spells followed by acute drinking water scarcity. The rivers hardly contain any water during the summer months; only a few reservoirs and lakes get filled up even in the monsoon and household wells and ponds are increasingly getting dry in summer. The water resource situation becomes worse in deficit monsoon years.

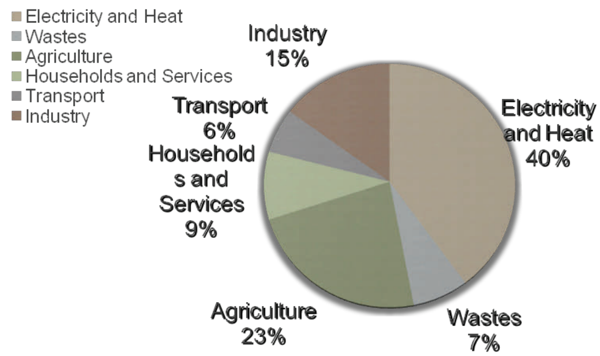


Figure 5.4 GHG emissions by India (2004) by sector (Source: PEW Centre's International Brief 2: `Climate Change Mitigation Measures in India', September, 2008).

Across the state, impacts of climate change are already in evidence. Extreme rainfall events and warm extremes have become more frequent and intense, intense dry spells during monsoon are common and patterns of rainfall are likely changing. Even if emissions of GHGs were substantially reduced now, climate would continue to change for some time to come and the potential consequences for humans and ecosystems are significant. In ecosystems, changing climate could alter the distribution patterns of plant and animal species, reduce the productivity and abundance of species, and change habitats. Sea level could be affected, threatening the natural and built environments on the coasts and in fresh water systems, especially when combined with effects of more intense coastal storms. This report presents the projections of possible climatic changes associated with global warming, impacts of climate change and some discussions on how we as a state can begin adapting to them in beneficial ways.

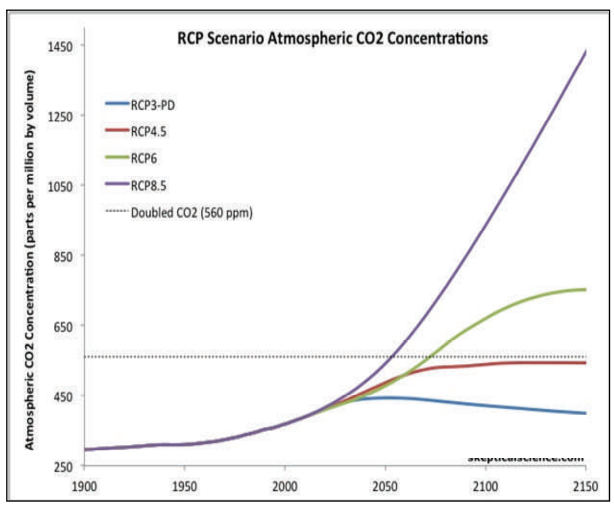
Kerala receives an annual average rainfall that is about 2.5 times more than that of all-India average. Southwest (SW, from June to September or JJAS) and Northeast monsoon (NE, from October to November or ON) are the two monsoon seasons of the state, of which SW monsoon is the dominant rainy season. About 84% of the annual rainfall is received during the monsoon period between June and November (68% during SW and 16% during the NE) and the remaining 16% during the non-monsoon period of December to May.

The climate of Kerala is changing in ways that can be attributed to human-caused emissions of GHGs. The state is warming. Average maximum and minimum temperatures for the last decade were the highest in the state from 1901 through 2007. This increasing trend is clear in both annual mean and the mean of SW monsoon season, for both maximum temperature (T_{max}) and minimum temperature (T_{min}). It is also to be noted here that there is a close linkage between rice grain yield and T_{min} with a tendency for reduction in yield with increase in the T_{min}. The observed rainfall trend over Kerala shows that there is significant decrease in southwest monsoon rainfall in recent times. Annual and SW monsoon rainfall departures from present-day reference period (1961-1990) climate and the recent trends using India Meteorology Department (IMD) sub-divisional rain gauge rainfall show clear decreasing trends over the state. The distribution of yearly rainfall for the JJAS period and rainiest period of July-August for the entire state also bring out the declining trend in rainfall.

Sajani Surendran and K Rajendran
Akio Kitoh (MRI, Japan)
Ravi S Nanjundiah (DCCC, IISc)

5.3 RCP8.5 scenario climate change projection for India using high resolution global climate model

We have analyzed 20-km model time-slice simulation under the forcing of representative concentration pathways (RCP) 8.5 (RCP8.5) which corresponds to a radiative forcing of 8.5 W m^{-2} in 2100, and represents an extension and improvement of the SRES-A2 emissions scenario of IPCC-AR4. Moreover, the RCP8.5 pathway serves as an upper bound of the RCPs. Future projections by time-slice simulations of 20-km AGCM under RCP8.5 global warming scenario (Figure 5.5) show widespread but spatially varying increase in rainfall over the interior regions of peninsular, west central, central northeast and northeast India (Figure 5.6) and significant reduction in orographic rainfall over the west coast (consistent with the recent observed trends.



RCP8.5 – The path we are on (unabated emissions)
RCP2.6 (RCP 3-PD) – Aspirational path

Figure 5.5: Four scenarios of IPCC AR5, named after the radiative forcing (global energy imbalance) caused by human emissions around the year 2100.

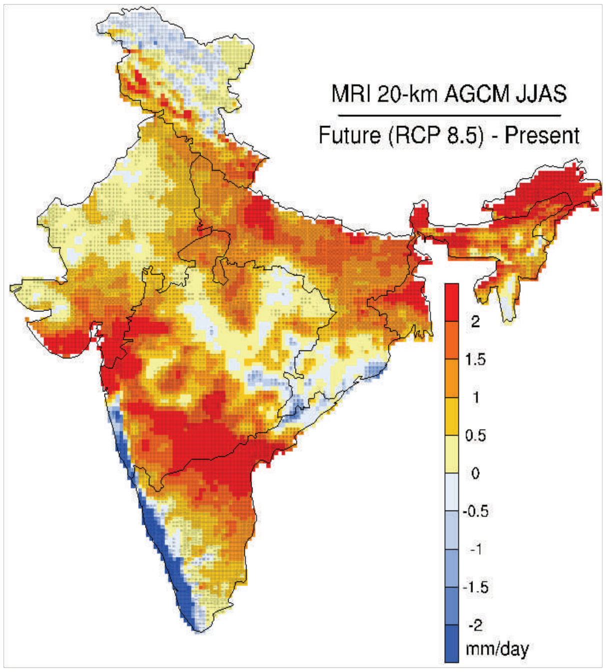


Figure 5.6 Projected future changes in JJAS mean rainfall over India by 20-km climate model under RCP8.5 scenario. Within each colour, the symbols corresponds to changes as percentage of mean summer monsoon rainfall (< 5%: no symbol, 5-15%: dots, 15-25%: open circle and >25%: plus)

Future projections of Indian summer monsoon rainfall with high-resolution regional climate models or IPCC models project relatively uniform change in monsoon rainfall over India. Spatial distribution of the changes in summer monsoon precipitation due to global warming shows larger spatial variability with more regional details in simulations with 20 km resolution (Figure 5.6). This shows that high-resolution simulations are essential to extract useful regional climate change information. The pattern in precipitation is uneven in ultra-high resolution models with distinct spatial heterogeneity (Figure 5.6).

K Rajendran and Sajani Surendran
Akio Kitoh (MRI, Japan)

5.4 Role of mean and variability of indian summer monsoon rainfall in reliability of future projections in CMIP5 coupled models

The state-of-the-art coupled general circulation models (CGCMs) from Coupled Model Intercomparison Project phase five (CMIP5) are used to quantitatively estimate the projected changes in the Indian summer monsoon, its variability, and the basic seasonal cycle. The CMIP5 models project clear future temperature increase but diverse changes in Indian summer monsoon rainfall (ISMR) with considerable intermodel spread. The interannual variability (IAV) measured based on the coefficient of variation shows nearly equal chance for future increase or decrease and it varies from -15.4% to 9.7% (Figure 5.7). This diverse nature lead us to classify the models to derive reliable estimates of the climate change impact on the mean ISMR and its IAV, and the seasonal cycle which are important for regional climate change impact assessments.

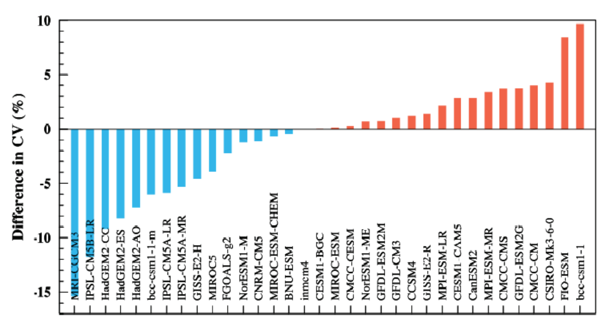


Figure 5.7 Projected change in coefficient of variation of ISMR for 34 CMIP5 models.

Observed seasonal cycle and the present-day and projected seasonal cycles from most of the models manifest not only the projected intensification in rainfall throughout the year but also changes in the

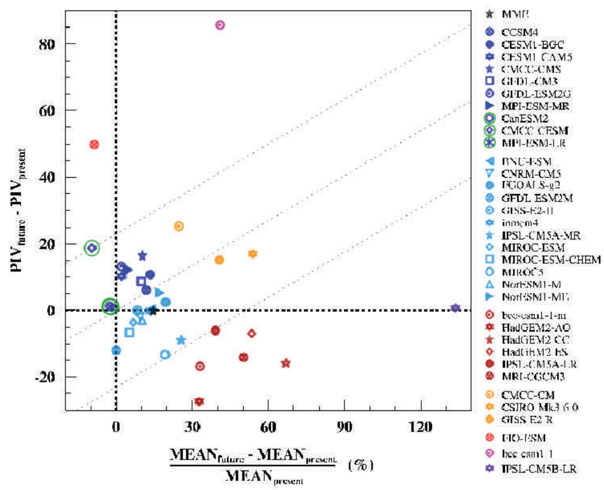


Figure 5.8 Projected change in PIV versus change in mean ISMR (w.r.t. present-day mean in %) for 34 CMIP5 models, groups A (7 models, blue), B (12 models, sky blue), C (6 models, red), and D (3 models, orange) and three outliers (outside slanted lines y = 0.45x ± 23, and around y = 0.45x). Three models are classified into group E (green circles around blue symbols).

timings of onset, peak, and withdrawal of indian summer monsoon in the future scenario. To obtain the robust signals from the existing models, we grouped the models based on their relative changes of mean and variability. Physically consistent groups of models are derived from the relationship between the projected changes in ISMR and its IAV (Figure 5.8). Further, these groups are validated based on the k-mean clustering based Dunn's Index and the reliability ensemble averaging (REA). We have chosen the most reliable groups such as Group A (having reliability of 0.724) and Group B (0.703) to derive the robust results (the groups and group member models are described in Figure 5.8). The frequency distribution of monthly rainfall shows, the extreme precipitation (>24.5 mm/day) frequency is enhanced by about 0.80% (0.31%) for group A (group B). Based on these both physically consistant group of models (together of 19 models) project a future increase of mean ISMR by 0.74 mm/day with an uncertainty of ±0.36 mm/day and also project future increase in IAV (change in CV) as 0.91%.

C B Jayasankar , Sajani Surendran, K Rajendran

5.5 Comparing statistically downscaled simulations of Indian monsoon at different spatial resolutions

Impacts of climate change are typically assessed with fairly coarse resolution General Circulation Models (GCMs), which are unable to resolve local scale features that are critical to precipitation variability. GCM simulations must be downscaled to finer resolutions, through statistical or dynamic modelling for further use in hydrologic analysis. In this study, we use a linear regression based statistical downscaling method for obtaining monthly Indian Summer Monsoon Rainfall (ISMR) projections at multiple spatial resolutions, viz., 0.05°, 0.25° and 0.50°, and compare them.

We use 19 GCMs of Coupled Model Intercomparison Project Phase 5 (CMIP5) suite and combine them with multi model averaging and Bayesian model averaging. We find spatially non-uniform changes in projections at all resolutions for both combinations of projections. Our results show that the changes in the mean for future time periods (2020s, 2050s, and 2080s) at different resolutions, viz., 0.05°, 0.25° and 0.5°, obtained with both Multi -Model Average (MMA) and Bayesian Multi-Model Average (BMA) are comparable. We also find that the model uncertainty decreases with projection times into the future for all resolutions. Figure 5.9 shows the uncertainty for SMR projections at differ

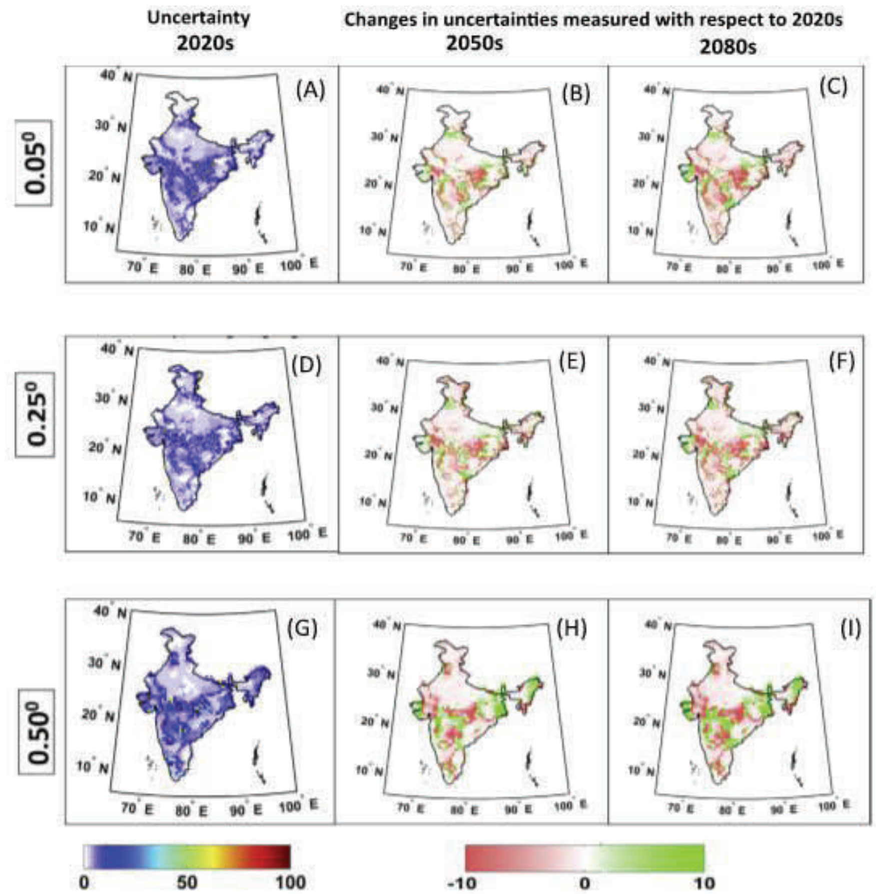


Figure 5.9 Projected change in coefficient of variation of ISMR for 34 CMIP5 models

ent resolutions and for different time windows 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099). The relative changes in uncertainties across different resolutions are measured with respect to 2020s. We find that the model uncertainty is highest for the 2020s and then it gradually decreases with the lead time. This is true at all resolutions. The possible reason is that with the increase in lead time, the climate change signal becomes more prominent compared to internal variability and model uncertainty due to the imposed radiative forcings (Hawkins and Sutton, 2009), resulting in a decrease in the CV values.

We compute Signal to Noise Ratio (SNR), which represents the climate change signal in simulations with respect to the noise arising from multi-model uncertainty. This appears to be almost similar at different resolutions. The present study highlights that, a mere increase in resolution by a way of computationally more expensive statistical downscaling does not necessarily contribute towards improving the signal strength. Denser data networks and finer resolution GCMs may be essential for producing usable rainfall and hydrologic information at finer resolutions in the context of statistical downscaling.

K Shashikanth, C G Madhusoodhanan, Subimal Ghosh and T I Eldho (IIT-Bombay)
K Rajendran
Raghu Murtugudde (University of Maryland, USA)

5.6 Implementation of regional climate model for climate change applications

A high-resolution non-hydrostatic model, Weather Research and Forecasting (WRF-CLIM) model is implemented to study climate change projection of Indian summer monsoon (ISM) at ultra-high resolutions. Here we present the simulation of 2002, a drought ISM year simulated by the model forced with reanalysis data. The model is integrated from 1st may and continuously ran up to 30th September (5 months) of the year.

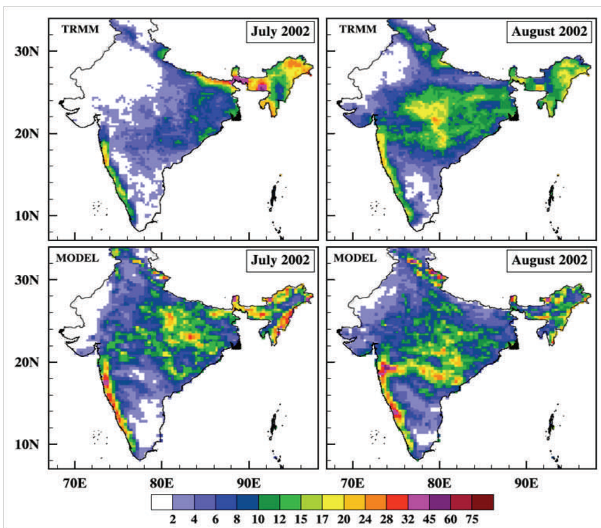


Figure 5.10 Observed and simulated (by WRF-CLIM) precipitation for July and August months of 2002.

The model-simulated precipitation is compared with the observed precipitation from TRMM. Figure 5.10 shows simulated and observed TRMM precipitation for the peak ISM months of July and August. We can see that, even though the simulated July precipitation is overestimated, the models capture the spatial heterogeneity seen in the observation especially in August and orographic rainfall is well simulated by the model in both months. We expect that suitable combination of physical schemes and numerics of the model configuration can give a better simulation of ISM rainfall. After extensive sensitivity experiments, the model can be used for future studies such as the climate change impact on regional scales.

C B Jayasankar and K Rajendran

5.7 Bivariate PDF analysis of latent heating over the tropics

A study with 13-year (1998-2010) mean apparent diabatic heating (Q_{1R}) along with its partitioning due to shallow, convective and stratiform heating for tropical land and ocean reveals that the vertical distribution of total latent heating modulates due to the difference in proportion of convective and stratiform contribution at each level and the positive convective heating is mainly confined in the lower troposphere below ~5 km, whereas positive stratiform heating contribution is in the upper troposphere (above ~7 km) for both land and ocean domains. Stratiform heating is mostly negative below ~5 km and positive above ~5 km, whereas convective heating is positive throughout 0 to 16 km.

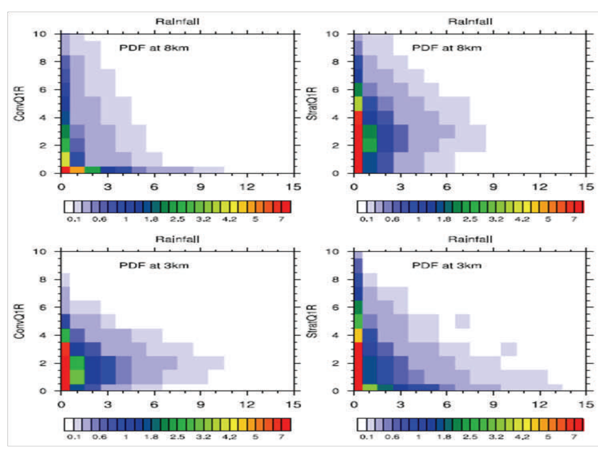


Figure 5.11 Bivariate PDF of rainfall with convective (left panels) and stratiform (right panels) heating at 8km (top panels) and 3km (bottom panels) for a representative oceanic domain of East Pacific.

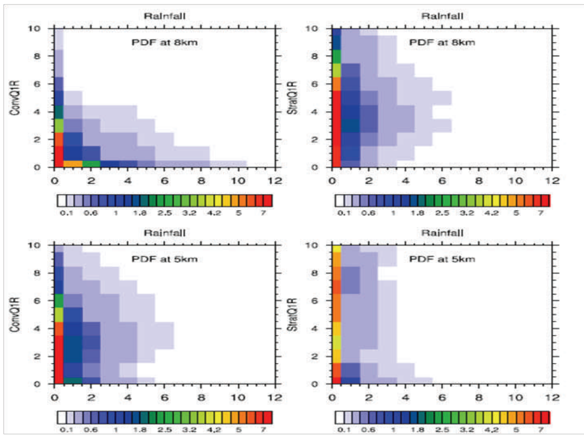


Figure 5.12 Bivariate PDF of rainfall with convective (left panels) and stratiform (right panels) heating at 8km (top panels) and 3km (bottom panels) for a representative land domain of India.

Bivariate Probability Distribution Function (PDF) analysis with Q_{1R} and rainfall data [only on the grids where heating is convectively positive] at each vertical level from 2 km to 9 km for stratiform as well as for convective heating depicts that over ocean lower level peak (~3 km) is primarily due to convective heating whereas at the same level the contribution from the stratiform heating is negligible (Figures 5.11 and 5.12). At higher altitude (~8 km), PDF over ocean confirms the major contribution from the stratiform heating to the total heating compared to convective heating. Over land the single peak from ~5-8 km is largely contributed by convective heating which peaks at ~5 km and with a small contribution from stratiform heating that peaks at ~8 km.

Ipsita Putatunda and K Rajendran

5.8 Cyclonic events in megha-tropiques data

Megha-Tropiques (MT) orbital data has been converted to daily layer averaged Relative Humidity (RH) data for six layers from 1000 hPa to 100 hPa. Figure 5.13 shows global RH for a single layer (1000-850 hpa) on a particular day of 20th June 2012.

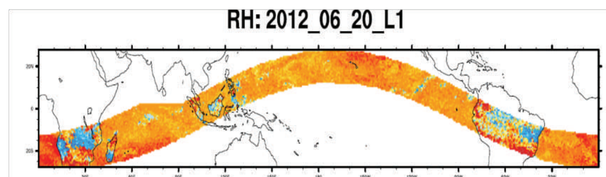


Figure 5.13 Relative humidity using Megha-Tropiques SAPHIR data for the first layer (1000-850 hPa) on 20 June 2012.

Initial analysis of MT Relative Humidity and Outgoing Longwave Radiation (OLR) data well captures weather events like the cyclones 'Nilam', 'Thane'. Figure 5.14 shows the progression of Thane cyclone from 27 October to 29 October 2012.

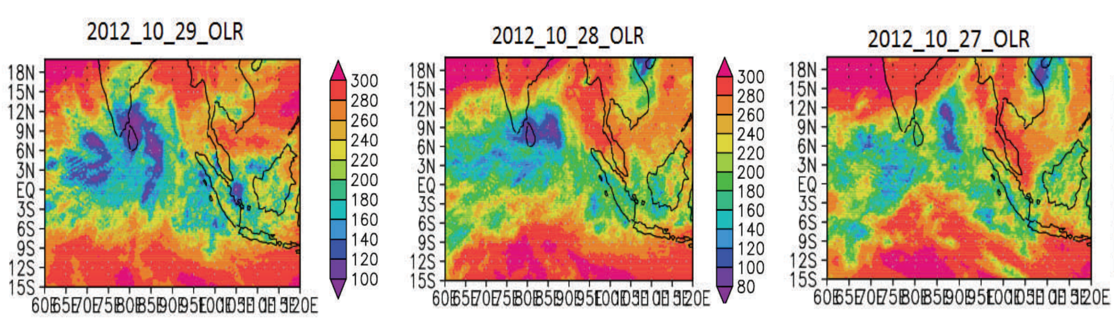


Figure 5.14: Megha-Tropiques OLR from SCaRaB showing the progression of cyclone THANE from 27 October to 29 October 2012.

Ipsita Putatunda and K Rajendran

5.9 Rainfall and aerosol optical depth in an aerosol coupled GCM during the abnormal Indian summer monsoon of 2000

The Asian monsoon region is known to have high concentrations of aerosols, which can significantly affect monsoon rainfall through direct and indirect shortwave radiative forcing. Additionally, rainfall variability is also governed by cloud occurrence and microphysics which play important roles in the radiative energy and water cycle balance. Previous studies investigated the influence of enhanced anthropogenic aerosol on convective precipitation due to indirect radiative forcing from General Circulation Model (GCM) simulations with a focus on the differences between the experiment with the present -day aerosol emissions (PD) and the pre-industrial aerosol emissions (PI), averaged for 5 years for the period from January 2001 to December 2005 (i.e., D=PD-PI).

The model simulates a wide spread and substantial change in column aerosol concentration due to anthropogenic emissions, which leads to a wide spread and strong surface cooling. This cooling is mainly due to aerosol absorption. A signal in precipitation is observed only over central India in the monsoon season. This reduction in precipitation mainly stems from convective precipitation.

The spatial distribution of seasonal rainfall in JJAS over India for the abnormal year 2000 is compared with the simulated rainfall and atmospheric aerosol parameters in Figure 5.15, to understand the mechanism behind the impact of aerosol perturbation on rainfall and to validate the simulated aerosol variables against the observations. Occurrence of high positive AOD ranging from 0.4 and 0.7 is evident over the Arabian sea, while the southern part of the Arabian Sea has very less AODs. The model is able to capture the magnitude over the Arabian Sea and

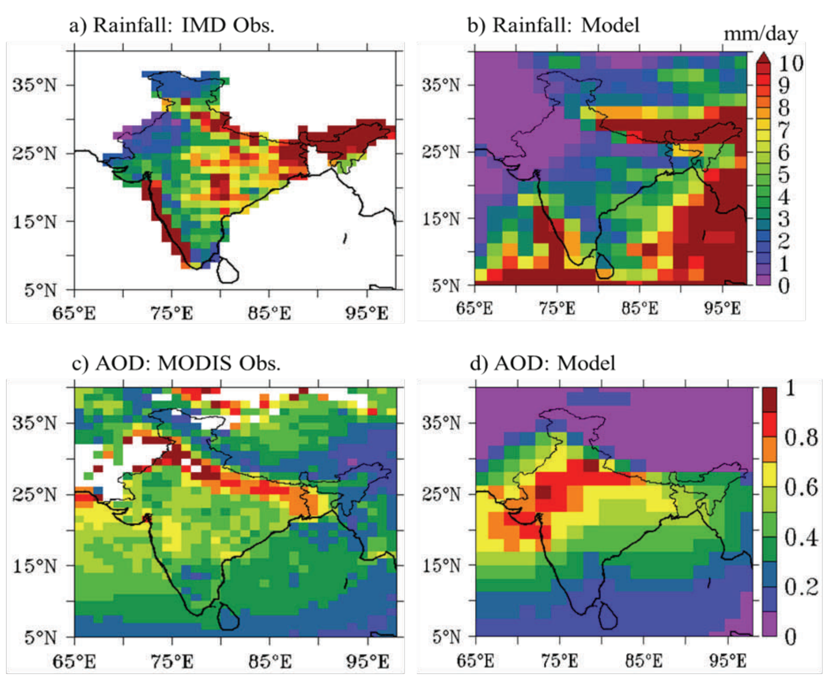


Figure 5.15 JJAS mean a) rainfall from IMD, b) rainfall from model, c) AOD from MODIS and d) AOD from model during the abnormal year 2000 of Indian summer monsoon.

some parts of Gangetic plain over India. Simulated rainfall shows disagreement with observation in central India and parts of Western Ghats, which needs to be addressed.

Nitin Patil and C Venkataraman (IIT-Bombay)
Sajani Surendran

5.10 Characteristics of MODIS aerosol optical depth during 2002 drought monsoon

The recent monsoon drought of 2002 resulted in economic losses of billions of dollars and caused the lowest rainfall in the historical records during the last 135 years. Much of the rainfall decrease occurred in the core rainy month of July 2002, when the rainfall distribution over the country was nearly 50% below the long-term normal. We investigated MODIS (MODerate Resolution Imaging Spectroradiometer) derived Aerosol Optical Depth (AOD) at 550 nm and its variability in the mid monsoon month of July, over India. AOD has been estimated using Level-2 MODIS Terra Data Version 6 and gridded to uniform grid and into monthly averages. The aerosol optical characteristics and rainfall during 2002 drought monsoon are compared against those during 2013 (Figure 5.16). Note that the AOD varies drastically over the Indian region during both years. The spatial loading of AOD during the drought year 2002, shows that there is persistence of high AOD values. The analysis shows that the high values of aerosol optical depth (AOD) occur during the drought monsoon month of July-2002, compared to July-2013 (Figure 5.16). Low rainfall amounts during the drought lead to an increase in AOD as compared to that in 2013.

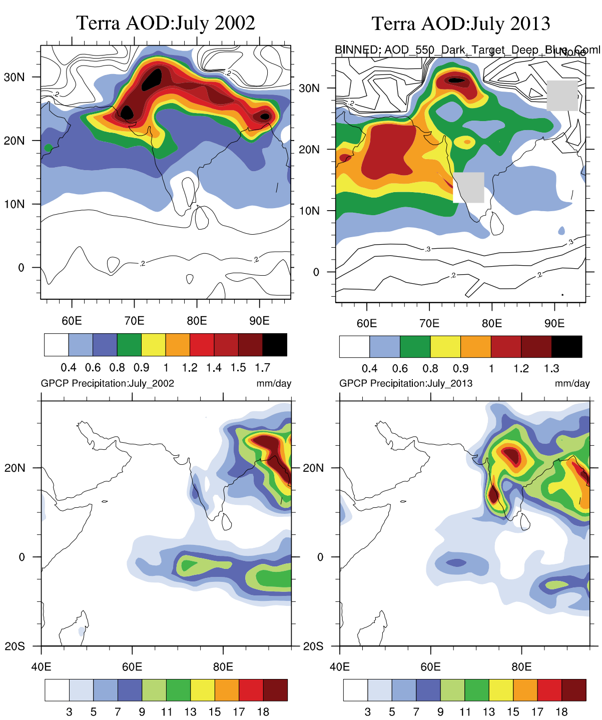


Figure 5.16 MODIS monthly averaged AOD's for July of a) 2002 and b) 2013 along with corresponding rainfall from GPCP data for July of c) 2002 and 2013.

Arya V B and Sajani Surendran