5

MULTISCALE MODELING AND SIMULATION

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

Under CSIR-4PI (erstwhile C-MMACS) 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

5.1 Coupled Ocean-Atmosphere General Circulation Model for Climate and Climate Change Studies: Installation, Optimization and Benchmarking

Ocean-atmosphere interaction and dynamical changes play a crucial role in natural climate variability on a broad range of time scales and in anthropogenic climate change. Thus, the development and continuous improvement of global coupled ocean-atmosphere general circulation model (CGCM) is essential for simulating, understanding, and predicting the global climate system. For example, the essence of Bjerknes (1969)'s postulate still stands as the basis of present day work, that ENSO arises as a self-sustained cycle in which anomalies of SST in the Pacific cause the trade winds to strengthen or slacken, and that this in turn drives the changes in ocean circulation that produce anomalous SST. At the same time, over the Indian domain, local SST-convection relationship is rather poor. These characteristics need to be represented well by a model in order to be useful for climate and climate change studies.

In a typical coupling scheme for an ocean-atmosphere model, the ocean model passes SST to the atmosphere, while the atmosphere passes back heat flux components, freshwater flux, and horizontal momentum fluxes. The numerical coupling interval (over which variables are averaged before being passed) is chosen for computational convenience or to satisfy assumptions of physical parameterizations. The atmospheric response to SST is rapidly redistributed vertically, especially in convective regions, and is nonlocal horizontally on time scales longer than dynamical adjustment times, of the order of a few days to a month. For most purposes, the atmosphere can be assumed to be in statistical equilibrium with given SST boundary conditions on time scales longer than a season. The ocean responds on a wide range of time scales, from days (for some features of the mixed layer) to millenia (for the deep-ocean thermal adjustment). Thus, it is common to characterize the ocean as having the *memory* of the system.

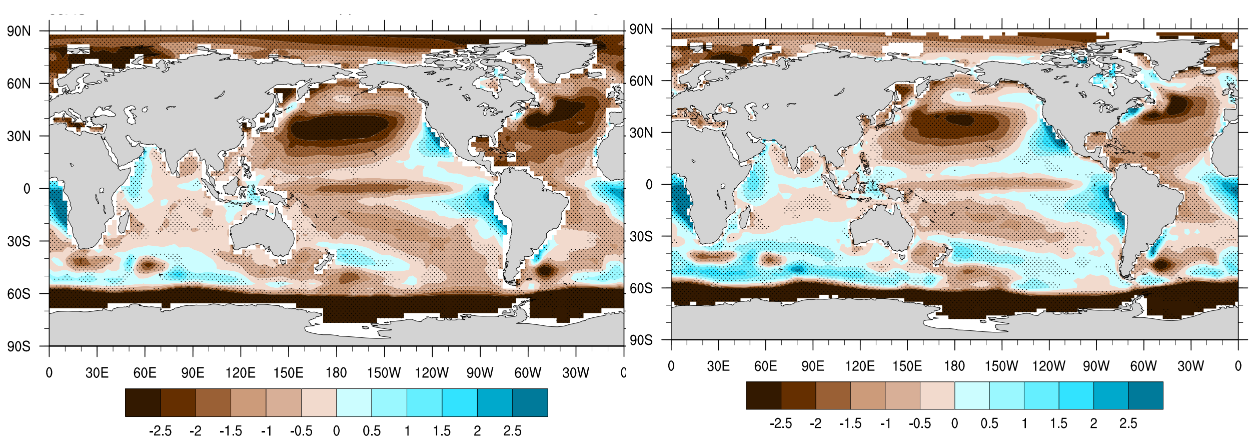

Figure 5.1 Difference between simulated and observed summer mean (June to September, JJAS) SST from multimodel ensemble of IPCC AR4 (left) and AR5 (right) climate models.

Climate bias in models, i.e, departure of the model climatology from the observed, is a common problem in coupled models. For example, the state-of-the-art coupled models participated in 4th and 5th Assessment Reports (AR4 & AR5) of Intergovernmental Panel for Climate Change

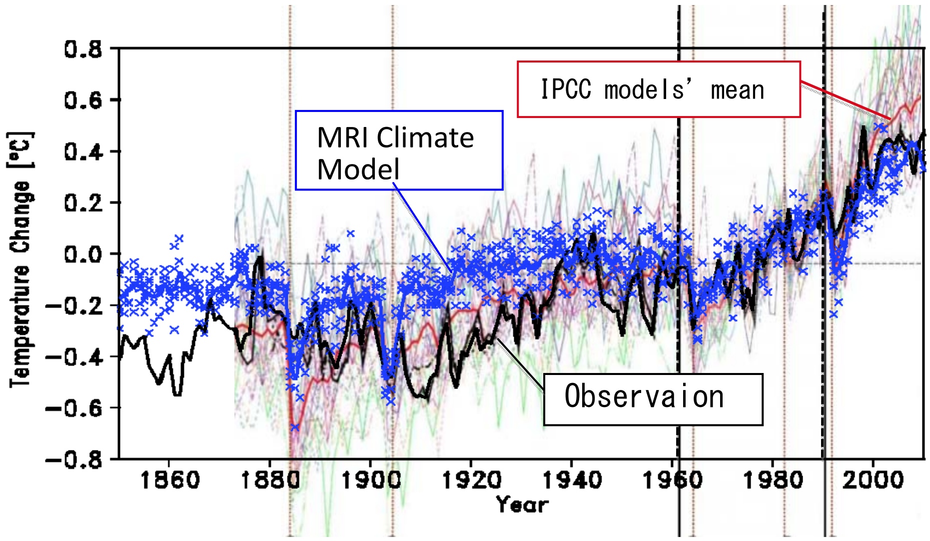

Figure 5.2 Time series of observed and simulated global mean surface air temperature from IPCC AR5 models and MRI climate model ensembles.

(IPCC) show large bias in simulating seasonal mean sea surface temperature (SST) with substantial cold bias evident over a large part of the ocean (Figure 5.1). Most of the models show significant cold bias over northern Pacific and significant warm bias over East Pacific. Further, it was found that the models that show a tendency for warm bias over the Indian Ocean tend to simulate the nonlinear SST-rainfall relationship slightly better. Similarly the time series of global mean surface air temperature change (Figure 5.2) manifests the systematic bias in its simulation from an ensemble simulation of a single climate model as well as from the multimodel mean of all the IPCC AR5 coupled models. The cold bias for a coupled version compared to its atmospheric-alone version results in shifting the mean SST-rainfall relationship to the colder SSTs, as seen in the IPCC AR4 version of a model (Figure 5.3).

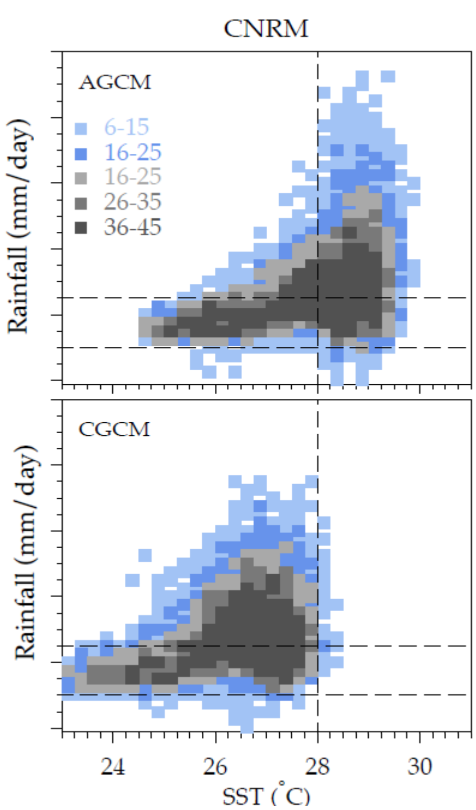

Figure 5.3 SST rainfall relationship simulated by IPCC AR4 CNRM atmosphere-alone (top) and coupled (bottom) GCMs.

Although numerics contribute, climate bias arises primarily from the cumulative effects of errors in the sub-grid parameterizations; as such the process of correcting it based on careful physical arguments can be slow and painstaking. Design specifications in the coupled models for the tropical problem include the use of moderate resolution ocean components to resolve equatorial wave dynamics with characteristic meridional scales of order 0.1°-0.5° latitude. For the global problem, the ocean models typically are used with coarser resolution because of the necessity of very long integrations for equilibration.

For climate applications over tropical regions, the common way to improve the bias is 1) enhanced resolution of individual components, 2) Improved subgrid-scale parameterizations and 3) Increased coupling frequency. We have initiated an in-house collaborative project involving CSIR-4PI (erstwhile C-MMACS), Meteorological Research Institute (MRI), Japan and Divecha Centre for Climate Change (DCCC), Indian Institute of Science (Project R-8-118) to develop a skillful coupled model for climate studies of Indian region. As part of the project a CGCM is installed and test integrations are performed at CSIR-4PI (erstwhile C-MMACS).

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5.2 Clouds and Aerosol Radiative Forcing

The degree to which the aerosol impacts the radiative forcing depends on many factors including non-aerosol properties, e.g., presence of cloud, surface albedo and aerosol single scattering albedo. Aerosol forcing is also influenced notably by the surface albedo and low-level cloudiness. The aerosol radiative forcing is highly impacted by the low level cloud which affects the aerosol direct radiative forcing at the TOA level. For example, previous study of Aerosol simulations show that changes in cloud amount associated with changes in rainfall can strongly limit temperature changes. To examine the perturbations caused by aerosols in the radiative forcing, a set of climate simulations were performed; the control simulation without any aerosol forcing (henceforth referred to as `NO_AERO') and simulations with three different representations of aerosol direct radiative forcing (1. different species of sulphate, carbonaceous, dust and sea salt, `ALL_AERO', 2. constant global aerosol simulation, `BKG_AERO' and 3. constant aerosols over the extended Indian region, prescribed from ISRO's ACE aerosol observations, `ACE_AERO').

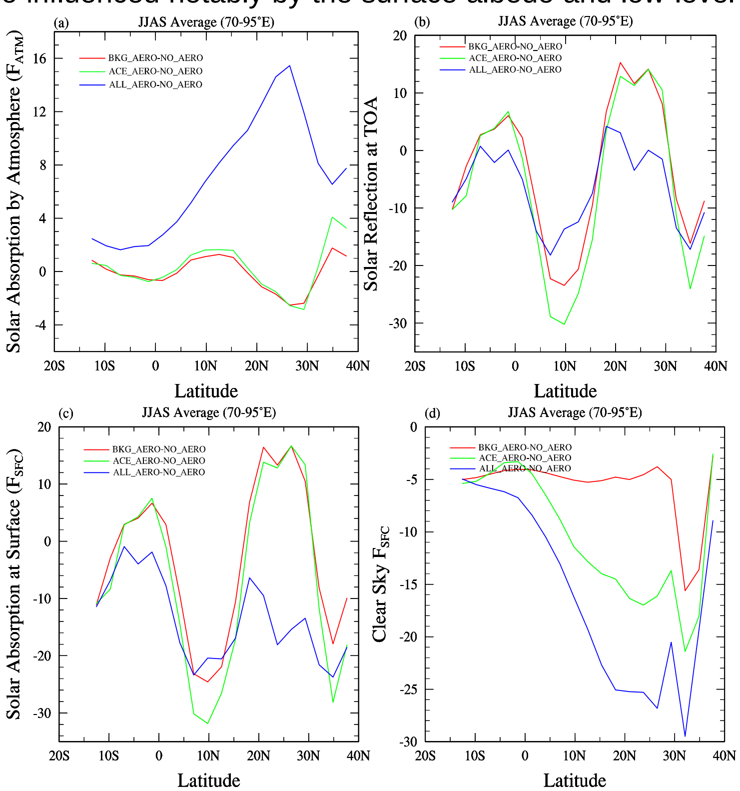

Figure 5.4 Simulated changes in JJAS mean aerosol solar radiative forcing (in Wm^{-2}) over India for BKG_AERO, ACE_AERO and ALL_AERO with respect to NO_AERO; a) solar absorption by the atmosphere, b) solar reflection at top of the Atmosphere (TOA), c) net solar absorption at the surface and d) net solar absorption by the surface under clear-sky condition.

Figure 5.4 shows the boreal summer (JJAS) aerosol solar radiative forcing averaged over Indian longitudes from BKG_AERO, ACE_AERO, and ALL_AERO simulations. Similarly, Figure 5.5 shows the distribution of corresponding changes in JJAS mean total cloud amount due to aerosols. We examine the absorption of shortwave radiation by the atmosphere (F_{ATM}) in Figure 5.4a. We notice that while there is a warming vis-a-vis the control in the ALL_AERO simulation, the other two simulations (BKG_AERO and ACE_AERO) show cooling. The impact of aerosols is seen to be the highest over the northern parts of the subcontinent between 20°N-30°N, a region where the aerosol concentration is the highest. When absorbing aerosols are absent (for example in BKG_AERO and ACE_AERO), this depletion is much less (opposite to that in ALL_AERO) and mainly due to scattering aerosols. F_{ATM} is reduced (gets negative) over regions where there are strong reductions in convection and cloud cover due to scattering aerosols (Figure 5.5). On the contrary, atmospheric absorption is increased over areas where scattering aerosol impact results in increased convection and cloud cover. Expectedly, in ALL_AERO in which absorbing species such as dust and carbonaceous aerosols are prescribed, there are wide spread increases in atmospheric absorption over the whole monsoonal region. In ALL_AERO, atmospheric absorption by aerosols such as carbonaceous and dust particles dominant than that by clouds. However, still the cloudiness is reduced over continental monsoon region.

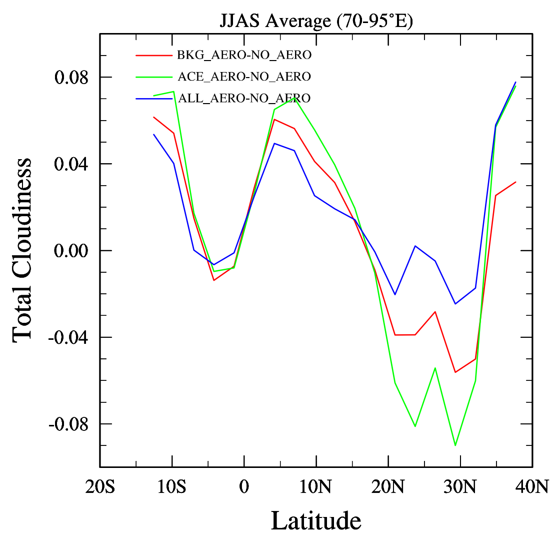

Figure 5.5: Simulated changes in JJAS mean total cloud amount (fraction) over India for BKG_AERO, ACE_AERO and ALL_AERO with respect to NO_AERO.

Summer mean solar reflection at the top of the atmosphere (TOA, F_{TOA}, Figure 5.4b), is mainly controlled by non-absorbing aerosols such as sulphate particles, and cloud-radiation interaction. The distribution of the aerosol reflection differs from that of the absorption, but both aerosol absorption and reflection reduce downward solar insolation, so the net solar absorption by the surface (F_{SFC}, Figure 5.4c) is reduced more than F_{TOA} (Figure 5.4b), especially in ALL_AERO simulation (in which atmospheric absorption is high). But, F_{SFC} under clear sky condition (Figure 5.4d) shows that both absorption of shortwave radiation by the atmosphere and reflection at the top of the atmosphere reduces the solar absorption by the surface uniformly. This also suggests that, in the absence of clouds, the total effect of aerosol radiative forcing is to reduce the incoming solar radiation at the surface. However, in the presence of clouds, the spatial distribution of radiative forcing (Figures 5.4a, b and c) is much more complex with some pockets where the incoming solar radiation is increased. For example, both F_{TOA} and F_{SFC} are increased over the regions such as northern India (north of ~17°N) where there is strong reduction in cloudiness due to aerosols (Figure 5.5). Thus, the aerosol forcing, which includes reflection and absorption, is considerably augmented by the internal climate feedbacks to result in a much more complex spatial distribution than the forcing associated with greenhouse gases which is fairly uniform in space. With all three ways of prescribing aerosols, the simulations tend to reduce the total cloud amount over the continental convective regions. The region with maximum reduction in cloudiness (e.g., north of ~17°N) experiences increased surface solar absorption (Figure 5.4c) associated with weakened atmospheric solar depletion (Figure 5.4a) due to reduced cloudiness. This suggests that the aerosol-climate direct effect itself is highly non-linear because of aerosols feedback into cloud-radiation interaction, particularly over continental monsoon regions.

Low-level clouds reflect solar radiation effectively, and so absorbing aerosols above low cloud have more absorption. Thus, absorbing aerosols above low cloud enhance aerosol forcing, just like absorbing aerosols over reflective surfaces. The difference between low cloud and highly reflective surface is that aerosols can be located below or above low cloud. Our study of absorbing aerosol forcing with respect to low cloud is focused on the contributions of BC aerosols above low clouds to the global burden and to the forcing.

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5.3 Physically Based Assessment of Wind Changes over Indian Region under Different Scenarios of Anthropogenic Aerosol Emissions

The climatological response of summer circulation to the direct radiative effects of natural and anthropogenic aerosols is investigated using the Community Atmosphere Model (CAM3) that has comprehensive treatment of the aerosol-radiation interaction, coupled to two different ocean boundary conditions: (1) prescribed climatological sea surface temperatures (SSTs) and (2) an ocean model (CCSM3). As atmospheric general circulation models (GCMs) cannot simulate aerosol loadings directly, we coupled the GCM to a chemical transport model driven by meteorological analysis fields to simulate different species of aerosols. We studied the changes in wind and associated circulation parameters' climatology under different aerosol scenarios (with respect to the control simulation without aerosols (CNTL or NO_AERO)) by analyzing a set of climate simulations with mainly three types of aerosol direct radiative forcing viz. due to (i) total aerosols (ALL_AERO), (ii) scattering aerosols and (iii) absorbing aerosols and doubled amount of anthropogenic absorbing aerosols (DABS_AERO).

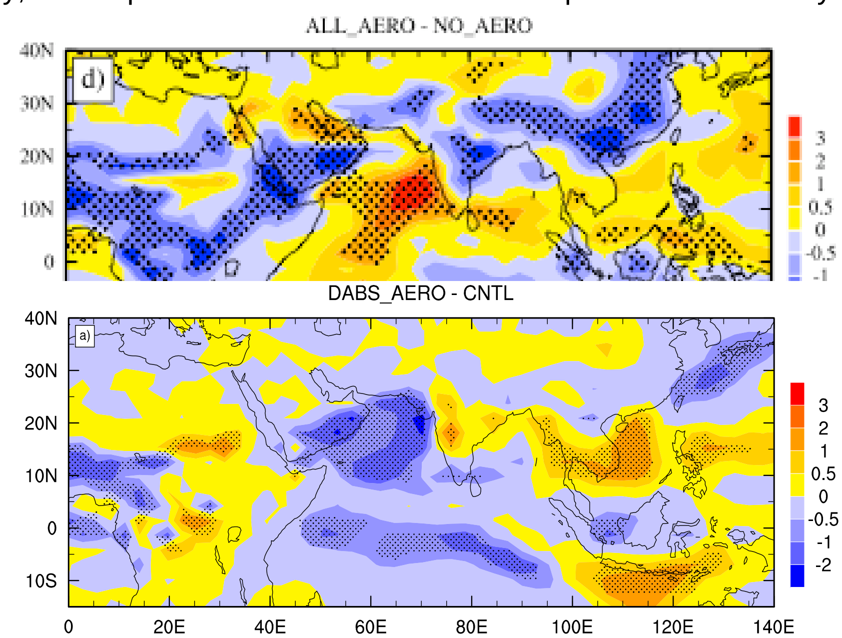

Figure 5.6: JJAS mean precipitation differences (mm day^{-1}) for A) ALL_AERO with respect to that from NO_AERO and B) DABS_AERO with respect to CNTL/NO_AERO. Differences significant at 95% level are stippled.

Aerosol forcing reduces surface solar absorption over the primary convective region of India and reduces the surface and lower tropospheric temperatures. Concurrent warming of the lower atmosphere over the warm oceanic region in the south reduces the land-ocean temperature contrast and thereby weakens the monsoon overturning circulation and the advection of moisture into the landmass. This increases atmospheric convective stability, decreases convection, clouds, precipitation, and associated latent heat release. Our analysis reveals a defining negative moisture-advection feedback that acts as an internal damping mechanism spinning down the regional hydrological cycle and leading to significant circulation changes in response to external radiative forcing perturbations of both scattering aerosols and total aerosols (mixture of scattering and absorbing aerosols).

When total aerosol loading (both absorbing and scattering aerosols) is prescribed, though dust and black carbon aerosols are found to cause significant atmospheric heating over the monsoon region, the aerosol-induced weakening of meridional lower tropospheric temperature gradient (leading to weaker summer monsoon rainfall) more than offsets the atmospheric heating effect of absorbing aerosols, leading to a net decrease of circulation and summer monsoon rainfall (Figure 5.6). Analysis of simulation with doubled anthropogenic aerosols suggests that anthropogenic and natural aerosols significantly affect the circulation but in nearly opposite ways; anthropogenic aerosols tend to have a net local warming effect and strengthening of the circulation and natural aerosols tend to result in net cooling and weakening of cross equatorial monsoon circulation.

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5.4 Aerosol Influence on Interannual Variability of Monsoon Rainfall

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 that play important roles in the radiative energy and water cycle balance. Studies suggest that aerosols may influence regional climate and the monsoon water cycle via the interplay of different factors relating shortwave radiative forcing by aerosols through direct and indirect pathways to changes in monsoon rainfall. Previous studies investigated the influence of enhanced anthropogenic aerosol on convective precipitation due to indirect radiative forcing from GCM simulations with a focus on the differences between the experiments with the present-day aerosol emissions (PD) and the pre-industrial aerosol emissions (PI). The model was found to simulate 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. Significant cloud changes via indirect effects are confined to a smaller region in central India, where a strong further surface forcing is exerted in the South West (SW) monsoon season. A signal in precipitation is observed only over central India in the SW monsoon season. This reduction in precipitation mainly stem from convective precipitation. The large surface cooling by the aerosol indirect radiative forcing is responsible for a reduction in precipitation over the central India (Figure 5.7).

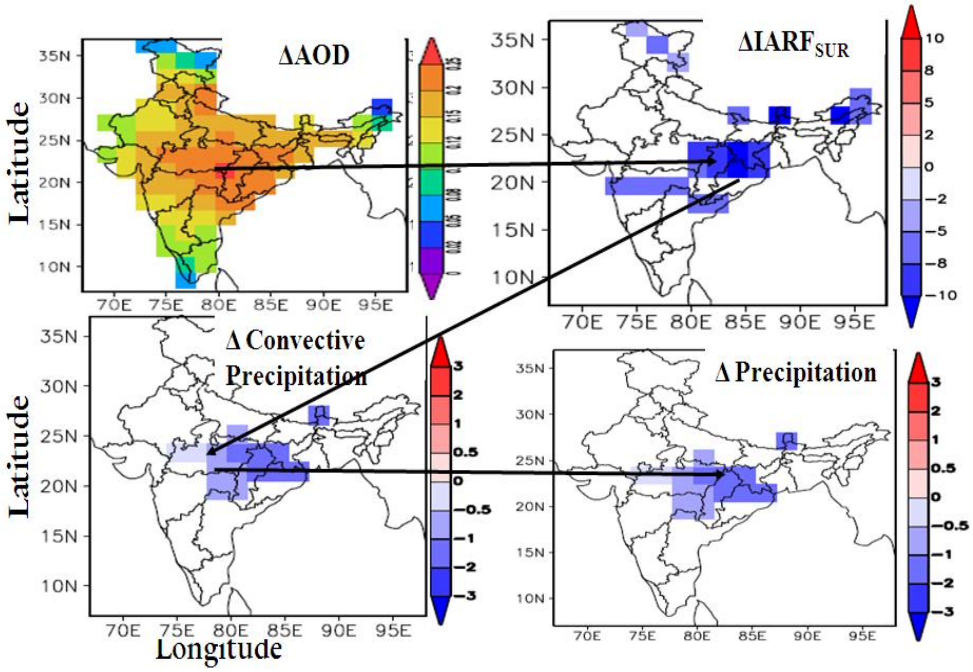

Figure 5.7: Spatial distribution of model simulated seasonal mean changes (Δ=PI–PD) in aerosol optical depth (AOD), convective precipitation (mm/day), indirect aerosol radiative forcing and precipitation due to anthropogenic aerosol emissions over the Indian subcontinent during the monsoon season.

In view of this, an attempt has been made to investigate the interannual variability in aerosol radiative effects over Central India (CI) and Gangetic Plain (GP) regions in monsoon season (June-September, JJAS). This work investigates the contrast between two years with normal and drought monsoon years. The more recent monsoon drought of 2002 caused the lowest rainfall in the historical records during the last 130 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. Similarly 2004 was also a significant drought year with 15% below the long-term normal rainfall.

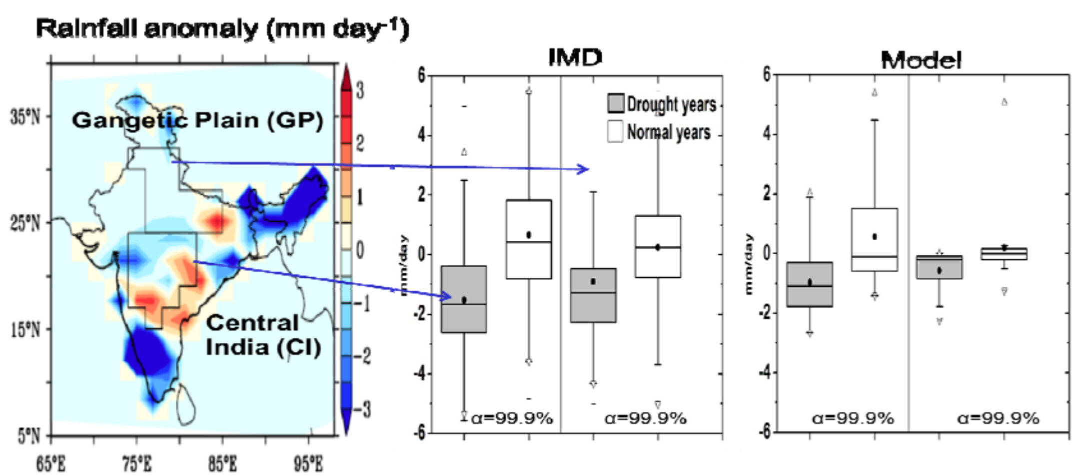

Figure 5.8 Drought-normal monsoon season rainfall over India from simulation (left) and the validation against observation (IMD) of rainfall difference over Central Indian region and Gangetic Plain.

In this study, we performed nudged simulations of a GCM combined with a comprehensive aerosol module. The spatial distribution of seasonal rainfall anomaly in JJAS is calculated for the normal and drought years of Indian summer monsoon to relate the modeled rainfall to atmospheric aerosol parameters, to understand the mechanism behind the impact of aerosol perturbation on rainfall in drought and normal monsoon years and to validate simulated aerosol variables against the observations. The model captures the sign and magnitude of observed rainfall anomalies i.e. negative in drought years and positive in normal monsoon years, over CI and GP regions (Figure 5.8). Behind aerosol influence on monsoon rainfall, two main pathways have been proposed which are the radiation-pathway and the aerosol-cloud-microphysics pathway because these pathways are important in affecting rainfall variability.

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5.5 Climate Change Impact on Seasonal Cycle and Indian Monsoon in CMIP5 Coupled Model Simulations

Future climate change projections for Indian summer monsoon variability and the basic seasonal cycle have been studied using a suite of coupled ocean-atmosphere general circulation models (CGCMs), which had participated in the Coupled Model Intercomparison Project-Phase 5 (CMIP5, IPCC AR5).

Most of the state of the art models project wide spread increase in seasonal and annual rainfall over the Indian region. However, the projected rainfall variability of Indian monsoon rainfall differs among models. Analysis of present-day climatological rainfall simulations over the Indian region shows that while a group of models compare well with observation, another group of models simulate less than 2 mm/day over the core monsoon region of Indian subcontinent. Unlike rainfall, all the models project an increase in surface temperature over the Indian region. Further, the biases in the mean monsoon simulation are found to be related to those in simulating mean seasonal variation of rainfall over the Indian region and mean SST over the Indo-Pacific region.

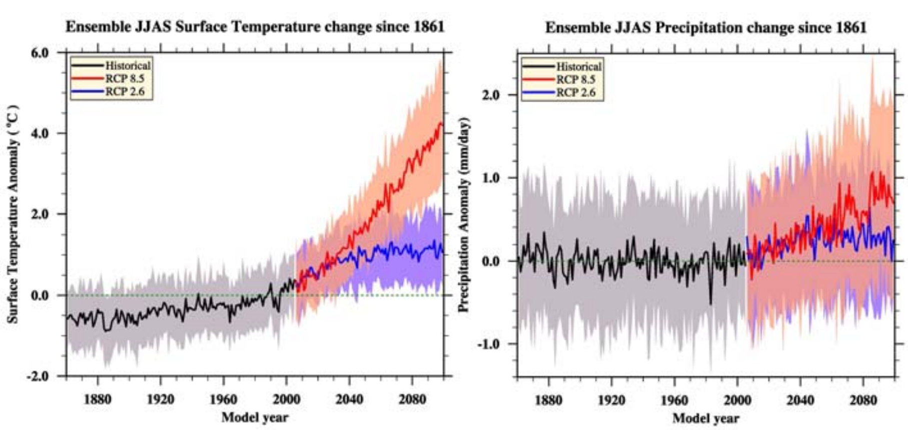

Figure 5.9: Time series of CMIP5 ensemble simulation and projection of JJAS surface temperature and precipitation anomalies.

The disparity among the CMIP5 models in projecting increased change in annual mean rainfall is evident from the large inter-model standard deviation (Figure 5.9). So, as per the projections, in the end of the 21st century there is a clear increase in annual surface temperature with a highly probable tendency for increased mean rainfall.

Indian summer monsoon rainfall exhibits large natural variability, which is strongly related to El Niño. In observation, the variation of summer rainfall with Pacific SST shows strong positive correlation in equatorial Pacific Ocean and negative correlation in the central Indian region. Future projections under different scenarios predict intensification of Indian summer monsoon rainfall over the interior parts of India and weakening of rainfall over parts of the equatorial Indian Ocean, towards the end of the 21st century. The dominant causative mechanisms and the significance of projected changes in Indian summer monsoon rainfall, in the light of SST bias in the present-day simulation, are also addressed.

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5.6 Characteristics of Rainfall and Cloud over the Tropics

Using TRMM 3G68 and infrared data of geostationary satellite, we study the characteristics of rainfall and cloud over the tropics. Many studies have shown that diurnal variation of rainfall is significant over the tropics especially land area. Our analysis demonstrates the semi-diurnal variation of rainfall over the tropics. The semi-diurnal variation was studied in relation to deep convective cloud (DC) defined by infrared data. We construct mean hourly rainfall from 14 years of TRMM 3G68 over the tropics. The data shows both diurnal and semi-diurnal variation of rainfall depending on the location. Semi-diurnal variation is seen over the southern Africa and Amazon region during DJF both in PR and TMI data. Further, the data indicates that afternoon primary peak is dominated by convective rain, while the morning secondary peak is consists of a larger percentage of strati-form rain than convective rain. Brightness temperature (TBB) threshold has been conventionally used to identify (estimate) rainfall. We have employed several TBBs for rainfall that show the existence of only diurnal modes with no semi-diurnal mode over southern Africa and the Amazon region. Here, we inspected mean size and number of DC defined by a TBB of 213K within the area (Figure 5.10). While, mean size of DC indicates clear semi-diurnal mode, the number of DC within the area shows weak semi-diurnal mode. Afternoon primary peak of rainfall coincides with the time when the mean size of

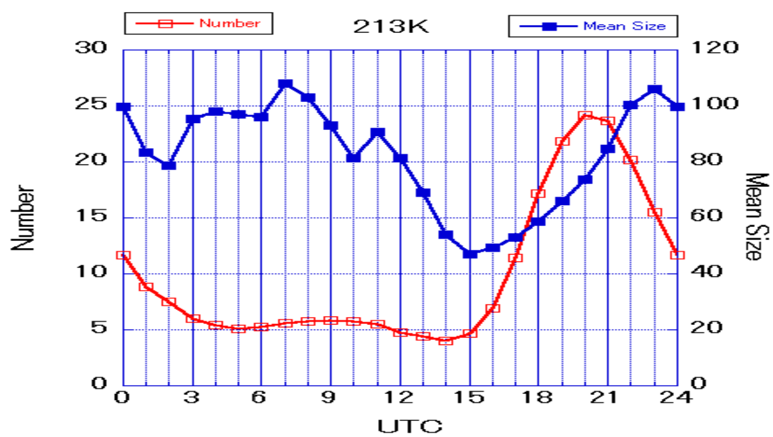

Figure 5.10: Daily variation of number and mean size of OLR from a global cloud resolving model (GCRM) simulation for the Amazon basin.

DC is rapidly increasing with the largest number of DC over the area. This suggests that convective rain is associated with the developing stage of DC. These characteristics of mean size and number of DC are seen over both southern Africa and the Amazon.

Over southern Africa, the morning secondary peak of rainfall coincides with the time of the secondary peak of mean size (almost comparable with primary peak) and number of DC. While the morning secondary peak over the Amazon coincides with the primary peak of mean size of DC with the secondary peak of number of DC. These suggest that the morning peak is associated with larger size of DC that is typical for stratiform rain. Semi-diurnal variation of rainfall is also found over the ocean area along the ITCZ.

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5.7 Dominant Modes of Vertical Profiles of Atmospheric Latent Heating

The analysis of the basic seasonal and annual mean pattern over different tropical domain clearly suggests that the vertical diabatic heating structure is seasonally dependent and varies from one geographical region to another. To figure out the dominant mode of the vertical profile for modeling application, Empirical Orthogonal Function (EOF) analysis is done for seasonal area averaged heating data over different tropical land and ocean regions (Figure 5.11). The reconstructed profiles show that the first three modes effectively represent mean profile over the tropical domains.

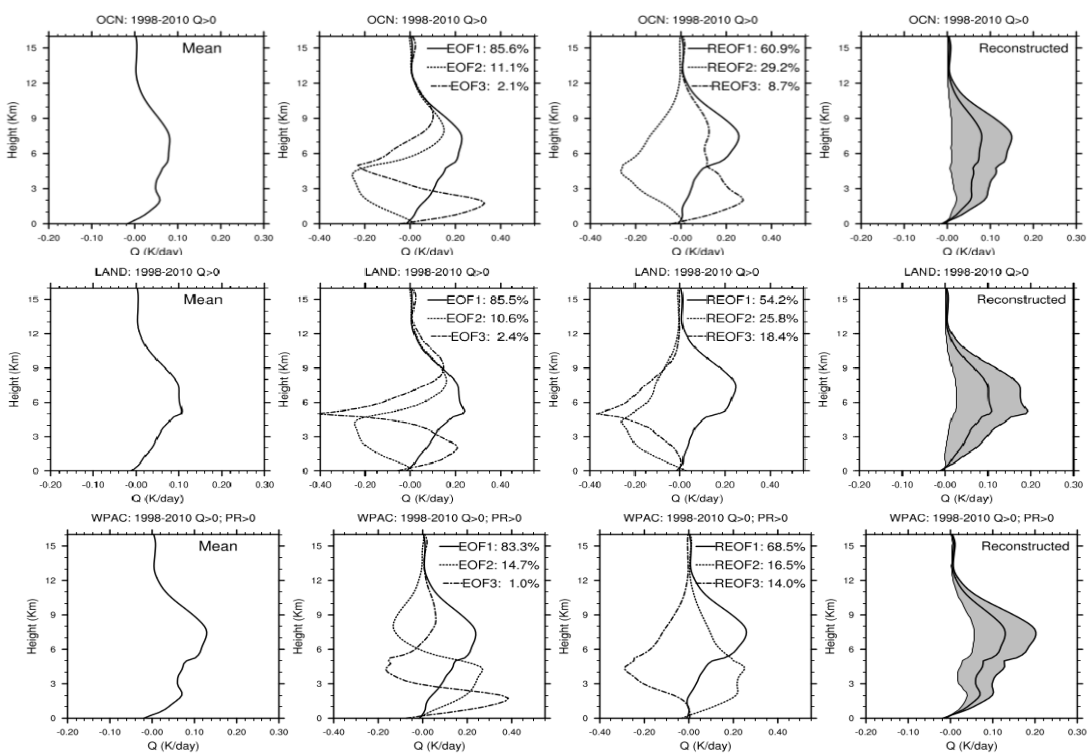

Figure 5.11: The panels (from left) are showing mean, EOF, REOF and reconstructed profile with standard deviation for latent heating for the entire tropical ocean (top), entire tropical land (middle) and for west pacific region (bottom).

To derive the basic moisture profile over the tropics, 15 years of annual mean profiles for total Q_2, convective Q_2, stratiform Q_2, and shallow Q_2 have been analyzed over selected tropical land and ocean domains.

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5.8 Do CMIP5 Simulations of Indian Summer Monsoon Rainfall Differ from those of CMIP3?

To understand the improvements in the simulations of Indian Summer Monsoon Rainfall (ISMR) by CMIP5 over CMIP3, a comparative study is performed with the original and statistically downscaled outputs of Five General Circulation Models (GCMs). Original GCM simulations are not bias corrected, while statistical downscaling is performed with bias correction and kernel regression (Figure 5.12).

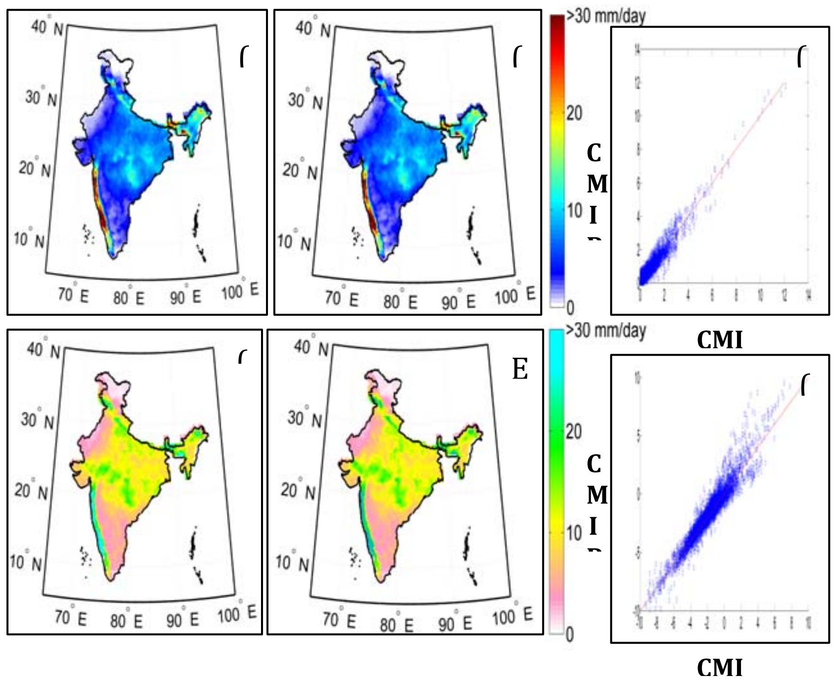

Figure 5.12: Multi-model average of downscaled Indian summer monsoon rainfall. Both CMIP3 and CMIP5 statistically downscaled simulations capture the orographic impacts on the spatial variability of ISMR in mean (a, b) and standard (deviation (d, e) respectively. The scatter plots of errors in mean (c) and standard deviation (f) for CMIP3 vs CMIP5 show no improvements in terms of bias in CMIP5 simulations over CMIP3. However, downscaling reduces the error in the rainfall simulations because of bias correction and kernel regression-based training method with observed data. The predictors used in kernel regression-based statistical downscaling are U wind, V wind, temperature both at surface and 500 hPa, specific humidity at 500 hPa and MSLP.

We observe that multi-model average of original CMIP5 simulations do not show visible improvements in bias, over CMIP3. We also observe that CMIP5 original simulations have more multi-model uncertainty than those of CMIP3. The statistically downscaled simulations show similar results in terms of bias; however, the uncertainty in CMIP5 downscaled rainfall projections is lower than that of CMIP3. Both the downscaled projections show spatially heterogeneous changes, which are not visible in original simulations.

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5.9 Fine Scale Projections of Indian Monsoon Rainfall using Statistical Models

General Circulation models (GCMs) simulate climate variables globally accounting for the effects of green house emission; however, they mostly work in coarse resolutions and hence their performances for simulations of precipitation are not always reliable. To overcome this limitation we are using statistical techniques as downscaling methods for projecting precipitation as finer resolution (25 km grid approximately, 0.22° latitude x 0.22° longitude). Here we use conventional statistical downscaling where the relationship between predictor climate variables (other than precipitation) and precipitation are determined and then applied to GCM output for projections of precipitation. Kernel regression is used for developing the statistical relationship. The results are compared with interpolated, quantile based bias corrected GCM simulated precipitation output. Both the methodologies are applied to CMIP3 and CMIP5 simulations and the multi-model averaged (MMA) results are compared.

We first evaluate the 20C3M simulations with the observed data, and we find that conventionally downscaled MMA simulations of CMIP5 do not show significant improvements over those of CMIP3, which suggests that there is no significant change in predictor simulations by the CMIP5 GCMs over those of CMIP3. However, when we do the same exercise with bias correction, we find bias corrected CMIP5 simulations are significantly improved. This shows that simulation of precipitation in Indian region for observed period has been improved with CMIP5 models.

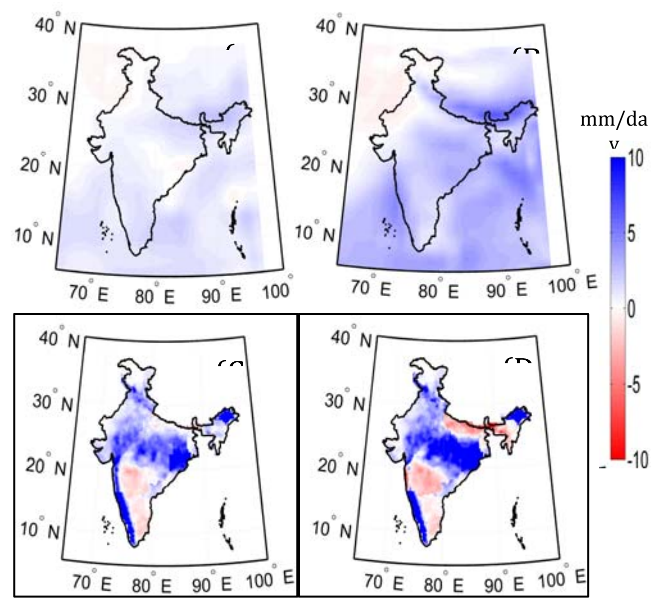

Figure 5.13: A) Raw difference between future–present from CMIP3 mean B) raw difference between future–present from CMIP5 mean C) downscaled difference between future–present from CMIP3 mean D) downscaled difference between future–present from CMIP5 mean.

After validation, both the models are applied for future projections. It is observed that, though bias corrected models perform well for observed period, they simulate spatially uniform changes of precipitation in the entire country (Figure 5.13). The conventional downscaling method, involving predictors other than precipitation, simulates non-uniform changes for future, which is similar to the trend of last 50 years of Indian precipitation pattern. The reason behind the failure of bias corrected model in projecting spatially non-uniform precipitation is the inability of the GCMs in modeling finer scale geophysical processes in changed conditions. The results highlight the need to revisit the bias correction methods for future projections and to incorporate finer scale processes.

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5.10 High Resolution Global Climate Change Projection for India: A Data Intensive Paradigm

Global warming will precariously affect agricultural production and the livelihood of farmers by unpredictably changing the abundance of rainfall and extreme events, which exhibits strong variation of rainfall. Hydro-power generation and water availability are some of the other concerns that depend on rainfall variation. Thus, identification of recent climate trends and projection of future climate change are crucial for agro-economic states. As we build strong observational networks and monitor climate indicators, parallel efforts in dynamical modeling should also be practiced. Since, the special nature of the geographical orientation of the country with low altitude coast lines and highly elevated mountains at the north, numerical models employed for projections should have sufficiently high spatial resolution to resolve these details. An ultra-high resolution global general circulation model (GCM) at 20-km resolution is used to investigate the future projection of climate change patterns for India. Deriving inferences by analyzing 4-dimensional multivariable global dataset at ultra-high resolution of 20-km and century time scale for climate change projections is highly data intensive and requires high performance computing with huge memory, visualization and storage. The results of high-resolution projections aim to fill the current knowledge gap about future climate change effects by a large extent.

The projections are determined through time-slice integrations of the model, which has shown marked fidelity in representing the present-day climate of India in all seasons especially the mean summer monsoon rainfall over India. Projected future scenarios show coherent and significant enhancement in summer rainfall over most parts of India along with significant reduction in rainfall along the southern parts of the Western Ghats (Figure 5.14). For example, the model predicts wide spread but spatially varying increase in rainfall which are significant compared to the seasonal mean rainfall over many states, in particular over the interior regions of Peninsular, West Central, Central Northeast and Northeast India (~5-20% of seasonal mean). However, over the southern west coast of India (~10-15%), and some parts of Northwest India and Jammu-Kashmir (~5-10%), future reduction in rainfall is projected by the model. Over the Western Ghats, the drastic reduction of wind by steep orography predominates over the moisture build-up effect (that causes enhanced rainfall under a warmer environment), in reducing the rainfall over the southern west coast. Over this region, faster rate of increase of temperature at higher levels as compared to lower levels (upper-tropospheric warming effect)

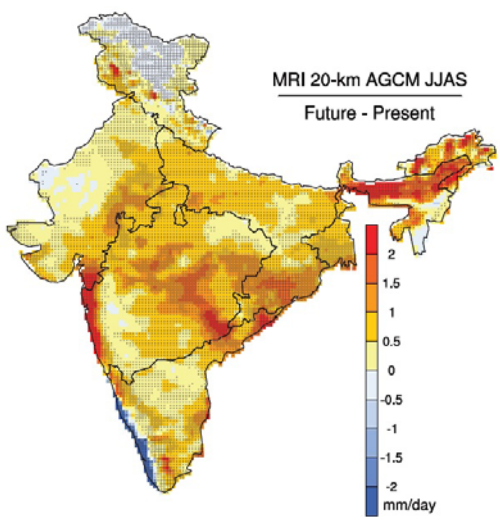

Figure 5.14: JJAS mean difference in rainfall between future projection and present-day simulation of the 20-km model over India. Within each colour the gradient in hue corresponds to changes as percentage of mean summer monsoon rainfall (< 5%: no symbol, 5-15%: dots, 15-25%: open circle and >25%: plus)

leads to increased dry static energy and vertical gross moist static stability which in turn weakens the vertical ascent, large-scale monsoon circulation and thereby rainfall.

The projections for the states of Kerala and Karnataka (Figure 5.15a) show reduction in future monsoon rainfall especially over the western coast. In addition, there is large spatial heterogeneity within state-level. For example, for the state of Maharashtra, there is significant quantitative variation in the projected climate change (Figure 5.15b). So far, IPCC future scenarios for the Indian summer monsoon rainfall even using high-resolution regional climate models have projected relatively uniform climate change over the whole country. Over the windward side of the west coast, the projected changes indicate significant weakening of rainfall in future. In the leeward side, marked increase in future rainfall is predicted by the model. These projected changes are qualitatively similar to the recent trends observed over this region. Another notable aspect is the opposite future change projected by the model in the northern parts of the Western Ghats along the west coast of Maharashtra compared to the coasts of Kerala and Karnataka (Figure 5.15).

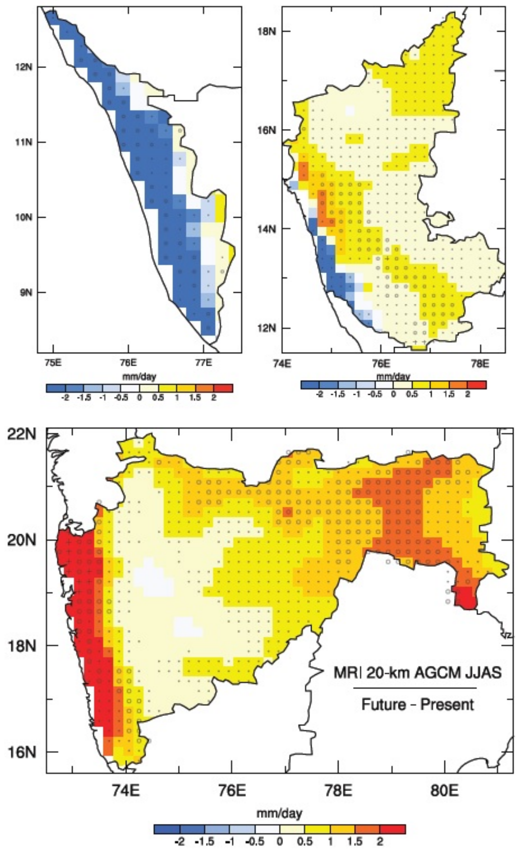

Figure 5.15: a) Projected change in future rainfall over the states of Kerala and Karnataka (upper panels) and b) for the state of Maharashtra (lower panel).

The pattern of changes in the frequency of intense precipitation events in monsoon season is similar to those of seasonal mean precipitation. Further, the model projects increased (decreased) occurrence of extreme rainfall events over interior parts of India (the southern Western Ghats). Over the southern west coast, the number of extreme rainfall events will be reduced due to climate change. The pattern of future precipitation change for summer monsoon season (Figure 5.14) suggests a weakening of the orographic rain over the states, due in large part to the changes in the intense precipitation regime. These results warrant the necessity for undertaking impact studies of such scenarios for accurate assessment of local and regional-scale vulnerability to climate change. Moreover, these outcomes are useful for state-specific climate change risk assessments, adaptation planning, improving their climate management strategies, and for providing information to policy makers.

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