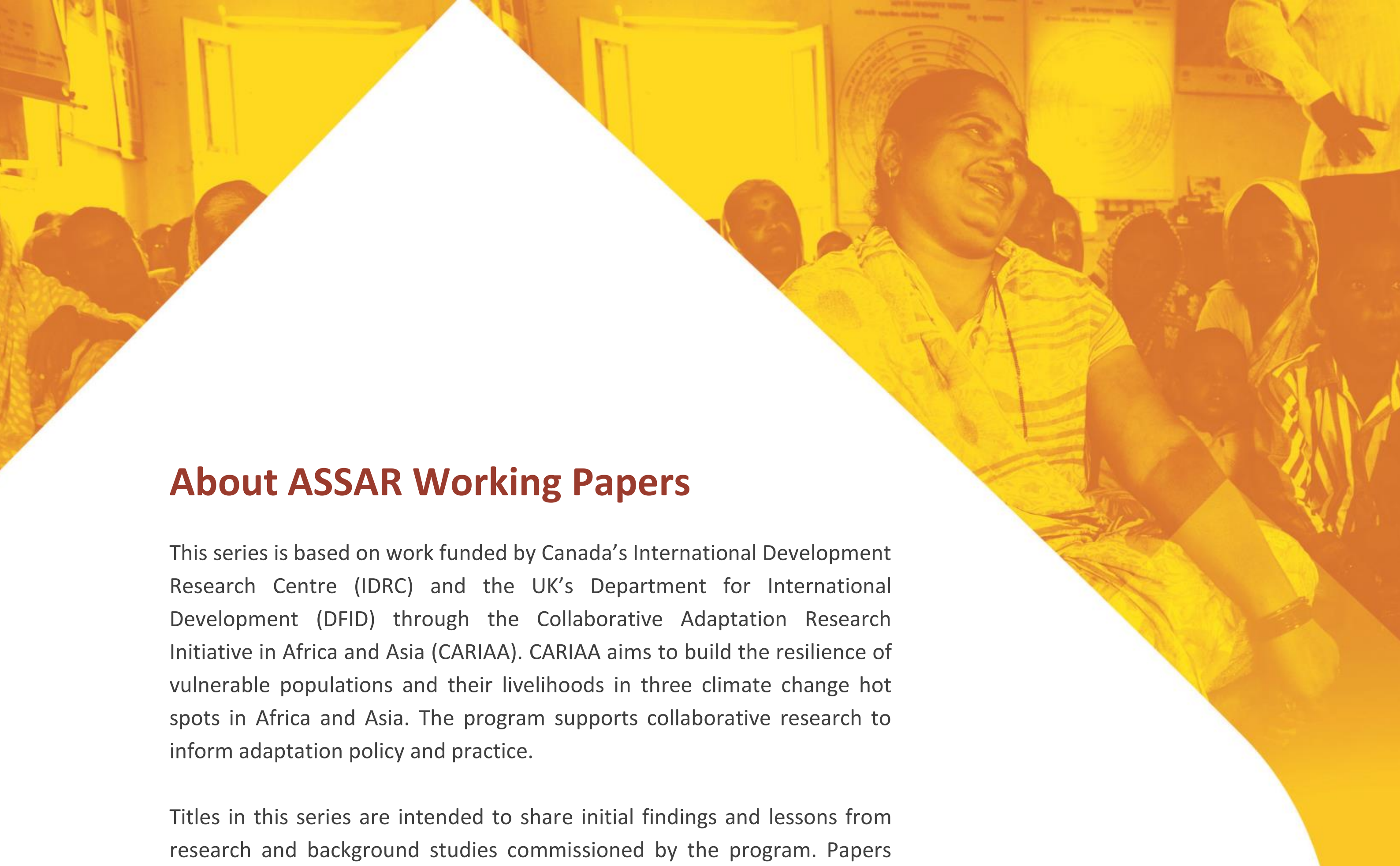
Regional Climate Messages for South Asia

CARIAA
Collaborative Adaptation Research Initiative in Africa and Asia

ASSAR
Adaptation at Scale in Semi-Arid Regions



About ASSAR Working Papers

This series is based on work funded by Canada's International Development Research Centre (IDRC) and the UK's Department for International Development (DFID) through the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA). CARIAA aims to build the resilience of vulnerable populations and their livelihoods in three climate change hot spots in Africa and Asia. The program supports collaborative research to inform adaptation policy and practice.

Titles in this series are intended to share initial findings and lessons from research and background studies commissioned by the program. Papers are intended to foster exchange and dialogue within science and policy circles concerned with climate change adaptation in vulnerability hotspots. As an interim output of the CARIAA program, they have not undergone an external review process. Opinions stated are those of the author(s) and do not necessarily reflect the policies or opinions of IDRC, DFID, or partners. Feedback is welcomed as a means to strengthen these works: some may later be revised for peer-reviewed publication.

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Regional Climate Messages for South Asia

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CHAPTER 1

Historical Climate

Historical Climate

1.1 General overview

India is home to more than 1.2 billion people, of these about 52% depend on the climate sensitive sectors such as agriculture, forestry, and fishing for their livelihood. Majority of these people are poor and have limited access to information and health-care facilities. Many of them live in the semi-arid-regions of the country and depend on rain-fed agriculture

India has already witnessed a temperature rise of about 0.6° C over the last century. Though summer monsoon rainfall largely remains stable, in recent years a weakening in monsoon as well as increase in very-heavy precipitation events is being reported (Dash et al. 2009, Goswami et al. 2006). Coupled Global circulation models provide an opportunity to project the future climate under different radiative-forcing scenarios or pathways. However due to their coarse resolution, GCMs are not very useful for regional and local level studies. For this purpose GCM projections are generally dynamically or statistically downscaled to higher resolutions using regional climate models. In India the climate downscaling effort has been spearheaded by the Centre for Climate Change Research at the Indian Institute of Tropical Meteorology. Most studies use global and regional climate projections for projecting the impact of future climate change on different natural, production and human systems; and based on these projections, vulnerabilities to future climate are assessed and suitable adaptation options suggested.

In the Indian case, it was premature to analyse the climatic future for the region, as outputs from the regional CORDEX experiment are still being generated and very few model outputs (out of an ensemble of models) are available. We emphasised understanding the nature of sub-region specific climatic trends and their drivers using a mix of historical model data (from the CORDEX ensemble) and station-level global data sources. It was essential to understand the extent of climatic variability and the associated biophysical response to ascertain appropriate entry points for the RRP phase. To enhance our understanding of historical climate change and climate variability in the three ASSAR sub-regions, we investigated trends in temperature and precipitation in the broader landscape surrounding the sub-regions (hereafter ASSAR sub-region envelopes). Although the spatial extent of these sub-region envelopes (Annexure 2, 3 and 4) was chosen to permit a comparison between the observed historical precipitation (i.e. APHRODITE) and temperature (i.e. CRU, Climate Research Unit) data, and the modelled historical climate (e.g. CORDEX) data, the present analysis focuses on the former data. We used the gridded temperature dataset from the University of East Anglia's CRU (1901-2009; Harris et al., 2014) to assess trends in temperature. To evaluate trends in precipitation and changes in precipitation regimes, especially extreme rain events, we used the APHRODITE gridded dataset (1951-2007;

Yatagai et al., 2009). These analyses were conducted using the Climate Data Operator tool (Schulzweida, 2014) and the R statistical software environment (R Core Team, 2014).

1.2 Climate Description: India

India has already witnessed a temperature rise of about 0.6°C over the last century (Attri and Tyagi, 2010). Though summer monsoon rainfall largely remains stable, a recent weakening in the monsoon as well as an increase in very-heavy precipitation events is being reported (Kulkarni et al. 2012, Goswami et al. 2006, Ghosh et al. 2011). Trends in the semi-arid regions under study are largely consistent with national trends, although regional differences have been observed.

Box 1

Summary of precipitation and temperature trends over India (1901-2009)

Mean annual temperature has increased in India during the 20th century. On the contrary, there is no discernible change in the trend in annual precipitation for India over the past century. This could be due to a lack of sufficient observational records to draw conclusive trends. The Indian summer monsoon is, however, known to have undergone abrupt shifts in the past millennium, giving rise to prolonged and intense droughts. South Asia has reported inter-decadal variability in seasonal mean rainfall, with an increasing frequency of deficit monsoons although this is not uniform across regions. The increase in the number of monsoon break days and the decline in the number of monsoon depressions are consistent with the overall decrease in seasonal mean rainfall. There is also an observed increase in heavy rain events and a concomitant decrease in light rain events. Changes in precipitation and the direct impact of atmospheric carbon dioxide (CO_2) concentrations could be especially important for semiarid ecosystems, making responses harder to predict. The recent weakening in seasonal rainfall as well as the regional redistribution has been partially attributed to factors such as changes in black carbon and/or sulphate aerosols, land use and sea surface temperatures. The confidence in precipitation changes over the Indian land area over the last century (from 1901- until 2009) remains low, with long-term positive or negative trends seen with different datasets.

Source: IPCC's Fifth Assessment Report (AR5), Working Group.

1.2.1 Overview of Temperature Trends

Accelerated warming has been observed in India from 1971 until 2007, caused by an intense warming observed in the recent decade (1998–2007). Temperatures (mean, maximum and minimum) have increased by about 0.2°C per decade for the period 1971–2007, with a much steeper increase in minimum temperature than maximum temperature. In the most recent decade, the maximum temperature was significantly higher than the long-term mean between 1901 till 2007. Minimum temperatures have also increased at a rate that nearly equals what was observed between 1971 and 2007 (Kothawale et al. 2010; Figure 1). Revadekar et al. (2012) have also reported an increase in the intensity and frequency of hot events and a decrease in the frequency of cold events.

Using heat wave information of 103 stations across India, during the hot weather season (March to July) between 1961 and 2010, Pai et al. (2013) observed a noticeable increase in heat waves or severe heat wave days between 2001-2010. This also corresponds with the warmest decade for the country as well as for the globe. In their analysis of heatwaves using station data for 217 urban areas across the globe, Mishra et al. (2015) reported an increase (albeit non-significant), in heat waves over Indian urban areas over a 40-year period. The authors also observed that hot nights had not increased significantly over India.

Figure 1

Trends in temperature across India during 1901-2007.

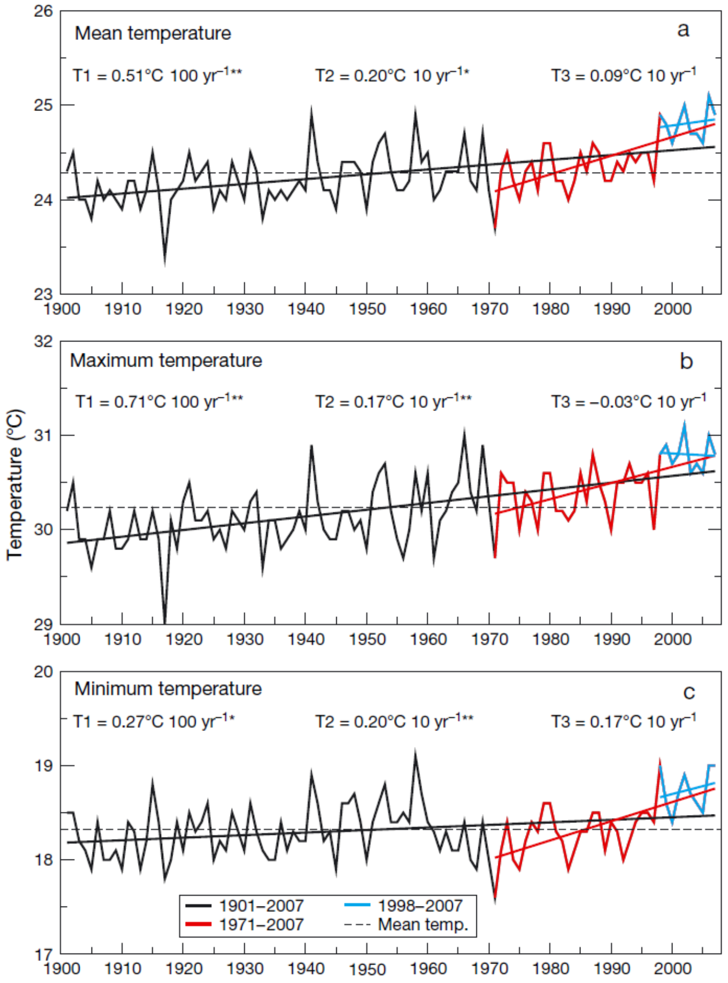


Fig. 2. Indian annual temperature variations during trend periods 1901–2007 (T1), 1971–2007 (T2) and 1998–2007 (T3). $^*p < 0.05$; $^{**}p < 0.01$

Source: Kothwale et al. 2010, http://dx.doi.org/10.3354/cr00857

1.2.2 Overview of Precipitation Trends

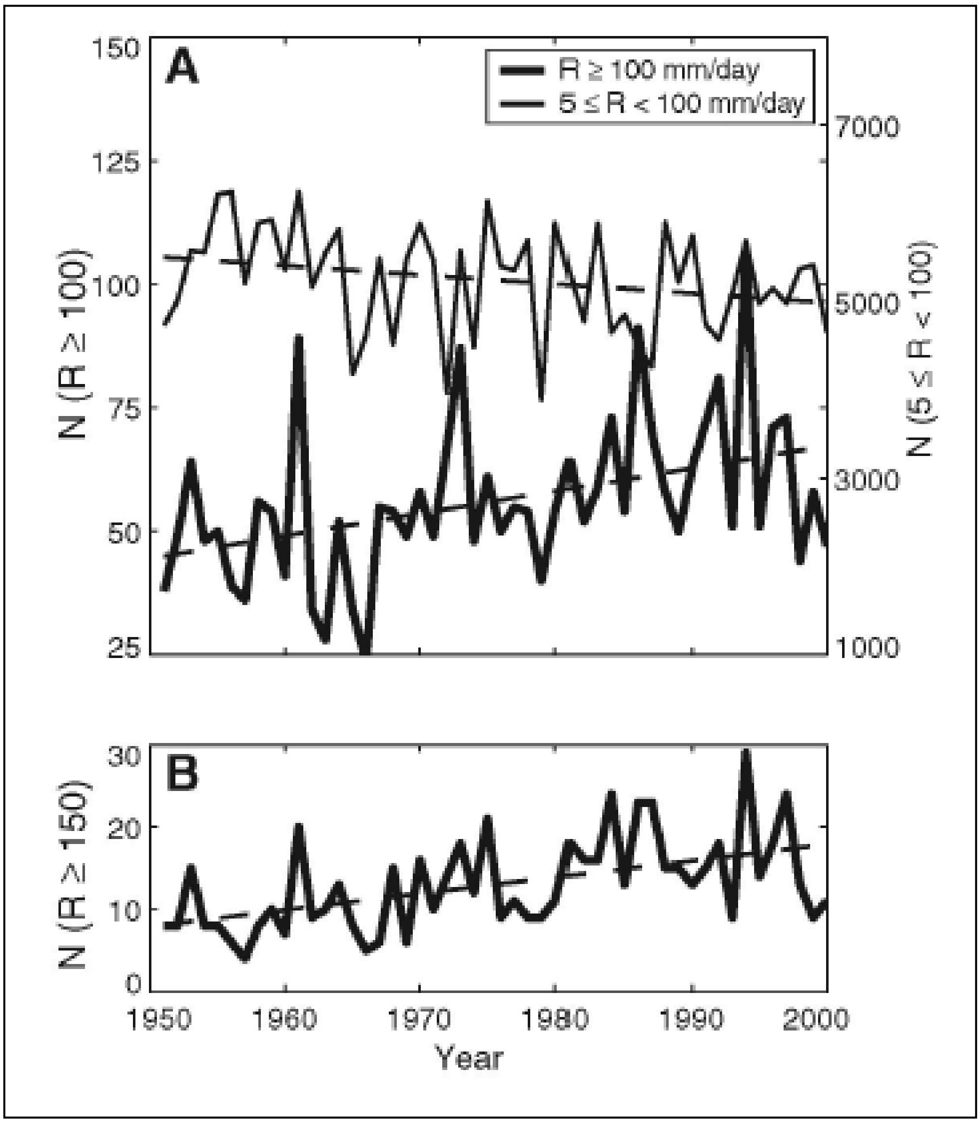
India, especially its semi-arid-regions, receives much of its share of rainfall from the summer monsoon. The observed precipitation records during the 20th century indicate an absence of any significant long-term trend in the summer monsoon rainfall for the country, although there are specific areas where monsoon rainfall trends are significant (Guhatakurtha and Rajeevan 2006). The Indian Meteorological Department (Attri and Tyagi, 2010) also observes that **'***the all India annual and monsoon rainfall for the period 1901-2009 does not show any significant trend***'**. However, Kulkarni et al. (2012) concluded in a recent paper that although the Indian summer monsoon rainfall (ISMR) series has been stable between 1871-2010, there is a decreasing trend over the last three decades of the 20th century. A significant decrease of summer monsoon precipitation over the Western Ghats and some SARs has been found in the APHRODITE (Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation) and the IMD (Indian Metrological Department) observed daily gridded rainfall datasets for the period 1951 to 2007 (Krishnan et al. 2013).

A large amount of precipitation variability is related to extreme rainfall events. Several researchers have noted an increasing trend in observed frequency of heavy precipitation events (Rajeevan et al. 2008; Krishnamurthy et al. 2009; Sen Roy 2009; Pattanaik and Rajeevan 2010), and a decreasing trend in light rainfall events (Goswami et al. 2006). Simultaneously, Krishnan et al. (2013) reported a decreasing trend in moderate to heavy rainfall events over the Western Ghats. Gridded daily rainfall data from the IMD for the period 1951-2000 indicates a significant increase in the frequency of heavy rainfall events during the summer monsoon over Central India and a concurrent decrease in the frequency of moderate and low rainfall events (Goswami et al. 2006, Figure 2), with the latter trend also being observed by Dash et al. (2009). These observations have recently been corroborated by Krishnaswamy et al. 2014 (Annexure 5); they observed that low-intensity rainfall events have decreased in the last three decades while the high intensity rainfall events have increased.

In their analysis of extreme rainfall indices over 57 major urban areas in India over the last century (1901-2010), Mishra et al. (2014) concluded that only four urban areas (i.e. Coimbatore, Kolkata, Solapur and Surat) showed a significant (p-value <0.05) increase in the maximum monsoon rainfall. They also observed that changes in the extreme rainfall in most of these urban areas were driven by large-scale climate variability. Krishnaswamy et al. (2014) also investigated the influence of larger climate drivers, i.e. the Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO) on monsoon variability and frequency of Extreme Rain Events (EREs). Their study suggests that the IOD has evolved independently of ENSO, and its influence on the monsoon and EREs has been strengthening in recent decades. In contrast, the influence of ENSO on the monsoon seems to be weakening, and is more uncertain over the same period. The authors suggest that improvements in modelling this complex system can enhance forecasting accuracy of the monsoon and EREs, and advocate mapping of spatially explicit influences of ENSO and IOD for larger regions to identify vulnerable and sensitive areas.

Figure 2

Temporal variation (1951-2000) in the number (N) of (A) heavy (R ≥ 100 mm/day, bold line) and moderate (5 ≤ R ≤ 100 mm/day, thin line) daily rain events and (B) very heavy events (R ≥ 150 mm/day) during the summer monsoon season over CI. The dashed lines indicate the statistical significance of the trends.



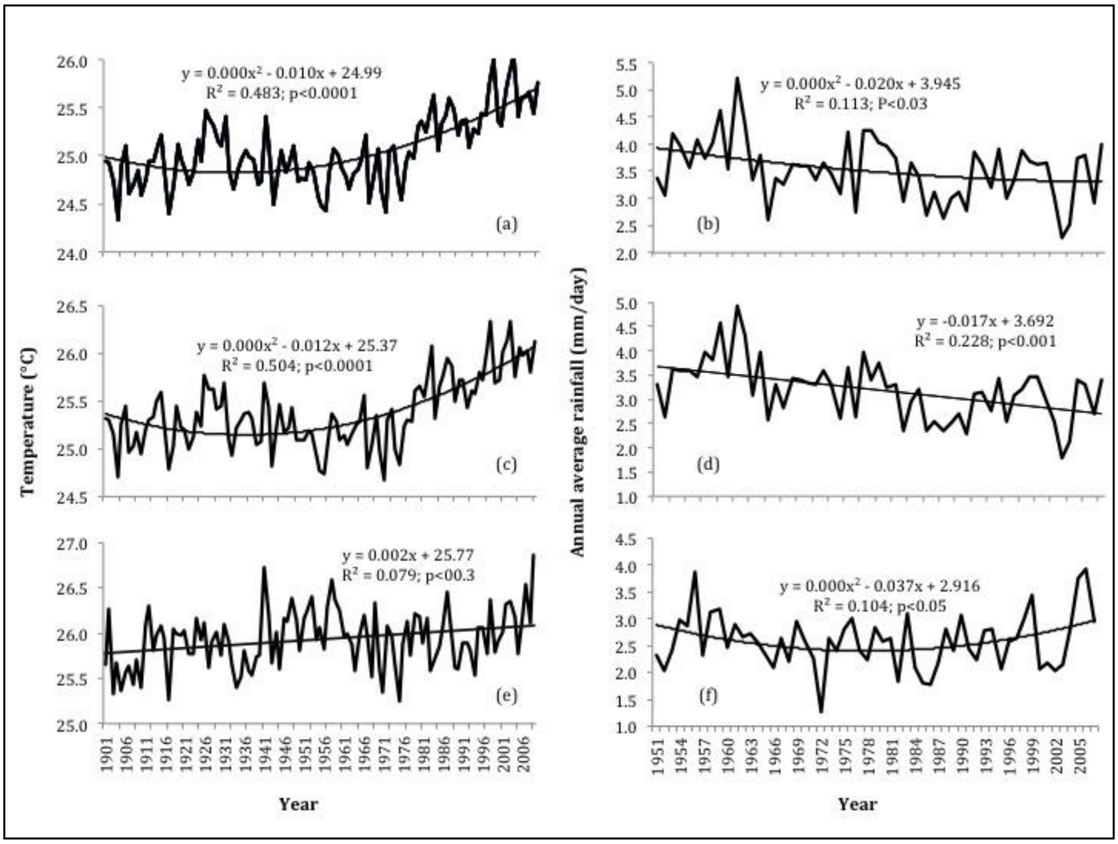
Source: Goswami et al. 2006; DOI: 10.1126/science.1132027

1.2.3 Climate trends in the Indian ASSAR sub-regions

We observed an increasing trend in temperatures in two ASSAR sub-region envelopes. Within the Moyar-Bhavani sub-region envelope, this increase has been observed in the last 50 years, while temperatures in the Bangalore sub-region envelope have increased over a shorter 30-year period. No significant trend in temperature was observed in the Sangamner sub-region envelope.

Figure 3

Historical trends (1901-2009) in mean annual temperature (left panels) and precipitation (right panels) in the Bangalore (a, b) Moyar-Bhavani (c, d) and Sangamner (e, f) sub-region envelopes.

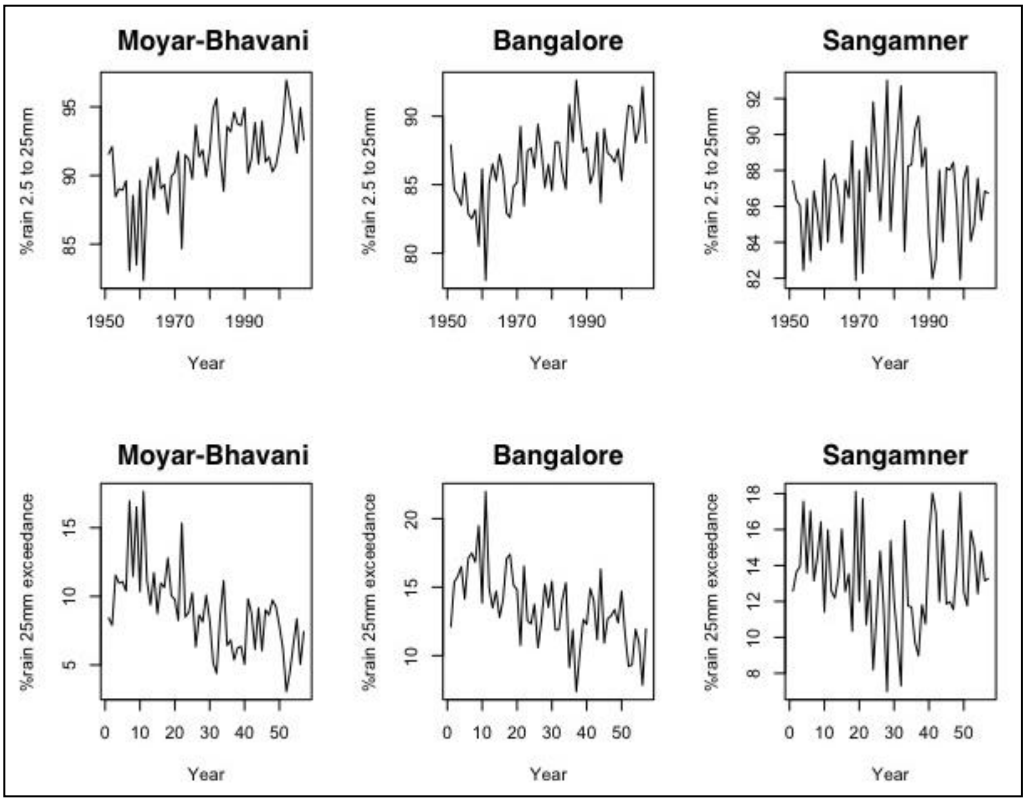


Source: ATREE-IIHS 2015 based on Climatic Research Unit, (temperature); and APHRODITE (precipitation) data

Our assessment of precipitation trends using the APHRODITE dataset revealed a significant decrease in annual average rainfall in the Bangalore and Moyar-Bhavani sub-region envelopes since the 1950s (Figure 3). In the Sangamner sub-region envelope, however, there has been a modest increase in annual average rainfall since the early 90s. We also recorded high variability in the contribution of sparse rain and moderate rain events in the Sangamner sub-region envelope while these events decreased in the Moyar-Bhavani and Bangalore-sub-region envelopes (Figure 4). The observations in the Bangalore and Moyar-Bhavani sub-region envelopes are consistent with broader national trends that have been previously reported (Goswami et al. 2006, Krishnaswamy et al. 2014, Figure 5). We do however note, that the ASSAR sub-region envelopes (defined above) often include the sub-humid and humid contributing catchment, and may not be indicative of patterns specific to the semi-arid part of the sub-regions (warranting caution in attributing influence).

Figure 4

Historical (1951-2007) trends in percentage contribution of sparse rain events (2.5 mm-25 mm) and moderate rain events (25mm exceedance) as a proportion of total rainy days in the Bangalore, Moyar-Bhavani and Sangamner sub-region envelopes.

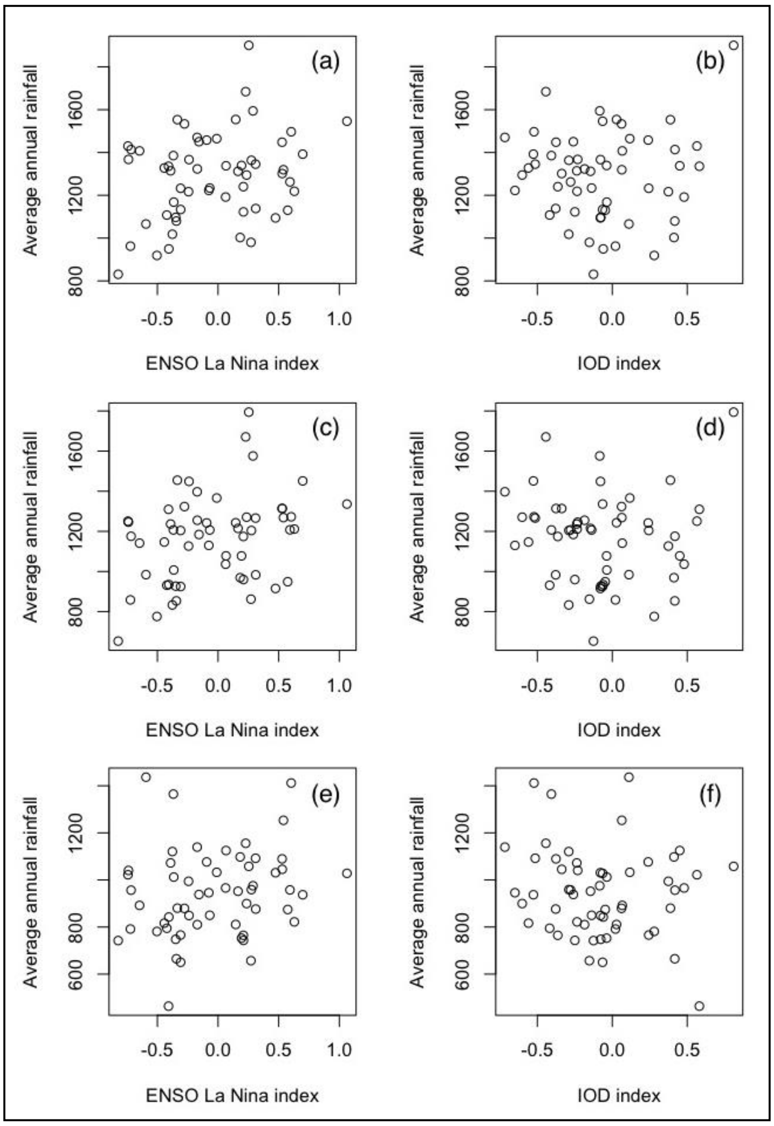


Source: ATREE-IIHS, 2015 based on APHRODITE data (Yagatai et al 2012)

We also assessed the influence of larger climate drivers in the region, i.e. the ENSO and IOD, on average annual rainfall across the ASSAR sub-region envelopes. The La Niña phase of ENSO was observed to have a significant positive impact on rainfall in the Moyar-Bhavani ($p = 0.01$) and Bangalore ($p = 0.02$) sub-region envelopes, but its influence on the Sangamner sub-region envelope was minimal ($p= 0.23$). Geethalakshmi et al., (2009) have also observed that the La Niña phase of ENSO has been linked with higher rainfall during the northeast monsoon in the state of Tamil Nadu, which overlaps with the Moyar-Bhavani ASSAR sub-region envelope. In contrast, the impact of the IOD on average annual rainfall was not significant across the Bangalore, Moyar-Bhavani and Sangamner sub-region envelopes ($p \geq 0.31$). Our conclusions are based on historical trends in rainfall (1951-2007) and we expect these relationships to have changed in the recent past as reported elsewhere (Krishnaswamy et al. 2014).

Figure 5

Influence of the El-Niño Southern Oscillation (ENSO La Niña index) and Indian Ocean Dipole (IOD) on average annual rainfall in Bangalore (a, b), Moyar-Bhavani (c, d) and Sangamner (e, f) sub-region envelopes.



Source: ATREE-IIHS, 2015 based on APHRODITE data (Yagatai et al 2012)

CHAPTER 2

Future Climate: India

Future Climate: India

Most climate projection studies in India are based on GCMs included in the CMIP3 (Coupled Model Inter-Comparison Project Phase 3) under different emissions scenarios. Climate projections for India's Second National Communication to the UNFCCC used simulations from the QUMP project, which is based on HadCM3 (Hadley Centre Coupled Model version 3), to drive PRECIS experiments over the short (2020s), medium (2050s) and long-term (2080s) time periods (MoEF 2012). For a detailed perspective on climate projection studies for India, refer to Table 2. MoEF (2012) projects an increase in annual mean surface air temperature rise of 3.5°C-4.3°C by the end of the century. No significant decrease in the monsoon rainfall has been projected over the same period, except in some parts of the southern peninsula. However, there is, likely to be a decrease in the number of rainy days, and an increase in rainfall intensity, which suggests an increase in extreme rain events.

Global climate projections are now available as part of the more recent CMIP5 that includes more than 40 GCMs. An evaluation of CMIP5 models revealed that the annual mean surface air temperature (at 2m) over most areas in the multi-model mean agrees with the ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis of the global atmosphere and surface conditions (ERA)-Interim to within 2°C, but there are several locations where biases are much larger (see AR5 WG1 Fig.9.2). The precipitation over India is not simulated well by the CMIP5 models, and the assessment is hampered by observational uncertainties. However, the CMIP5 multi-model mean is closer to observed records than most of the individual models and there is an evident improvement in South Asia in the rainy season (Sanjay et al. 2013).

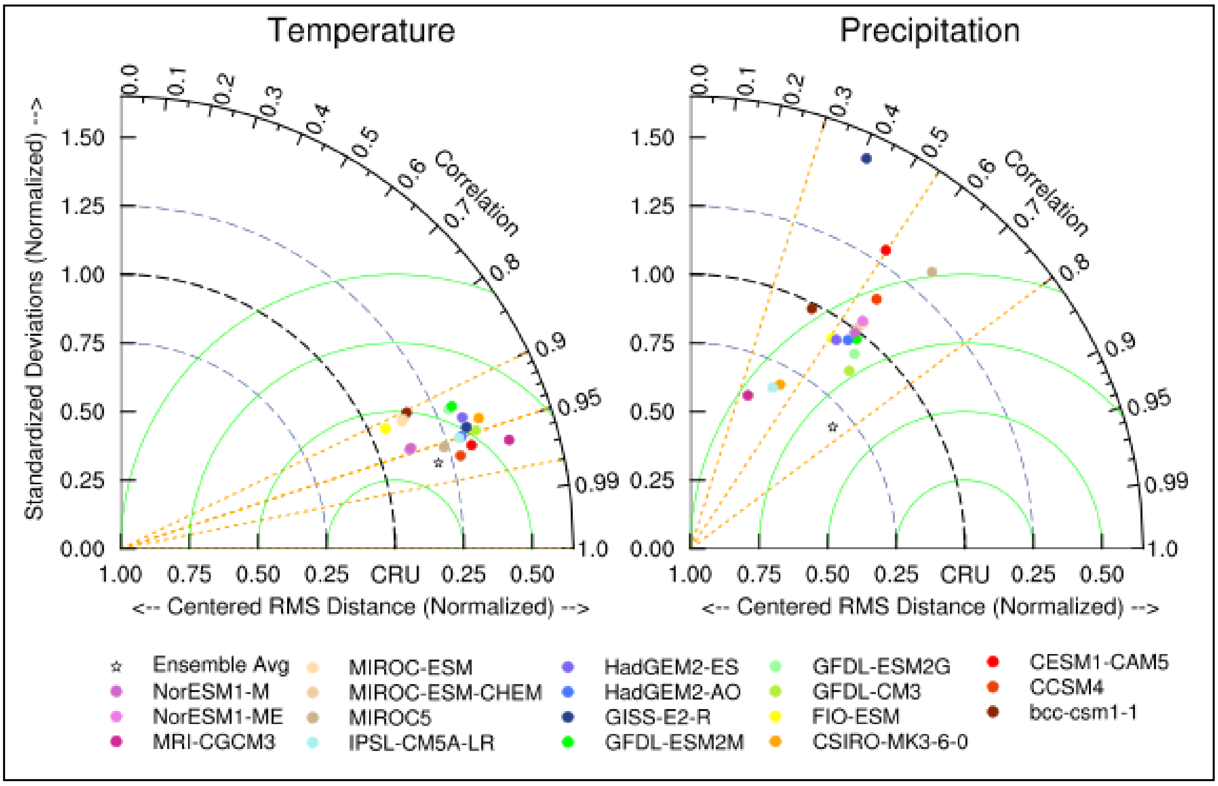
In a comparison of five atmosphere-ocean GCMs and their statistically downscaled counterparts, the CMIP5 simulations did not show improvements in the simulation of the Indian summer monsoon rainfall (ISMR) over the corresponding CMIP3 simulations. The CMIP5 original simulations had more multi-model uncertainty than those of CMIP3 and the statistically downscaled simulations have similar statistical biases. However, the uncertainty in the CMIP5 downscaled rainfall projections was lower than that of CMIP3 (Shashikanth et al. 2014)

In their evaluation of CMIP5 models, Chaturvedi et al. (2012) observed that the ensemble mean climate is closer to observed climate than any individual model for the period 1971-2000 (Figure 6). The authors evaluate future climate using the recently developed Representative Concentration Pathways (RCPs; Hibbard et al. 2011). RCP values are linked to the atmospheric radiative forcing (W/m^2) due to emissions by the year 2100. Four scenarios: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 have been chosen by the IPCC to represent the full range of emission scenarios available in the literature. Of these, RCP 8.5 is considered representative of the business as usual scenario and RCP 4.5 that of the balanced mitigation scenario. In their evaluation, Chaturvedi et al. (2012) observed that precipitation under the business-as-usual scenario is projected to increase from 4% to 5% by 2030s and from 6% to 14% towards the end of the century (2080s) compared to the 1961–1990 baseline (Figure 7).

The authors also observed that long-term precipitation projections are generally more robust than they are over the short-term.

Figure 6

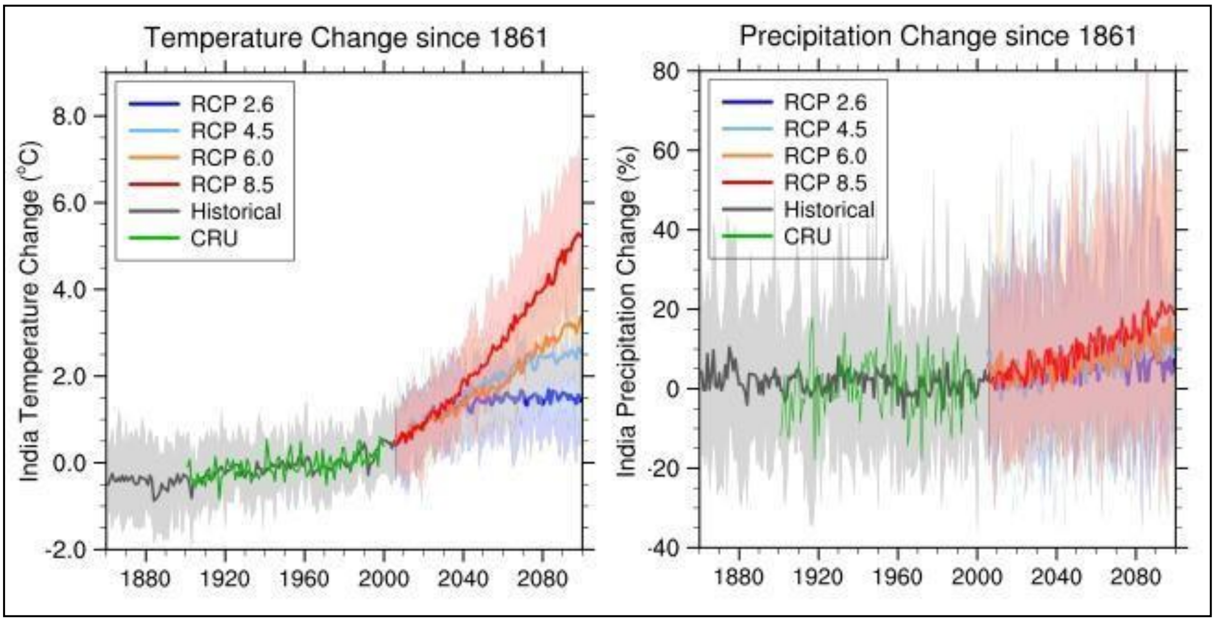
Performance of individual CMIP5 (solid circles) and ensemble (solid star) models for temperature and precipitation. The green circles centred at the reference point represent loci of constant root mean square (RMS) distance and the circles centred at the origin represent loci of constant standard deviation. Correlation is represented as cosine of the angle from the X-axis. Models with as much variance as observation, high correlation and low RMS error are considered to be performing well.



Source: Chaturvedi et al. 2012; http://eprints.iisc.ernet.in/id/eprint/45488.

Figure 7

CMIP5 model based temperature and precipitation anomalies for India (1861-2099) relative to 1961-1990 baseline for four Representative Concentration Pathways (RCPs). The shaded area represents the range of changes projected by the 18 models and model ensemble averages are represented as solid lines. The observed temperature and precipitation trends from CRU are shown by the green line and the solid black line refers to model ensemble values for historical simulations.



Source: Chaturvedi et al. 2012; *http://eprints.iisc.ernet.in/id/eprint/45488*

Recently, the Indian Institute of Tropical Meteorology (IITM) performed a simulation of surface mean air temperature and precipitation using two RCMs, one variable grid atmosphere global climate model (AGCM) simulation and an ensemble of these 3, for the period 1976–2100 (Table 2).

Table 1: List of CORDEX South Asia Regional Climate Model (RCM) Experiments

EXPERIMENT NAME	RCM DESCRIPTION	DRIVING GCM	CONTRIBUTING INSTITUTE
CCLM(MPI)	COnsortium for Small-scale MOdelling (COSMO) model in CLimate Mode version 4.8 (CCLM; Dobler and Ahrens, 2008)	Max Planck Institute for Meteorology, Germany, Earth System Model (MPI-ESM-LR; Giorgetta et al 2013)	Institute for Atmospheric and Environmental Sciences (IAES), Goethe University, Frankfurt am Main (GUF), Germany
SRCA(ECEH)	Rossby Centre regional atmospheric model version 4 (RCA4; Samuelsson et al., 2011)	Irish Centre for High-End Computing (ICHEC), European Consortium ESM (EC-EARTH; Hazeleger et al. 2012)	Rosssy Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden
LMDZ(IPSL)	Institut Pierre-Simon Laplace (IPSL) Laboratoire de Me´te´orologie Dynamique Zoomed version 4 (LMDZ4) atmospheric general circulation model (Sabin et al., 2013)	IPSL Coupled Model version 5 (IPSL-CM5-LR; Dufresne et al. 2013)	Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM), India

Boundary conditions for these models were taken from coupled atmosphere-ocean global climate models (AOGCMs) that participated in the Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor et al. 2012) medium forcing scenario (RCP4.5) experiments. This analysis conducted at a relatively fine horizontal resolution of 50 km was assessed against the CRU temperature and precipitation data for 1976-2005 (v 3.1; Mitchell & Jones 2005) over the Indian summer monsoon, (June-September, JJAS) and winter (December-February; DJF) months. Simulated air temperatures agreed reasonably well with the observed climate. However, systematic biases were more common during winter months when compared to the summer monsoon months, with biases exceeding 2˚C across most of south India. Compared to the CRU data set, precipitation in the three-member ensemble mean is underestimated in a large fraction of the Indian subcontinent during summer, while statistically significant overestimation is found over the south peninsula during winter. For future climates (2066-2095), the three-member ensemble mean indicates a large increase of more than 2˚C over central and northern parts of India (see Figure 8.2 and 8.3). The ensemble mean precipitation changes by the end of the 21st century over most parts of India are not found to be significant in both summer monsoon (see Figure 9) and winter (see Figure 10) seasons. This may be caused by large changes of opposite signs in the individual models that tend to cancel each other when added, implying that the simulated precipitation change over India is uncertain not just in magnitude but also in sign in large parts of the year.

Figure 8.1

(a) Summer monsoon (JJAS) season mean 2-m air temperature (˚C; CRU) for 1976-2005 and biases of 2-m air temperature in the CORDEX South Asia simulations driven by CMIP5 AOGCM historical experiments: (b) multi-model ensemble mean and (c-e) three different RCMs listed in Table 1. Only 2-m air temperature differences significant at the 5% significance level are shown.

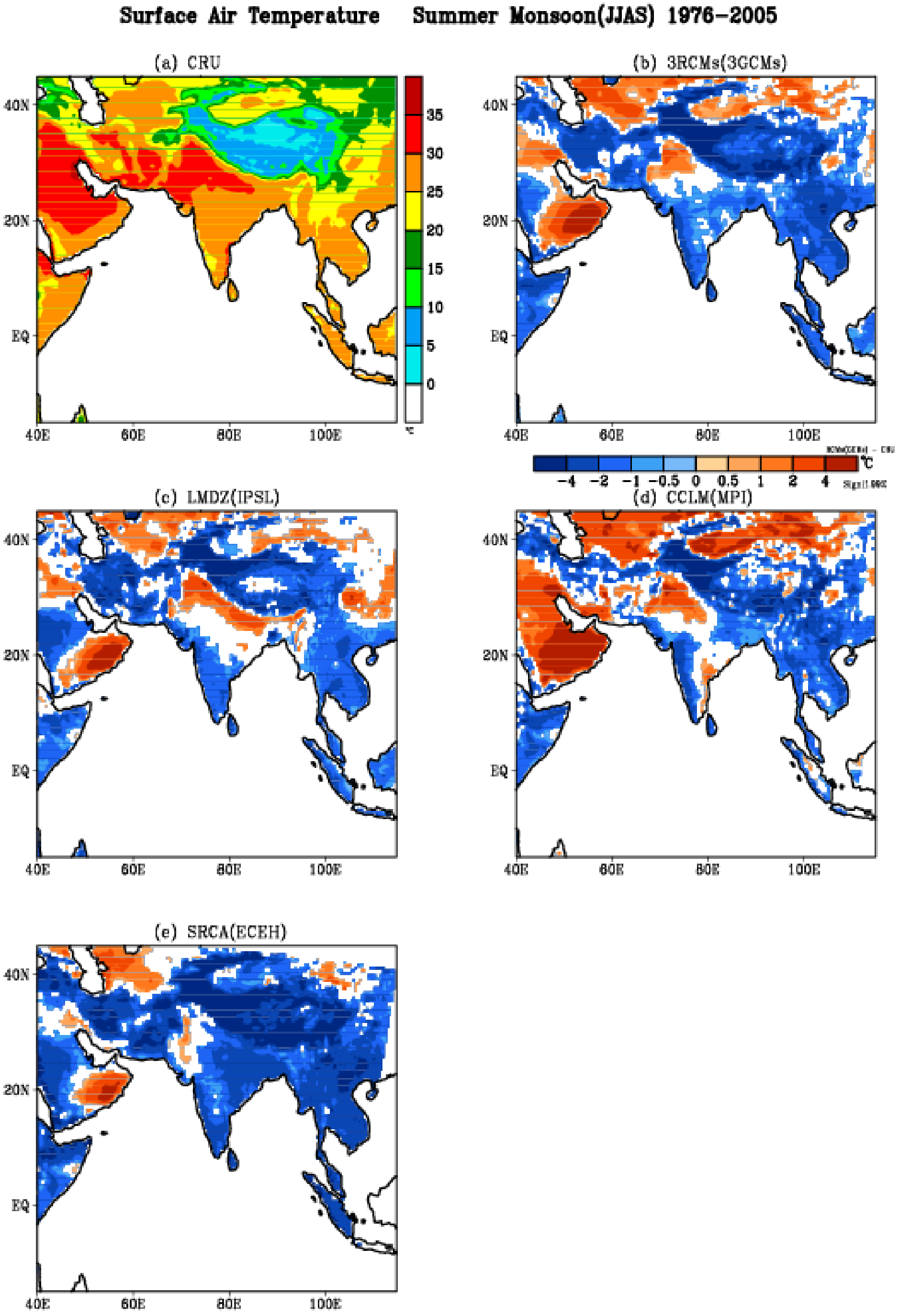


Figure 8.2

(a) The CORDEX South Asia multi-model ensemble mean of summer monsoon (JJAS) season mean 2-m air temperature (˚C) for 1976-2005 and the changes of 2-m air temperature in 2066-2095 relative to 1976-2005 for the CORDEX South Asia simulations driven by CMIP5 AOGCM RCP4.5 scenario experiments: (b) multi-model ensemble mean and (c-e) three different RCMs listed in Table 1. (f) same as (e) except for the RCP8.5 scenario experiment with SRCA RCM. Only 2-m air temperature differences significant at the 5% significance level are shown.

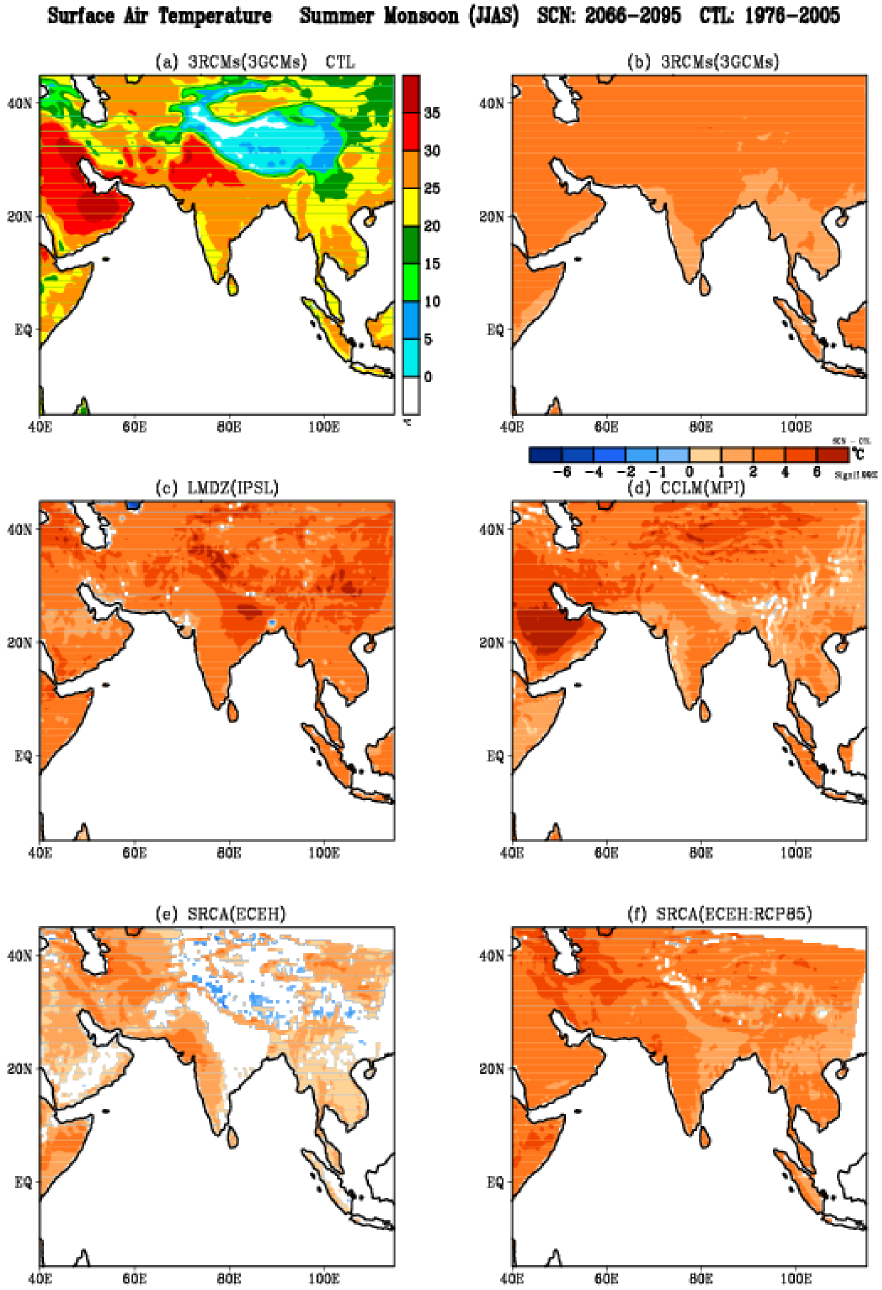


Figure 8.3

(a) The CORDEX South Asia multi-model ensemble mean of winter (DJF) season mean 2-m air temperature (˚C) for 1976-2005 and the changes of 2-m air temperature in 2066-2095 relative to 1976-2005 for the CORDEX South Asia simulations driven by CMIP5 AOGCM RCP4.5 scenario experiments: (b) multi-model ensemble mean and (c-e) three different RCMs listed in Table 1. (f) same as (e) except for the RCP8.5 scenario experiment with SRCA RCM. Only 2-m air temperature differences significant at the 5% significance level are shown.

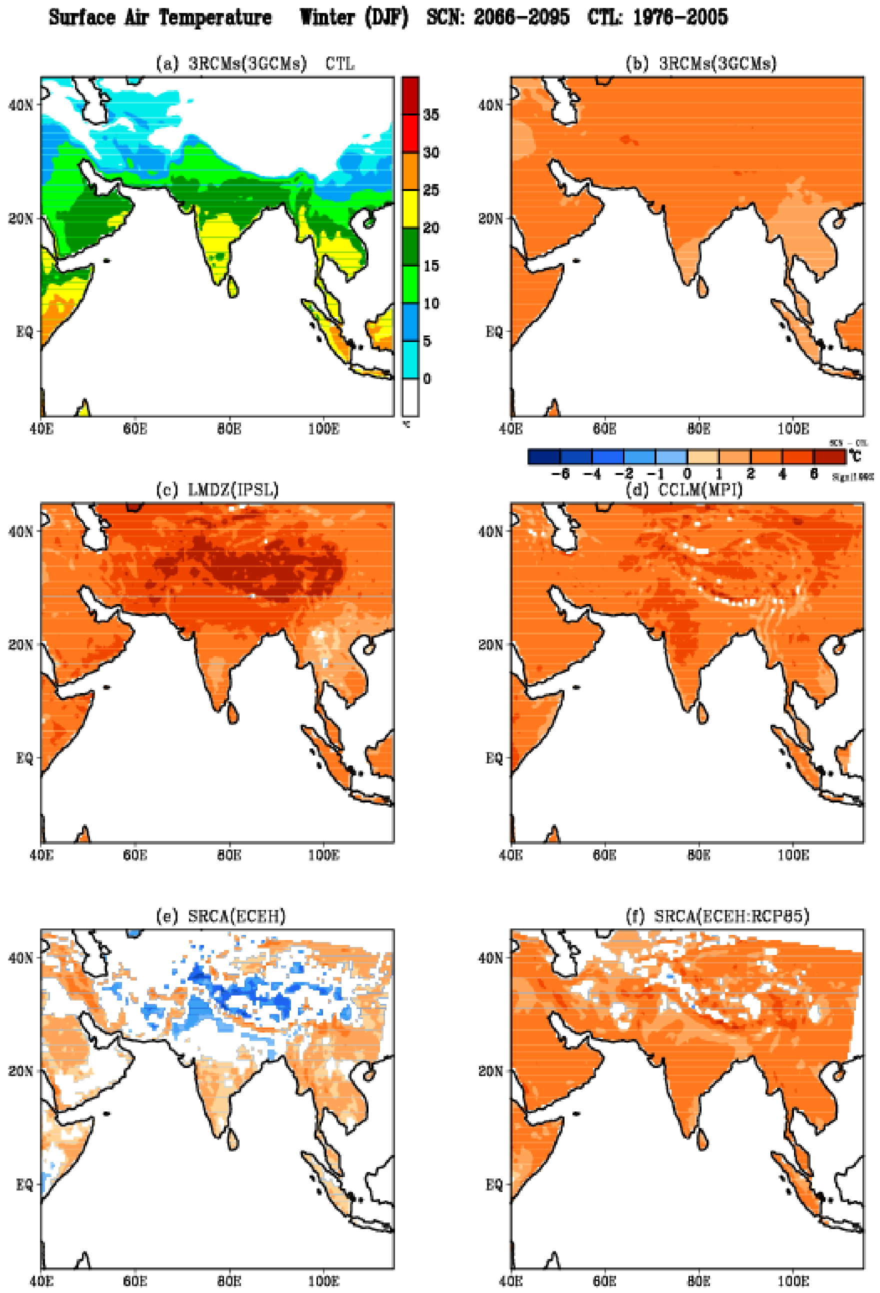


Figure 9

(a) The CORDEX South Asia multi-model ensemble mean of summer monsoon (JJAS) season mean precipitation (mm day^{-1}) for 1976-2005 and the changes of precipitation (%) in 2066-2095 relative to 1976-2005 for the CORDEX South Asia simulations driven by CMIP5 AOGCM RCP4.5 scenario experiments: (b) multi-model ensemble mean and (c-e) three different RCMs listed in Table 1. (f) same as (e) except for the RCP8.5 scenario experiment with SRCA RCM. Only precipitation differences significant at the 5% significance level are shown.

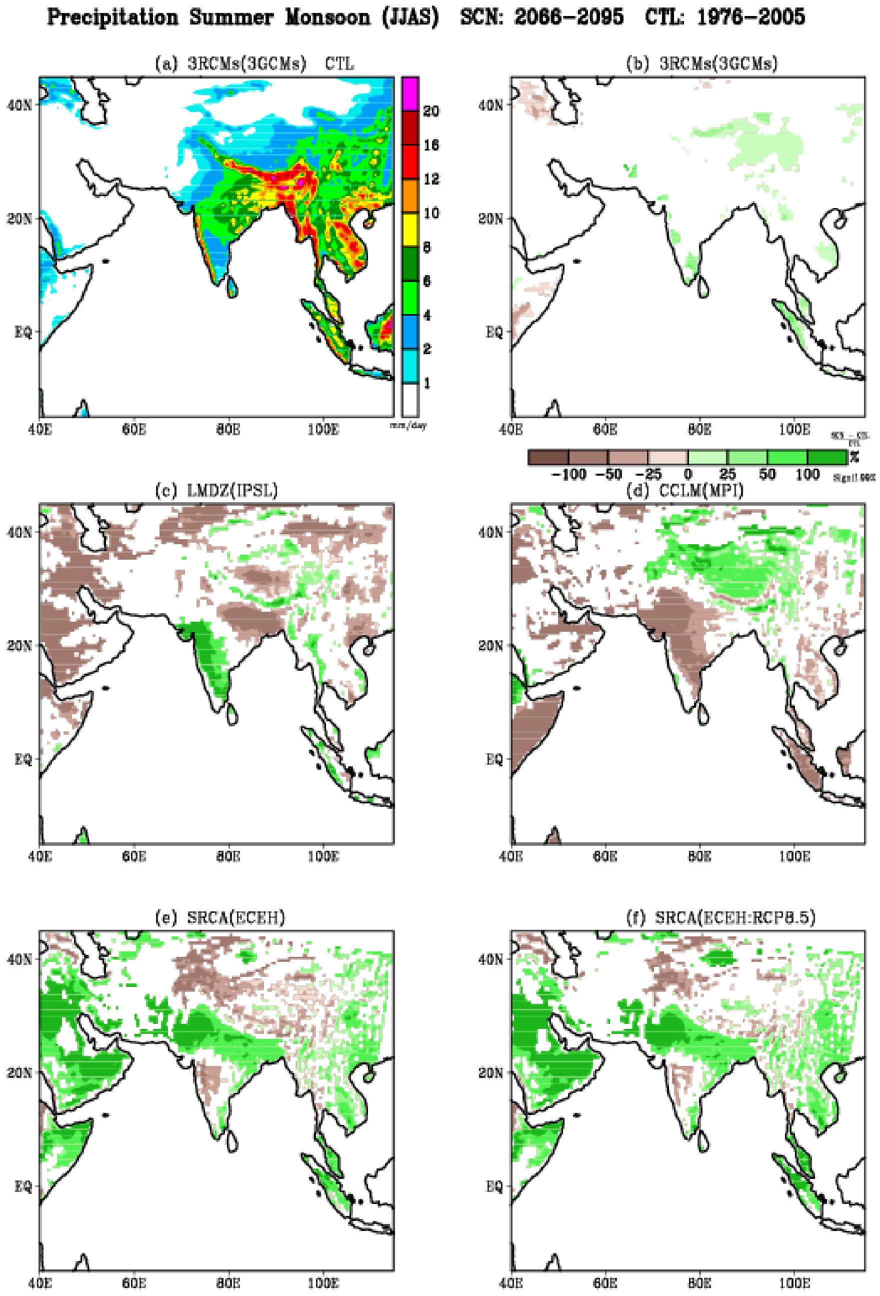
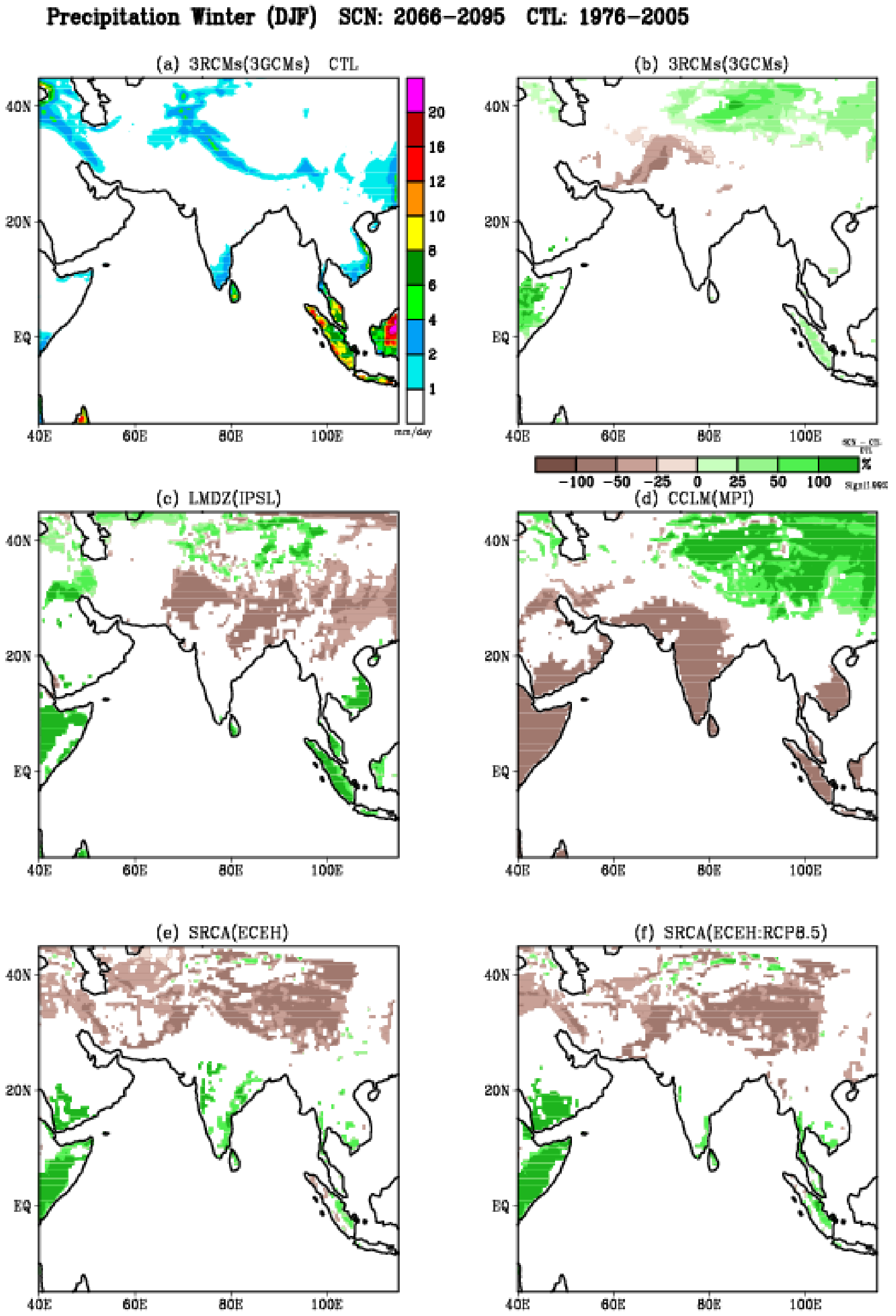


Figure 10

(a) The CORDEX South Asia multi-model ensemble mean of winter (DJF) season mean precipitation (mm day^{-1}) for 1976-2005 and the changes of precipitation (%) in 2066-2095 relative to 1976-2005 for the CORDEX South Asia simulations driven by CMIP5 AOGCM RCP4.5 scenario experiments: (b) multi-model ensemble mean and (c-e) three different RCMs listed in Table 1. (f) same as (e) except for the RCP8.5 scenario experiment with SRCA RCM. Only precipitation differences significant at the 5% significance level are shown.



Our understanding of climate change and climate variability over the Indian subcontinent has benefitted from recent advances in understanding the Indian climate system. Nonetheless, the peculiarities of the Indian monsoon, and the influence of both larger and regional climate drivers, necessitate further study of this system. For instance, the Centre for Climate Change Research (CCCR, IITM) is building an earth system model (ESM) that uses high-resolution coupled ocean-atmosphere modelling that aids in attribution and projection of global and regional climate change. CCCR is also involved with the use of high-resolution models and dynamic downscaling of regional climate and monsoons to provide reliable input for impact assessment studies. Concurrently, Mondal and Mujumdar (2015) have recently investigated the spatially explicit influence of ENSO and warming on EREs. A similar investigation currently underway, attempts to explore the influence of ENSO and IOD on rainfall (Krishnaswamy and Vaidyanathan in prep).

Despite these efforts, researchers (assessed through an intense literature review process and aided by inputs from focussed Key Information Interviews (KIIs)) acknowledge that the production of reliable downscaled data may not be achieved with current models. For example, several climatic interactions such as the impact of wind velocity on monsoons have not been modelled accurately, which hamper predictions regarding the Indian monsoon. Additionally, the spatial scale of currently available downscaled climate products (RCMs) may preclude its use in the local decision-making process. The Moyar-Bhavani and Sangamner sub-regions, for example are located entirely within a couple of RCM cells (Annexures 3 and 4). Further, neighbouring RCM cells in these sub-regions are located in sub-humid and humid areas, confounding the attribution of observed changes. In order to enhance the grain of our analysis, we intend to explore the statistical downscaling of climate projections during the upcoming Regional Research Programme (RRP) phase. Most studies that consider the impacts of climate on the biophysical environment are at large spatial scales and lack granular detail. This detracts from their use at smaller scales that are more relevant to local stakeholders. Impact studies are also often limited in scope and restricted to the water sector and major agricultural crops (e.g. rice, wheat). Additional research is needed to understand climatic impacts on other natural and ago-ecosystems (however, see MoEF 2012). Often, locally significant drivers such as land use-land cover change overwhelm the influence of climatic drivers. Research needs to assess trends in the response of coupled socio-ecological systems to climate induced perturbations at global and local scales. A system of long-term ecological and agro-ecological observatories needs to be established to understand changes in these systems and attribute these changes appropriately. Additionally, understanding the northeast monsoon (especially in certain ASSAR sub-regions) behaviour is a major gap that needs focussed attention/research.

Table 2: A review of key climate change projections for India

STUDY	GCM USED	DOWNSCALING MODEL	RESOLUTION	CLIMATE SCENARIO	TIME-PERIOD	KEY RESULTS	KEY LIMITATIONS
Rupakumar et al. 2006	HadCM3	PRECIS	0.44×0.44°	A2, B2	1960-1990; 2070-2100	All India temperature projected to increase 2.9°C (B2) and 4.1°C (A2) by 2080s relative to 1960-1990 baseline. All India precipitation projected to increase 18% (B2) and 23% (A2) by 2080s relative 1960-1990 baseline	Single GCM, only two SRES used, uncertainty in precipitation projections, lack of further downscaling
Krishnakumar et al. 2011	HadCM3 – QUMP≠	PRECIS	0.44×0.44°	A1B	1960-2098	All India temperature projected to increase 3.5°C to 4.3°C under the three Qs of A1B scenario by 2080s relative to 1960-1990 baseline. All India precipitation projected to increase 12% to 15% under the three Qs of A1B scenario by 2080s relative 1960-1990 baseline	Single GCM, single SRES scenario, uncertainty in precipitation projections, lack of further downscaling
Geethalaxmi et al. 2011	EH5OM GCM	RegCM3	0.5×0.5°	A1B	129 years (1971-2099)	For Tamil Nadu, while PRECIS projected a maximum temperature increase of 3.7°C, the RegCM3 projected a rise of 3.1°C. The increase in minimum temperature in PRECIS was 4.2°C and in RegCM3 it was 3.7°C during the same period. The increase in minimum temperatures was higher than that in maximum temperatures in both models.	Used only two RCMs

Pankaj Kumar et al. 2013	ECHAM5-MPIOM and HadCM3	The Regional Model (REMO) HadRM3 CCLM (COSMO model in Climate Mode)	0.25×0.25°	A1B	1900-2100	For India the annual spatial warming is estimated between 2.5 °C to 5.5 °C with a maximum over Himalaya, north, central and west India. The summer monsoon season has regionally different precipitation projections like robust significant increase over peninsula (20%–40%) and Western Ghats and NE (10%–20%) by the end of the 21st century.	Use of SRES
Chaturvedi et al. 2012	18 GCMs	None	0.9-3°	RCP2859.6, RCP4.5, RCP6.0, RCP8.5	2006-2100	Chaturvedi et al (2012) projected a warming of 3.3°C to 4.6°C (relative to pre-industrial) for the Indian region under the business as usual scenario by 2080s and suggest that temperatures may rise to 2°C by as early as 2030s All-India annual precipitation under the business-as-usual scenario is projected to increase from 4% to 5% by 2030s and from 6% to 14% towards the end of the century (2080s) compared to the 1961–1990 baseline	Coarse resolution, uncertainty in precipitation projections; high uncertainty in extreme precipitation events

CHAPTER 3

Biophysical Impacts

Biophysical Impacts

3.1 Impact of climate change on natural and production systems

India's National Communication to UNFCCC (MoEF 2004) for the first time brought together a group of climate scientists, economists and sectoral impact assessment experts for assessing the impact of climate change on different natural systems such as water resources, agriculture systems and forest resources. The Indian Network for Climate Change Assessment (INCCA) launched in 2010 by the Ministry of Environment and Forests (MoEF) published its first study in the same year (INCCA 2010). The study projects the climate change to 2030 and its impacts on four eco-sensitive zones covering the Himalayan region, the North-Eastern region, the Western Ghats and the Coastal region. India's second National communication to UN (MoEF 2012) provided another opportunity and platform to the impact assessment community to come together once again. Most of the individual contributors to the NATCOM1, INCCA 2010 and NATCOM2 have published their findings separately in peer-reviewed journals. More details about these three Government of India sponsored studies can be viewed from Table 4.

Table 3 provides a snapshot of the state of the knowledge on the impact of climate change in India on key natural systems. It paints a really bleak picture about the state of our knowledge about the observed impacts on different natural systems due to the lack of long term observations. It also points to the lack of studies projecting the impact of climate change on different systems.

Table 3: State of the knowledge on the impact of climate change in South Asia on different natural systems relevant to SARs (as per IPCC 2014)

PROJECTED IMPACTS	OBSERVED IMPACTS	TOPIC/ISSUES	SECTOR
X	√	Major river runoff	Freshwater resources
X	X	Water supply	
X	X	Phenology and growth rates	Terrestrial Ecosystems
√	X	Distributions of species and biomes	
X	X	Inland waters	Inland water systems
√	X	Rice yield	Food production systems & Food security
√	X	Wheat yield	
X	X	Corn Yield	
X	X	Other crops (e.g. Barley, Potato)	
X	X	Vegetables	
X	X	Fruits	
X	X	Fisheries	
√	X	Pest & disease occurrence	
√	√	Flood-plains	Human settlements, Industry &
√	√	Population & assets	
√	√	Industry & Infra	

			Infrastructure*
X	√	flood related	Human health & Livelihood
X	X	drought related	
X	X	Heat related	
X	√	Water-borne	
X	√	Vector-borne	
X	√	Livelihood & Poverty	
X	X	Livestock	Livestock

Key: √ = Relatively abundant/sufficient information; knowledge gaps need to be addressed but conclusions can be drawn based on existing information; X = Limited information/no data; critical knowledge gaps, difficult to draw conclusions

* Not covered in the present review

In rain fed systems of the semiarid tropics, the constant risk of drought increases the vulnerability of livelihoods and decreases human security. Thus drought management is one of the key strategies for agricultural development in regions of Maharashtra (ICRISAT, 2006).

Over the past three decades, area under sorghum and millet, two important crops, has fallen by nearly one third and new crops like maize, soybean and cotton have become popular in the SAT (Sangamner Transect) areas because of their rising market demand (Singh and Bantilan, 2009). Studies on the productivity of sorghum also showed adverse effects in rainfed areas (Sivakumar et al. 2005). Lal et al. (1999) found that soybean crops in Central India are found to be more vulnerable to increase in maximum temperature than in minimum temperature. A decline in daily rainfall amount by 10% restricts the grain yield to about 32%. They concluded that acute water stress due to prolonged dry spells during monsoon season could be a critical factor for the soybean productivity even under the positive effects of elevated CO2 in the future.

For almost all crops, the productivity in Maharashtra is much lower than the national average and there are fluctuations in yield which clearly indicates the consequences of failure of monsoons (Shroff and Kajale, 2013).

In Maharashtra, during Kharif season of 2013-14, the area under cereals and pulses decreased by 1% and 4% respectively, while that under oilseeds increased by 22% compared to the previous year. The rise in the area under oilseeds is due to a substantial rise in area under soyabean. The production of cereals, pulses, oilseeds and cotton is expected to increase by 21%, 5%, 3% and 11% respectively, while that of sugarcane is expected to decrease by three per cent as compared to the previous year (Economic Survey, 2013-14).

3.2 Impact of climate change on freshwater resources

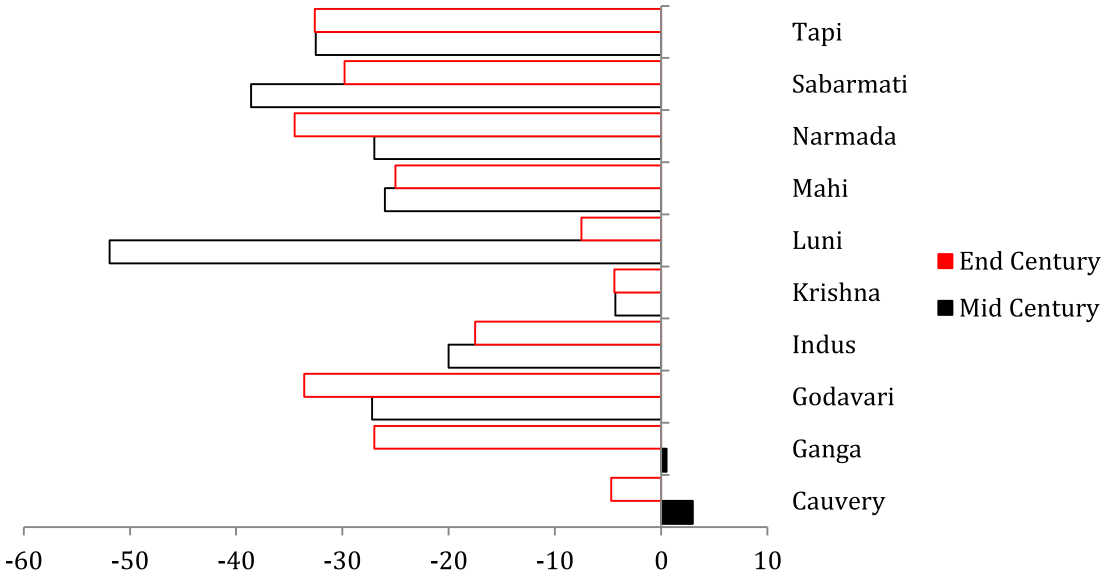
In the recent decades, freshwater resources in the country have faced a large stress due to multiple factors. A satellite based study from NASA observed that over the Indian states of Rajasthan, Punjab and Haryana (very relevant SARs areas) groundwater is being depleted at a mean rate of 4.0±1.0 cm yr^{-1} equivalent height of water (i.e. 17.7±4.5 km^3 yr^{-1}) between August 2002 and October 2008. During this period, groundwater depletion was equivalent to a net loss of 109 km^3 of water, which is double the capacity of India's largest surface-water reservoir (Rodell et al 2009). Mall et al (2006) further suggest that 'changes in cropping pattern and land-use pattern, over-exploitation of water storage and changes in irrigation and drainage in the Gangetic basin show a reduction in the Ganges discharge by 60% over 25 years. This has led to about 50% drop in water availability in surface water resources'. However there are no studies attributing the observed changes to climate change.

Fung et al (2011) as part of a global study projected the impact of projected 2°C and 4°C rise in temperature over the Ganga Basin in India. This study finds that stress in the Ganges will decrease as climate change progresses. However, it further cautions that 'the increase in surface run-off may be unevenly distributed across the year, and unless storage is available to smooth out the peaks in water availability throughout the year, the greater run-off volumes may present more difficulties, e.g. flooding, rather than alleviating water stress'. Relevant technical details and the limitations of the study can be found in Table 4.

Gosain et al (2006) projected increased water scarcity in the semi-arid basins of Sabarmati, Luni, Krishna, Tapi and Narmada due to decreasing rainfall and increasing ET, and an increase in drought intensity in most of the Krishna basin. Further Gosain et al (2011) projected the impact of climate change on the 17 most important river basins in India up to mid-century and towards the end of the century. They estimated a decline in rainfall in 14 out of the 17 river basins towards the 2030s (mid century) and the 2080s (end century). In almost all river basins (including the river basins in semi-arid regions) rainfall declines from 4% to 23%, following changes in precipitation (Figure 11). As a result of the decline in basin level rainfall, water yield in most of the river basins is projected to decline by the 2030s and almost all by the 2080s.

Figure 11

Impact of climate change on water yield in river basins relevant to SARs



Source: Gosain et al (2011)

Climate change will enhance the criticality of groundwater for drought-proofing agriculture and simultaneously multiply the threat to the resource due to over extraction, use of diesel & electricity for pumping water which accounts for about 16-25 million tonnes of carbon emission, which is 4-6% of the country's total emission (Shah, 2009). Western and Peninsular India concentrated in arid and semiarid areas of western and Peninsular India, especially in Punjab, Rajasthan, Maharashtra, Karnataka, Gujarat, Andhra Pradesh and Tamil Nadu are India's groundwater hot spots.

The Maharashtra groundwater (regulation for drinking water purposes) Act 1993 was modelled on the Model bill of 1970. The Model bill of 1970 requires registration of owners of tubewells, allocation of water rights, registration of drilling contractors and prior permission beore drilling a tube well. Maharashtra water resources regulatory authority act (MWRRA) 2005 excludes dug wells used for drinking water purposes from the ambit of the act. Phansalkar and Kher (2006), observe that the Act does not try to control the problem from arising but only takes steps if a problem has been created. The Act does not make itself relevant for any over exploitation of groundwater being done by wells located beyond the specified distance of 500 m from the public water source. There is also no role in regard to ‘competitive deepening of wells’ that keeps occurring between neighboring farmers.

The dugwells are most suitable structures for ground water development in the Ahmednagar district as 95% of the area is covered by Deccan Trap Basalt. The sites for borewell and tubewells wherever feasible, need to be selected only after proper scientific investigation. The expected yield of dugwells may vary from 20-120 m^3/day depending on the local hydrogeological conditions (GoI, 2011).

Adaptation cost in water sector has been quantified sparsely, for specific aspects and regions (e.g. MacNeil, 2004; Hall et al., 2005) but adaptation costs are expected to be high. Also, some potential water management adaptation measures (e.g. desalination, pumping of deep groundwater, or water treatment) are very energy-intensive and their implementation would increase greenhouse gas emissions (Mata & Budhooram, 2007).

3.3 Impact of climate change on food production and food security

The IPCC (2014 WG2 Draft) suggests that "... climate change will affect food security by the middle of the 21st century, with the largest numbers of food-insecure people located in South Asia". IPCC (2014 WG 2, Draft) further cautions that "there is very limited data globally on the observed impacts of CC on food production". However, a landmark study by Lobell et al (2011) published in Science concludes that "global maize and wheat production has declined by 3.8 and 5.5%, respectively over the period 1980-2008, relative to a counterfactual without climate trends. For India it finds wheat yields to have declined by >5% and rice yields to be by about 2% over the same time period.

Wassmann et al (2009) looked at the increasing heat stress and its implication for rice production in different parts of Asia, including the SARs of India. They suggest that, in terms of risks of increasing heat stress, there are parts of Asia where current temperatures are already approaching critical levels during the susceptible stages of the rice plant. These places, among other areas include: North India (October) and South India (April, August).

'Studies conducted by the Indian Agricultural Research Institute (IARI) indicate the possibility of loss of 4-5 million tons in wheat production with every rise of 1°C temperature throughout the growing period even after considering carbon fertilization' (Planning Commission, India, 2011).

Naresh kumar et al (2010) analysed the impact of climate change on sorghum and conclude that climate change is projected to reduce monsoon sorghum grain yield to the tune of 14% in CZ (Central Zone) and SWZ (South Western Zone) by 2020. Yields are likely to be affected even more in 2050 and 2080 scenarios. Climate change impacts on winter crop are projected to reduce yields upto 7% by 2020, 11% by 2050 and 32% by 2080. Impacts are projected to be more in SWZ region than in SCZ and CZ. But, the yield loss due to rise in temperature is likely to be offset by a projected increase in rainfall.

On the effect of climate change on rice yields Naresh Kumar et al (2013) suggests that climate change is likely to reduce irrigated rice yields by ~4 % in 2020 (2010–2039), ~7 % in 2050 (2040–2069), and by ~10 % in 2080 (2070–2099) climate scenarios. On the other hand, rain-fed rice yields in India are likely to be reduced by ~6 % in the 2020 scenario, but in the 2050 and 2080 scenarios they are projected to decrease only marginally (<2.5 %). Asseng et al (2014) using multiple GCMs outputs estimated the uncertainty in wheat yield simulations under climate change. The sensitivity analysis suggests higher decline is wheat yields at higher temperature rises

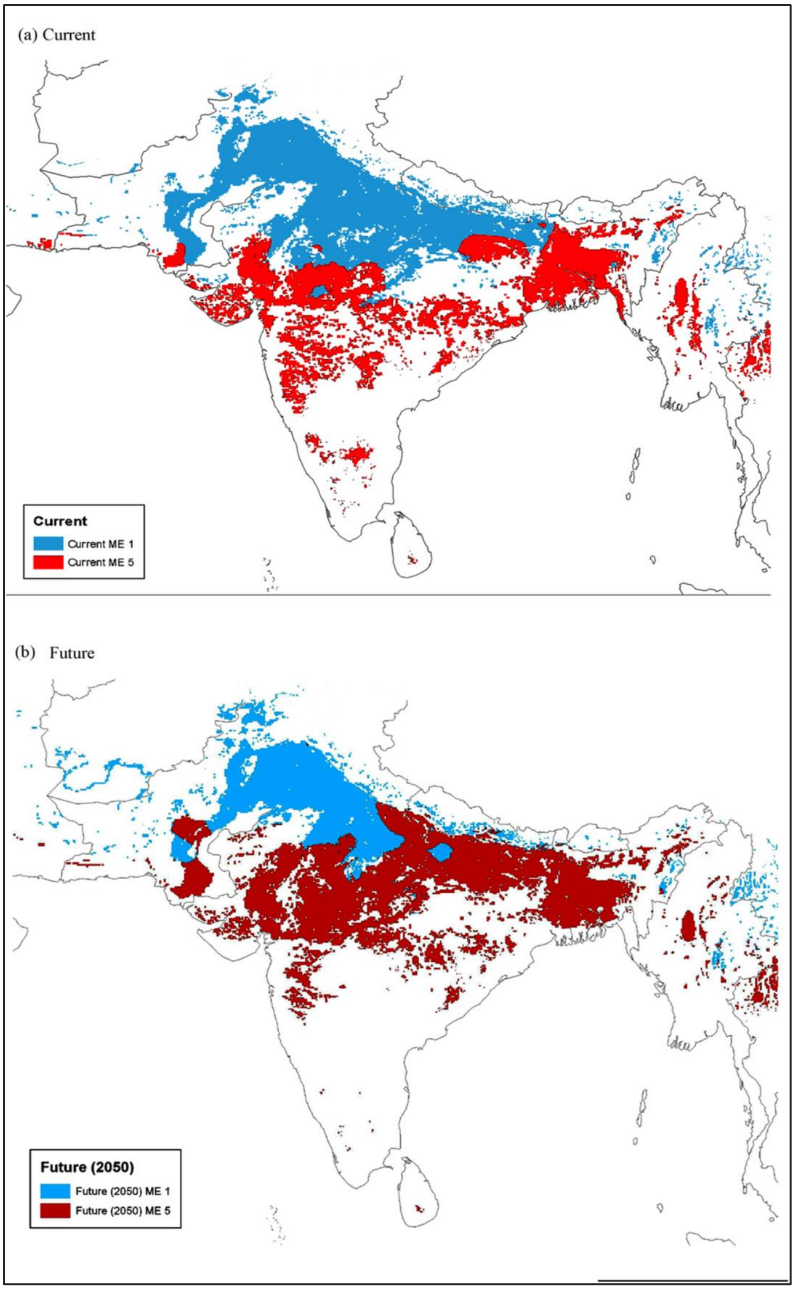
Geethalakshmi et al (2011) projected a decline of 356 Kg/ha/decade, in rice yield in Cauvery delta without considering the CO_2 fertilization effect for the PRECIS outputs, whereas the decline was 217 kg/ha/decade for RegCM3 outputs. However, when CO_2 fertilization effect was considered, the PRECIS output showed decreasing trend at the rate of 135 kg/ha/decade, whereas RegCM3 projected a modest increase in the yield (24 kg/ha/decade; see Table 4 for details).An Asia-wide study by Masutomi et al 2009 assessed the impact of climate change on rice yields. It suggested that under the climate change scenarios rice yield will reduce over a large part of the continent. Northern part of South Asia was found to be one of the most vulnerable regions.

Ortiz et al (2008) project a large reduction in wheat yielding area in the Indo-Gangetic Plains. Indo-Gangetic plain currently produces 90 million tons of wheat grain annually (about 14-15% of global wheat production). Climate projections based on a doubling of CO_2 using a CCM3 model downscaled to a 30 arc-second resolution as part of the WorldClim data set (Bala et al. 2003) showed that there will be a 51% decrease in the most favourable and high yielding area due to heat stress – adversely impacting about 200 million people. This study is especially useful from the perspective of the SARs as much of the wheat area reduction is seen in this area (Figure 12).

A systematic review and meta-analysis of data in 52 original publications projected mean changes in yield by the 2050s across South Asia of 16% for maize and 11% for sorghum (Knox et al., 2012). The IPCC (2014) cautions that crop physiology simulation models may generally overstate the impact of CO_2 fertilization. Free atmosphere carbon exchange (FACE) experiments show that measurable CO_2 fertilization effects are typically less than modelled results.

Figure 12

(a, b) Changes in wheat yielding area (ME1 and ME5 are two high yielding wheat Mega Environments); [Source: Ortiz et al 2008]



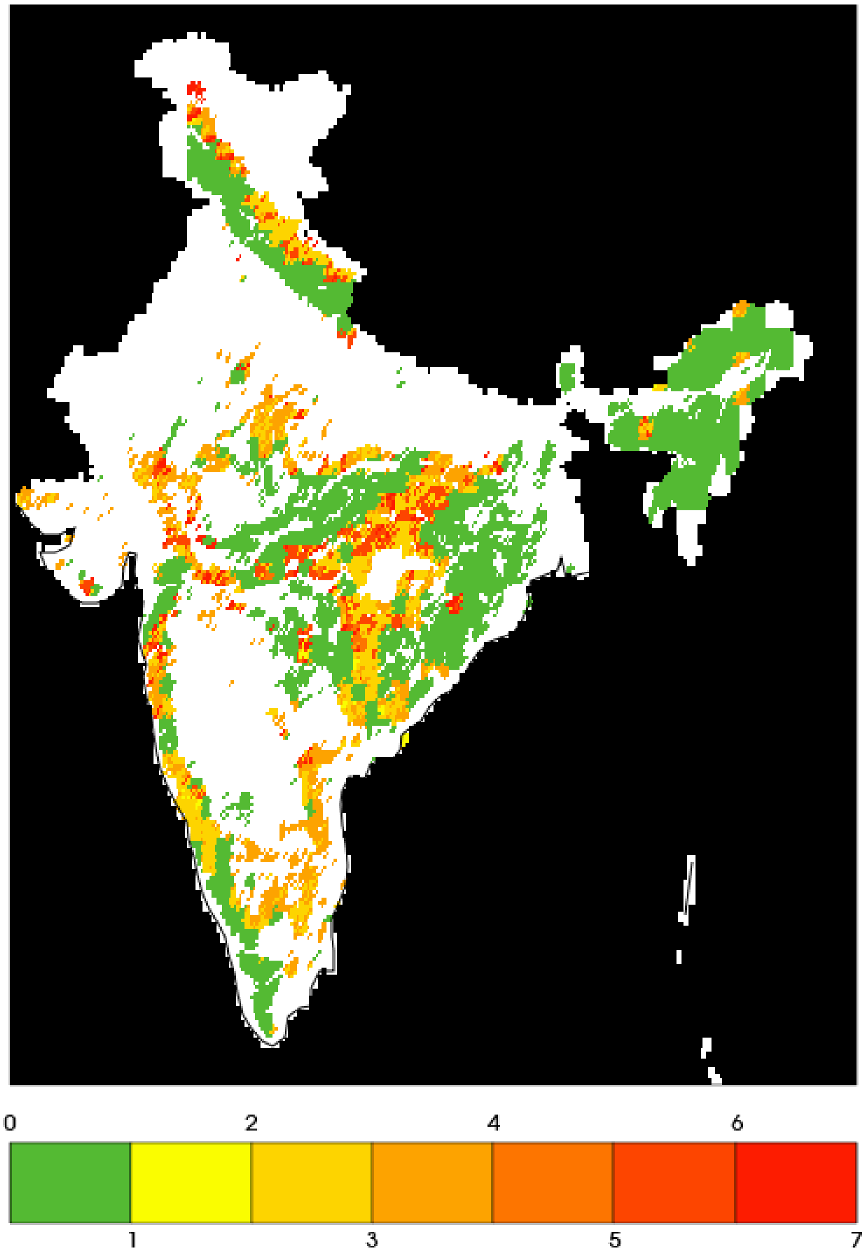
3.4 Impact of climate change on terrestrial ecosystems

At the global level a number of recent studies have documented the ongoing impacts of climate change on terrestrial ecosystems. For example observations across the world suggest that climate change is causing many species, including plants, to shift their geographical ranges, distributions, and phenologies at faster rates than previously thought (Michelle et al 2012, Chen et al 2011). In India biological changes consistent with climate trends have been reported in the north and at high altitudes. For example, a study by Telwala et al (2013) based on extensive field sampling and historical data estimated the vegetation shift patterns for 124 endemic species in the eastern Himalayan state of Sikkim, over the period 1849-1850 to 2007-2010. They estimated that 87% of the 124 endemic species showed geographical range shifts in response to observed warming experiencing a mean upward displacement rate of 27.53±22.04 meters per decade. It concludes that the "present-day plant assemblages and community structure in the Himalaya is substantially different from the last century and is, therefore, in a state of flux under the impact of warming". They further caution that the continued warming is likely to result in ongoing elevation range contractions, and eventually species extinctions, particularly at mountaintops. However few observational studies are available for the semi-arid-regions.

Ravindranath et al. (2006), used the BIOME4 model projected the impact of climate change on forest ecosystems and concluded that about 77% and 68% of the forest grids in India are likely to experience vegetation shift under the A2 and B2 scenarios of climate change respectively by 2080s. Further, Chaturvedi et al. (2011) projects the impact of climate change on Indian forests and conclude that 39% and 35% of the forests grids in India may likely undergo change under the A2 and B2 scenarios respectively (Figure 13).

Figure 13

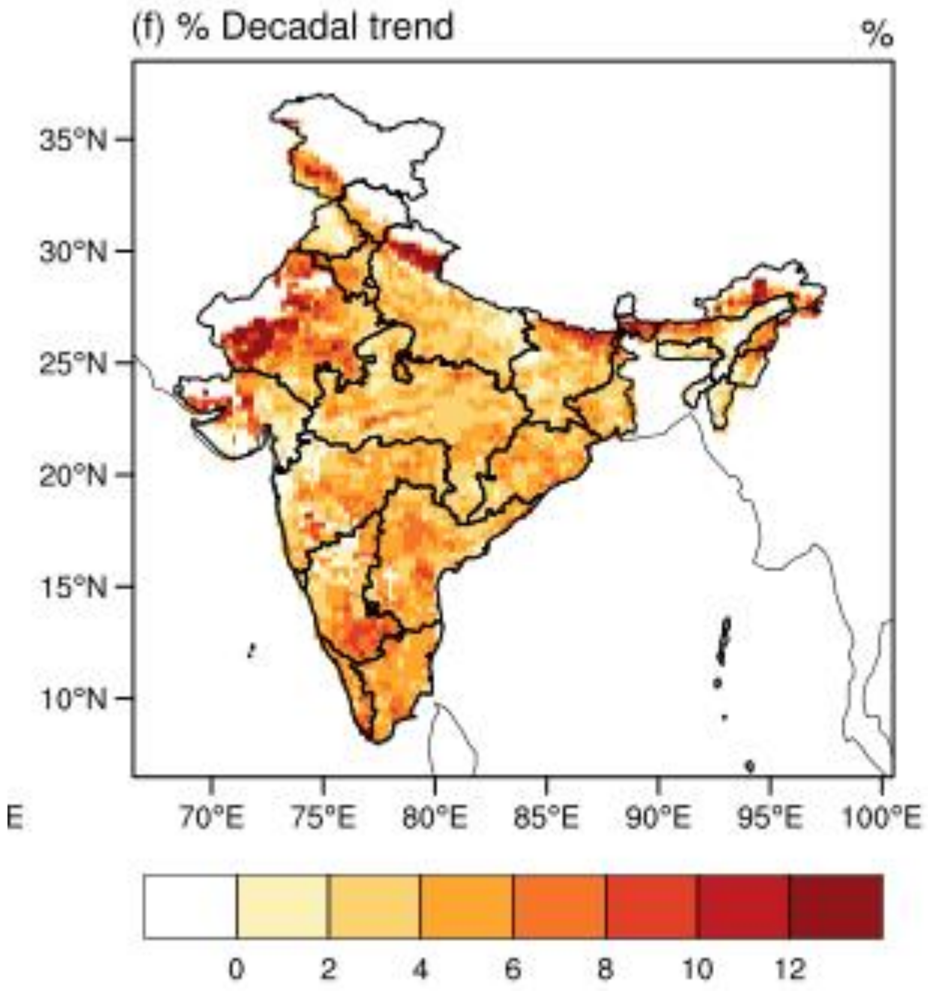
Distribution of forest vulnerability in India (for FSI grids). Green indicates a vulnerability index of 1 (least vulnerable), while yellow to red indicate increasing levels of vulnerability; Source: Chaturvedi et al (2011)



Based on satellite observations of net primary productivity over the period 1982-2006, Bala et al. (2013) estimated an increasing NPP trend of 3.9% per decade over India (Figure 14). A multivariate linear regression analysis indicates that this increasing NPP trend is partly driven by increasing atmospheric CO_2 concentration and the consequent CO2 fertilization of the ecosystems. However, human interventions such as increased irrigation and increased fertilizer use may have also played a key role in the NPP increase. Under climate change scenarios Ravindranath et al. (2006) and Chaturvedi et al. (2011) project an increase in NPP.

Figure 14

Decadal NPP trend over India (Bala et al 2013)



3.5 Impact of climate change on livestock

Livestock rearing is often viewed as an adaptation strategy to cope with the climate stress. However, the livestock sector itself is vulnerable to the impacts of climate change. Sirohi and Michaelowa (2007) suggest that "climate change poses formidable challenge to the development of livestock sector in India..."The anticipated rise in temperature and precipitation is "likely to aggravate the heat stress in dairy animals, adversely affecting their productive and reproductive performance, and hence reducing the total area where high yielding dairy cattle can be economically reared". Upadhaya (2007) investigated the influence of climate variability on milk production for local cows. The annual loss at present due to heat stress among cattle and buffaloes at the national level is estimated to be 1.8 million tonnes, which is nearly 2% of the total milk production in the country. India's fourth national biodiversity report to Convention on Biological diversity (CBD; MoEF 2009) suggests that almost all indigenous breeds of livestock are showi*ng* declining trends in the country. It further suggests that "estimates indicate that 50% of indigenous goat, 30% of sheep, 20% of cattle, and almost all poultry breeds are threatened".

The Indian livestock sector contributes to 40% of the agricultural GDP in the semi-arid regions and 70% in the arid regions (WOTR, 2013). Statistics reveal that resource-poor small and marginal farmers and landless labourers own 71% of cattle, 63% of buffaloes, 66% of small ruminants, 70% of pigs and 74% of poultry in India (GoI, 2003). With respect to sheep and goats in India, almost all belong to small-holders who own 1 ha of land or less, or are landless (Birthal and Taneja, 2006). These owners depend entirely on common property resources (CPR) for their survival, and rear livestock through this extensive system. Evidence shows that smallholders obtain nearly half of their income from livestock (Birthal et al., 2003).

It is generally considered that the environmental impacts of livestock production in India have more positive implications than negative ones as the production system is still largely predominated by the rural livestock-crop integrated smallholder mixed farming system (Chacko et al, 2006). The emergence of large scale industrial production units, declining grazing resource base, increasing relevance of livestock towards climate change etc. are important concerns around livestock production in the context of sustainability.

In Maharashtra, the Ahmednagar district ranks first in milk production in the state and has well developed dairy infrastructure (Ghule et al. 2012). Geographically, the district is positioned at the centre of the state having easy access to some important markets like Mumbai, Thane, Pune, Nashik and Aurangabad cities. This led to establishment of a large number of commercial herds in the area. Adaptation by the small-scale livestock farmers are several and they include strategies such as changing herd size and composition, change in grazing and feeding patterns, or diversifying of livelihoods, also use new varieties of fodder crops suited to the changing conditions (Salema et al., 2010).

3.6 Impact of climate change on human-health

Human health is invariably linked to climatic variations, and extreme events. Health is impacted by excessive heat, and floods, and through various water-borne and vector-borne systems (Majra and Gur, 2009). For example, epidemics have been reported after floods and storms (Bagchi, 2007) as the drinking water quality gets compromised and excessive -mosquito proliferation (Pawar et al. 2008). Sohan et al. (2008) have documented how contaminated urban flood waters have caused exposure to pathogens and toxic compounds in India. A Relationship between high temperatures and mortality has been shown for populations in India (McMichael et al. 2008). Intense heat waves have been shown to affect outdoor workers in South Asia (Nag et al. 2007; Hyatt et al 2010). Heat stress and its various health implications are especially relevant to the SARs. Studies from India and Nepal have found correlations between malaria prevalence and the rainfall variability, though malaria is often influenced by non-climate variability factors as well (e.g. Dev and Dash 2007). Linking health effects to climatic variability is one thing, however attributing certain changes in human health patterns to climate change is a different ballgame altogether – and such studies are not available for Indian region.

Using a simple transmission window approach Bhattacharya et al. (2006) projected malaria transmission suitability for different parts of the country using climate change projection from HadRM2 model till 2050. The study finds the central and eastern Indian regions of the country covering Madhya Pradesh, Jharkhand, Chhatisgarh, Orissa, West Bengal and Assam to be the most endemic malaria regions under the current climate and projects that under the climate change projections of HadRM2 "malaria is likely to persist in Orissa, West Bengal and southern parts of Assam, bordering north of West Bengal. However, it may shift from the central Indian region to the south western coastal states of Maharashtra, Karnataka and Kerala....The duration of the transmission windows is likely to widen in northern and western states and shorten in the southern states."

3.7 Impact of climate change on Urban Areas

Bangalore, one of the largest cities in India, is located in a semi-arid region and has an annual average maximum temperature of 29°C and average minimum temperature of 19°C. A mean temperature increase of approximately 2-2.5°C during the last decade has been reported, attributed both to urban heat island effect and potential early climate signals. This urban heat island effect is exacerbated by a decline in tree cover and has serious health implications for the local population, resulting in local temperature variations and irregular rain showers (Ramachandra and Kumar 2009, Ramachandra and Kumar, 2010). This in turn has resulted in a significant increasing trend in both the frequency of rainy days in a year, and in one day extreme rainfall (maximum rainfall day for each year) for the period from 1901 to 2005 (Guhathakurta et al., 2011).

Simultaneously, the built-up area has increased by 134% from 1992 to 2009. The coverage of water bodies in the city has reduced from 3.4% to 1.5% of the land area in the same time period (Ramachandra and Kumar 2008, Sudhira et al., 2007). More than 70 % of the wetlands have disappeared since the 1970s as a result of cascading anthropogenic pressures and rapid urbanization (State of Environment Report, 2008). Additionally, city lakes have dried up in the absence of sufficient runoff inhibiting groundwater recharge. This is compounded by reclamation of dry lakes and diversion of these to construction, increasing the exposure to floods.

3.8 Impact of climate change on Gender related issues

While climate change impacts are felt by all, the socio economic and political scenarios in different communities make certain groups and sections of society more vulnerable. Women constitute one of the most vulnerable groups, as they have multiple disparities to contest with. Of the world’s 1.2 billion poor people, two thirds are women (IFAD 2001a) with least access to resources as well as to major assets.

Habtezion (2012) compiled the following facts from different sources ((World Bank, FAO, UNDP HDR) that highlight gender disparities: Approximately 70% of the global poor (those who live on less than $1 a day) are women; Women work two-thirds of the world’s working hours, yet receive only 10% of the world income; Women own only 1% of the world’s property; 75% of the world's 876 million illiterate adults are women; Around 45 million people — at least 6 million of them women — fish for a living and are threatened by overfishing and climate change.

Little is known currently about how poor men and women respond to climate change due to the social and gender disparities they face. The scarcity of gender-disaggregated data is also hampers better understanding of these issues. If inequitable access to information, extension services and communication technologies persists, we will continue to see lack of adaptive innovation, increased food insecurity and increased vulnerability to risk among women and other disadvantaged groups (CCAFS 2011).

In India, it is reported that 53% of male workers and 75% of all women workers are in the agricultural sector (Planning Commission, 2007). But women's increased involvement in agriculture, forest and livestock has not resulted in increasing their ownership or rights to control their livelihood resources and produce; compared to men, women have much poorer access, control and ownership of land and other productive assets. The daily agricultural wage of women was reported in the range of Rs. 35-38, while that of men was Rs. 45-50 (Parikh et al., 2004).

There have been studies that have looked at the yield gaps between farms cultivated by men and women separately and found that it averages around 20–30 percent; they associated this with differences in resource use. The learning from this could be that the yield gap can be reduced if the same resources are accessible to both men and women, which could raise total agricultural output by 2.5-4% (FAO, 2011). A one standard deviation change in the Gender Inequality Index (GII) will increase long term income per capita by 9.1% and the Human Development Index (HDI) by 4% (Ferrant, 2010).

Rural women often undervalue their knowledge and capabilities and thus do not volunteer to participate in irrigation and other government projects, though they are interested in them. Low literacy and the resulting lack of participatory skills, and low self-confidence, as well as prevailing social norms prevent women from taking leadership positions at the institutional level (IFAD, 2007).

In the state of Maharashtra, the sex ratio, which was 959 in 1977-78 shows steady decline to 952 in rural and from 904 to 858 in urban areas, though some improvement has been observed during the last ten years in the rural areas of the state (Government of Maharashtra, 2012). It was also found that the worker population ratio is observed to be steadily decreasing in rural area but is more or less stable in urban area over the last two decades in the Usual Principal Activity Status; as per the quinquennial survey estimates. A study of sector-wise distribution of usually employed persons indicates that higher proportions of females are engaged in primary sector. In urban areas, a significant shift from primary sector to tertiary sector is observed over last two decades for both males and females, which is more pronounced in case of females. The unemployment rate in rural areas is found to be 1.1% for males and 0.6% for females; this increases to 2.2% for males and 5.3% for females in urban areas.

Table 4: Summary of impact assessment studies for India for different sectors

STUDY	KEY IMPACT FINDINGS	IMPACT MODEL USED	STUDY AREA	CC SCENARIOS	CC PROJECTIONS USED*	SYSTEM	LIMITATIONS/ HIGHLIGHTS OF THE STUDY
MoEF, 2004 (NATCOM1)	Projects that the "River basins of Sabarmati and Luni, which occupy about one quarter of the area of Gujarat and 60 % of the area of Rajasthan, are likely to experience acute water scarce conditions. River basins of Mahi, Pennar, Sabarmati and Tapi are likely to experience constant water scarcity and shortage". Further Simulations using dynamic crop models "indicate a decrease in yield of crops as temperature increases in different parts of India". The forest modelling suggests "shifts in forest boundary, changes in species-assemblage or forest types, changes in net primary productivity, possible forest die-back in the transient phase, and potential loss or change in biodiversity"	BIOME3 - forest sector; SWAT – water;	All India	IS92a	HadRM2 (Unpublished)	Cross-sectoral (Water and Forest)	**Findings are having large uncertainties, preliminary assessment**
INCCA, 2010	Provides an assessment of the impact of climate change in 2030s on four key sectors of the Indian economy: Agriculture, Water, Natural Ecosystems and Biodiversity and Health, in four climate sensitive regions of India: the Himalayan region, the Western Ghats, the Coastal Area and the North-East Region.	SWAT-Water; IBIS-Forests; and InfoCROP for agriculture	Four hotspots: coastal, WG, NE, Himalaya	A1B	Krishnakumar et al 2011	Cross-sectoral (Water, Agriculture, Forests)	**The regions covered under the in-depth study are not very relevant for the SARs**
MoEF, 2012 (NATCOM2)	Projected the impact of climate change on water, agriculture and forest ecosystems.	BIOME4 - forest sector; SWAT – water;	All India	A1B	Krishnakumar et al 2011	Cross-sectoral	

Gosain et al 2006	Study projects increased water scarcity in the semi-arid basins of Sabarmati, Luni, Krishna, Tapi and Narmada due to decreasing rainfall and increasing ET. It projects increased drought intensity in majority of the Krishna basins and	SWAT	All India; Gosain et al 2006 covering 12 major river basins, Gosain et al 2011 covering >18 basins, including those in the SARs region	A2 and B2	Rupakumar et al 2006	Water	**Lack of observed data on the impact of CC on water resources, Single climate model, Single Hydrological mode – hence lack of robust uncertainty assessment, Lack of climate data downscaling, Precipitation projections are highly uncertain**
Gosain et al 2011	Projects increased water scarcity in the semi-arid basins of Tapi, Sabarmati, Narmada, Mahi, Luni, Krishna, Indus and Godavari due to decline is water yield (see figure 13). Drought weeks during monsoon are projected to increase for the semi-arid basins	SWAT		A1B	Krishnakumar et al 2011	Water	
Fung et al 2011	Finds that stress in the Ganges will decrease as climate change progresses. However, further cautions that 'the increase in surface run-off may be unevenly distributed across the year, and unless storage is available to smooth out the peaks in water availability throughout the year, the greater run-off volumes may present more difficulties, e.g. flooding, rather than alleviating water stress'	MaCPDM Global Hydrological model	Global, covering Ganga basin in India	+2°C and +4°C World	Ensemble* of HADCM3L GCM	Water	**1) GCM resolution of 3.75 and 2.5°. Lack of regional downscaling, 2) Large parts of Ganga basin is not relevant to SARs in India. 3) cautions that 'GCMs find it notoriously**

							difficult to model the Indian monsoon, so the results for the Ganges should be treated with particular caution'
	Conclude that “global maize and wheat production declined by 3.8 and 5.5%, respectively, relative to a counterfactual without climate trends. For India it finds the wheat yields to have declined by >5% and rice yields by about 2%		Global, covering India	Climate observation over 1980-2008		Agriculture	**This is a global study and it is unable to properly address many of the important sub-national issues**
	Wassmann et al. (2009) looked at the increasing heat stress and its implication for rice production in different parts of Asia. They suggest that, in terms of risks of increasing heat stress, there are parts of Asia where current temperatures are already approaching critical levels during the susceptible stages of the rice plant. These places, among other areas include: North India (October) and South India (April, August)		Asia, including north and south India	Observation		Agriculture	
Srivastava et al 2010	Climate change is projected to reduce monsoon sorghum grain yield to the tune of 14% in CZ (Central Zone) and SWZ (South Western Zone) by 2020. Yields are likely to be affected even more in 2050 and 2080 scenarios. Climate change impacts on winter crop are projected to reduce yields up to 7% by 2020, up to 11% by 2050 and up to 32% by 2080. Impacts are projected to be more in SWZ region than in SCZ and CZ. But, the yield loss due to rise in temperature is likely to be offset by projected increase in rainfall.	InfoCROP-SORGHAM	All India	A2A	HadCM3 GCM	Agriculture	**Naresh Kumar, Srivastava papers and Geethalaxmi’s paper faces the issues of Single climate model, Single Hydrological model, Lack of climate data downscaling. However Asseng Kumar et al 2014 as part of**

							AgMIP experiment used multi-model climate projections and also used multiple impact assessment models
Naresh kumar, 2013	The study suggests that climate change is likely to reduce irrigated rice yields by ~4 % in 2020 (2010–2039), ~7 % in 2050 (2040–2069), and by ~10 % in 2080 (2070–2099) climate scenarios. On the other hand, rain-fed rice yields in India are likely to be reduced by ~6 % in the 2020 scenario, but in the 2050 and 2080 scenarios they are projected to decrease only marginally (<2.5 %)	InfoCROP - RICE	All India	A1B, A2, B1 and B2	MIROC3 GCM Rupakumar et al (2006)	Agriculture	
Asseng et al. 2014	Assessed the uncertainty in simulating wheat yields under climate change. The sensitivity analysis suggests higher decline is wheat yields at higher temperature rises	27 different wheat Crop models	World, including India	A2	16 downscaled GCMs	Agriculture	
Geethalaxmi et al 2011	Geethalakshmi et al (2011) projected a decline of 356 Kg/ha/decade, in rice yield without considering the CO_2 fertilization effect for the PRECIS outputs, whereas the decline was 217 kg/ha/decade for RegCM3 outputs. However, when CO_2 fertilization effect was considered, the PRECIS output showed decreasing trend at the rate of 135 kg/ha/decade, whereas RegCM3 projected a modest increase in the yield (24 kg/ha/decade).	DSSAT		RegCM3	EH5OM GCM	Agriculture	
Masutomi et	Projects that under the climate change scenarios rice		Asia-wide	A1B and	Multiple	Agricult	

al 2009	yield will reduce over a large part of the continent and northern part of South Asia is found to be one of the most vulnerable regions.		including India	A2	GCMs	ure	
Ortiz et al 2008	Suggests that there will be a 51% decrease in the most favourable and high yielding wheat area due to heat stress – adversely impacting about 200 million people in Indo-Gangetic plains, much of this area lying under SARs	Wheat mega-environment classification	Indo-Gangetic plains	$2XCO_2$	Worldclim CCM3 downscaled	Agriculture	
	Based on extensive field sampling and historical data estimated the vegetation shift patterns for 124 endemic species in the Eastern Himalayan state of Sikkim, over the period 1849-1850 to 2007-2010. They estimated that 87% of the 124 endemic species showed geographical range shifts in response to observed warming experiencing a mean upward displacement rate of 27.53±22.04 meters per decade	Historical data and field sampling	Sikkim Himalaya	Historical data (1849-1850 to 2007-2010)		Forests	**The study is very interesting, however is not relevant for the SARs**
	Bala et al (2013) estimated an increasing NPP trend of 3.9% per decade over India. A multivariate linear regression analysis indicates that this increasing NPP trend is partly driven by increasing atmospheric CO2 concentration and the consequent CO2 fertilization of the ecosystems. However, human interventions such as increased irrigation and increased fertilizer use may have also played a key role in the NPP increase.		All India	Satellite based observation 1982-2006		Forests	**Due to lack of ground estimates extensive NPP observations from India the satellite based NPP is not validated for Indian region. Though its validated for many other regions of the world**
Ravindranath et al 2006	- Projected NPP to generally rise under climate change scenarios - Projected the impact of climate change on Indian	BIOME4-Equilibrium	All India	A2 and B2	Rupakumar et al 2006	Forests	**a) Lack observed climate change impacts, b)Single**

	forests and conclude that about 77% and 68% of the forest grids in India are likely to experience vegetation shift under the A2 and B2 scenarios of climate change respectively by 2080s						**Climate Model and Single Scenario, c) Climate Projections based on SRES scenarios, d) Single DGVM, e) Lack of species Level Assessment, f) Lack of integrated assessment at the landscape level, f)In sufficient representation of Nitrogen Cycle, Fire/ Pest dynamics in the DGVMs**
Chaturvedi et al 2011	Used a dynamic global vegetation modeling (DGVM) approach projected that about 39% to 45% of forest grids in India may not remain optimally suitable for the current vegetation by 2080s under A2 and B2 scenarios respectively. Projected NPP to generally rise under climate change scenarios.	IBIS - Dynamic	All India	A2 and B2	Rupakumar et al 2006	Forests	
Chitale and Behera, 2012	Looks at the possibility of shift of Sal (*Shorea robusta)* distribution to northern and eastern India under climate change. It identifies moisture as the key driver that would influence the distribution to shift towards northern and eastern India, with greater than 90% certainty.	Maxent software, version 3.3.3e	All India	A1B	Worldclim dataset	Forests	**The study finds moisture to be the key determinant of shift of Sal distribution, however GCM as well as RCMs have less confidence in rainfall**

							projections
Bhattacharya et al 2006	Bhattacharya et al (2006) suggests the central and eastern Indian regions covering Madhya Pradesh, Jharkhand, Chhatisgarh, Orissa, West Bengal and Assam to be the most endemic malaria regions under the current climate and project that under the climate change projections of HadRM2 "malaria is likely to persist in Orissa, West Bengal and southern parts of Assam, bordering north of West Bengal. However, it may shift from the central Indian region to the south western coastal states of Maharashtra, Karnataka and Kerala. Also the northern states, including Himachal Pradesh and Arunachal Pradesh, Nagaland, Manipur and Mizoram in the northeast may become malaria prone. The duration of the transmission windows is likely to widen in northern and western states and shorten in the southern states."	Simple Transmission Window method	All India	IS92a	HadRM2 (Unpublished)	Health	**Single climate model, single scenario, Malaria transmission is highly complex and depends on multiple factors other than climate.**
Dhiman et al 2011	The study projects that "some parts of Uttarakhand, Jammu and Kashmir and Arunachal Pradesh are likely to open transmission windows in new districts with increase in 4–6 months category of transmission".North-eastern states are projected to face an increase in the intensity of transmission from 7–9 months to 10–12 months. On the other hand, the eastern coastal districts see reduction in transmission months due to increased temperatures. No change is reported in Western Ghats.	Simple Transmission Window method	Western Ghats, Himalaya, Coastal regions, Northeast India	A1B	Krishnakumar et al 2011	Health	

3.9 Adaptation options and strategies to coping with the impacts

Adaptation is needed to prepare communities, regions, countries and societies for the consequences of climate change. Different impact assessment studies consider the issue of climate adaptation to different extents; some studies take a cursory look whereas others run simulations and tests for adaptation scenarios. Table 5 summarizes the adaptation options coming out from the key impact assessment studies in India.

Table 5: Adaptation options suggested for different sectors

ADAPTATION OPTIONS	KEY IMPACTS	STUDY	SECTOR
- Adaption options should be no different from the present day stresses. - Application of Integrated Water Resource Development at different levels (from households to catchments) - It concludes that the best adaptation option may to go in for artificial restoration of hydrological system by enhancement of water storage and infiltration	Decreased water availability in many of the semi-arid basins	Gosain et al 2006	**Water**
Do not prescribe specific adaptation options, rather sub-basin level model outputs for the whole country (**http://gisserver.civil.iitd.ac.in/natcom)** and users are urged to draw adaptation inferences at local levels	Decreased water yield in many of the river basins in the SARs areas	Gosain et al 2011	**Water**
Since the increase in surface run-off may be unevenly distributed across the seasons, there is a need to create storage space to smooth out the peaks in water availability throughout the year, otherwise the greater run-off volumes may present more difficulties, e.g. floodings	Increased water availability in Ganga basin	Fung et al 2011	**Water**
New wheat cultivars are needed to adapt the crop to changing environments	High yielding wheat area loss	Ortiz et al 20008	**Agriculture**
The study tested the impact of the following two low-cost adaptation options: a) change in variety and b) change in sowing Date. Adaptation strategies are found to yield positive results as these are projected to reduce the climate change impacts in both the monsoon and winter sorghum	Decreased yields of Sorghum under climate change scenarios	Naresh Kumar et al 2013	**Agriculture**
Suggest the following adaptation strategies - system of rice intensification, - using temperature tolerant cultivars - using green manures/biofertilizers for economizing water	Rice yield loss	Geethalakshmi et al 2011	**Agriculture**
Inclusion of climate change concerns in long term	Forest type shifts	Ravindranath et	**Forestry**

forest policy planning		al 2006	
Need to reduce forest fragmentation and need for anticipatory planting to cope with future climatic changes	Forest type shifts	Chaturvedi et al 2011	**Forestry**
Bala et al (2013) suggest that conservation efforts such as large scale afforestation, reforestation and forest conservation in India may have led to NPP increase in Indian forests over 1982-2006	NPP increase	Bala et al 2013	**Forestry**

ICRISAT data show that increases in temperature will have a significant (8-30%) reduction in grain yields of dryland crops. Consequently, farmers in the semi-arid tropics will have to adapt their farming practices to cope with the future environmental, social and economic constraints (Singh, N P and Bantilan, M C S, 2009).

3.9.1 Limitations in impact assessment studies

The IPCC (2014 WG2 Draft) identifies the following key limitations in the IVA literature in the Asia region:

1. Precipitation projections are an area of concern and improved projections for precipitation and water supply are most urgently needed for effective adaptation decision making.
2. More research is also needed on the health effects of changes in water quality and quantity.
3. Understanding the impacts of climate change on ecosystems and biodiversity in Asia is limited by the poor quality and low accessibility of biodiversity information.
4. In terms of the impact of climate change on terrestrial ecosystems, major research gaps remains in tropics in form of the studies on thermal tolerances and acclimation capacities of both plants and animals, and the direct impacts of rising CO_2.
5. Rice is the most studied crop but there are still significant uncertainties in model accuracy, CO_2-fertilization effects, and regional differences; for other crops, there is even greater uncertainty.

From our India specific assessment we note the following key limitations from the IVA studies conducted in the Indian region:

1. Lack of observed data
2. Lack of climate data downscaling for local level applications
3. Uncertainty in the precipitation projections are largely unaddressed
4. Overall uncertainty in the climate change impact projections are not coming out due to use of a single climate model, single scenario and single impact assessment model

5. Most of the impact assessment is based on mean climate, whereas climate extremes causes maximum damage
6. Modelling and projections of extreme precipitation events remains a challenge as a recent study by Mishra et al shows that even an ensemble of CORDEX models is not able to capture the extreme precipitation dynamics accurately
7. Most of our impact assessment models are coming from either Europe/US and these are tailor made for these regions,

3.9.2 Way forward; options for improving the IVA studies

Many of the limitations and uncertainties such as lack of observations cannot be addressed in a short term. However it is important that the uncertainty is adequately represented and acknowledged in the impact assessment studies. We suggest the following specific improvements for the future research to capture the full range of uncertainty in the impact assessments:

1. Use of multiple climate models and use of multiple impact assessment models: Global ISIMIP experiment provides a very good example for Indian impact assessment teams to emulate wherein the impact assessment is carried out using multiple climate models with multiple impact assessment models
2. Integrated modelling of the natural and production system: To date, almost all the modelling efforts in India has focussed exclusively on individual sectors, whereas in reality all the sectors (e.g. agriculture, forestry and water) co-exist and co-interact at the landscape level. It is desirable that these sectors are simulated in an integrated manner.

CHAPTER 4

References

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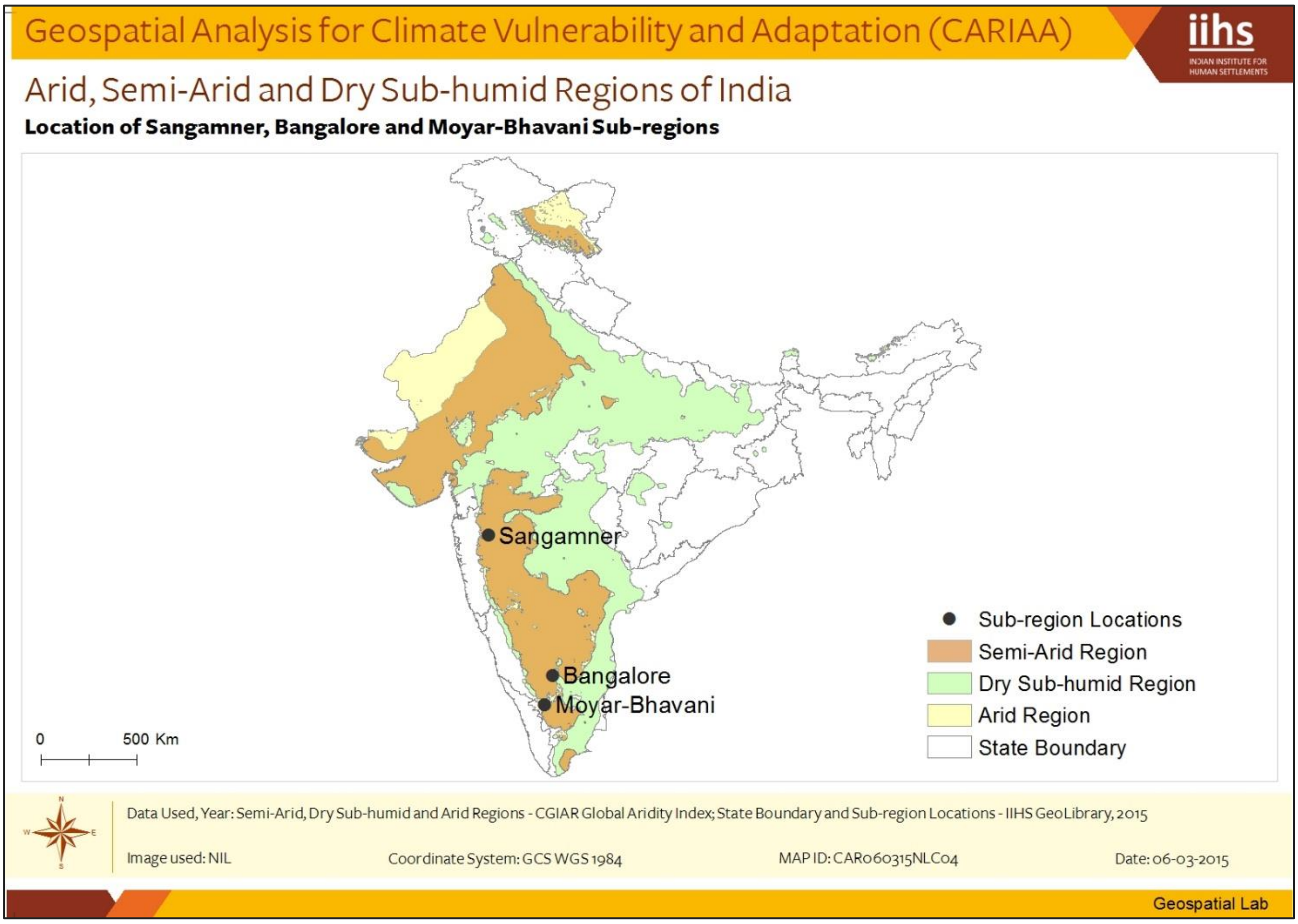
CHAPTER 5

Annexes

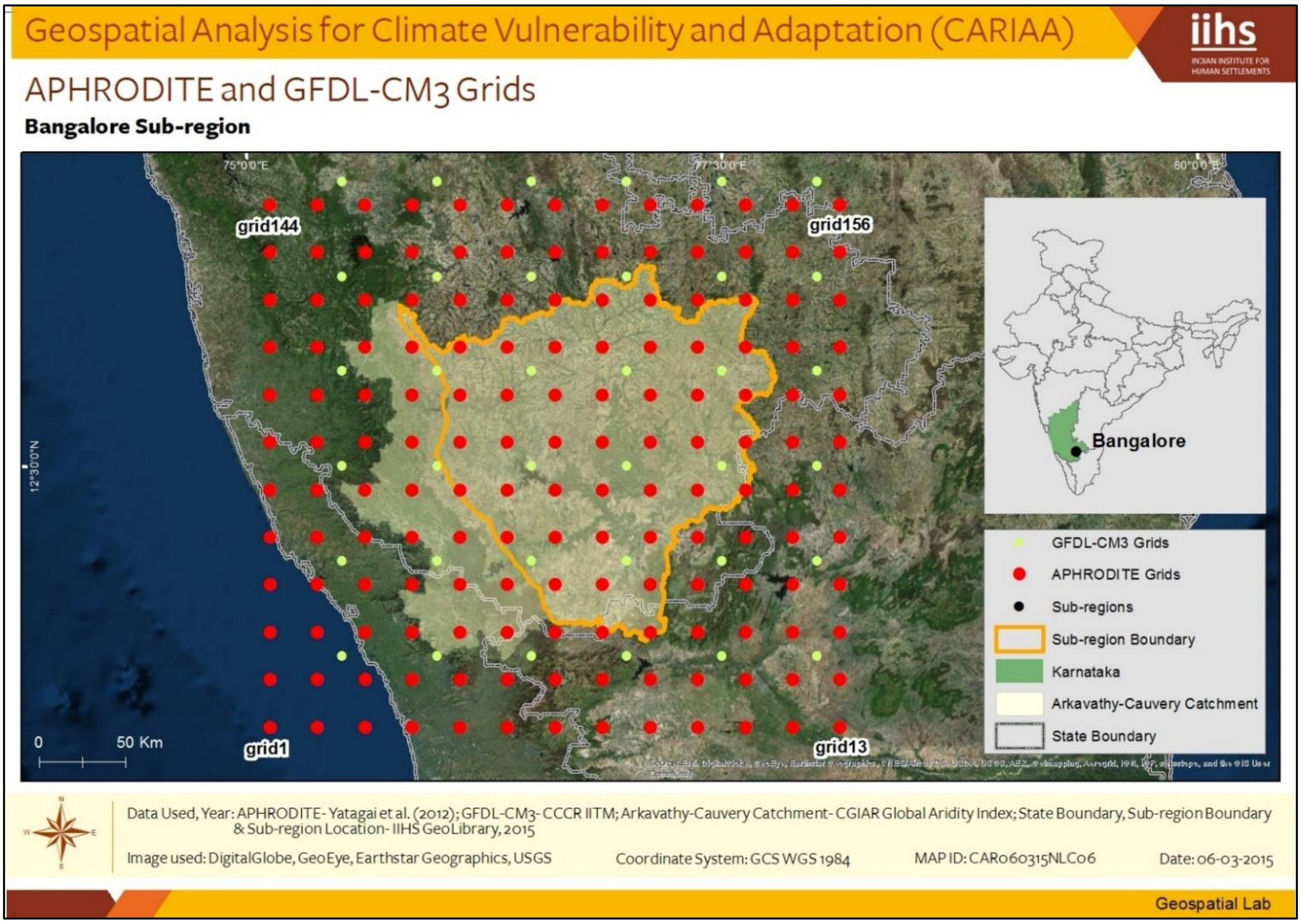
Annexure 1

Map depicting semi-arid regions in India and the three transects



Annexure 2

APHRODITE pixel corners (grids) used in the assessment of historical (1951-2007) precipitation trends in the Bangalore sub-region envelope. The watershed (WS), semi-arid region (SAR) and pixel corners of the CSIRO-GFDL CM3 climate model1 have been shown for illustrative purposes. Pixel corners located offshore were not included in this assessment.



Geospatial Analysis for Climate Vulnerability and Adaptation (CARIAA)

APHRODITE and GFDL-CM3 Grids

Bangalore Sub-region

Data Used, Year: APHRODITE- Yatagai et al. (2012); GFDL-CM3- CCCR IITM; Arkavathy-Cauvery Catchment- CGIAR Global Aridity Index; State Boundary, Sub-region Boundary & Sub-region Location- IIHS GeoLibrary, 2015

Image used: DigitalGlobe, GeoEye, Earthstar Geographics, USGS Coordinate System: GCS WGS 1984 MAP ID: CAR060315NLC06 Date: 06-03-2015

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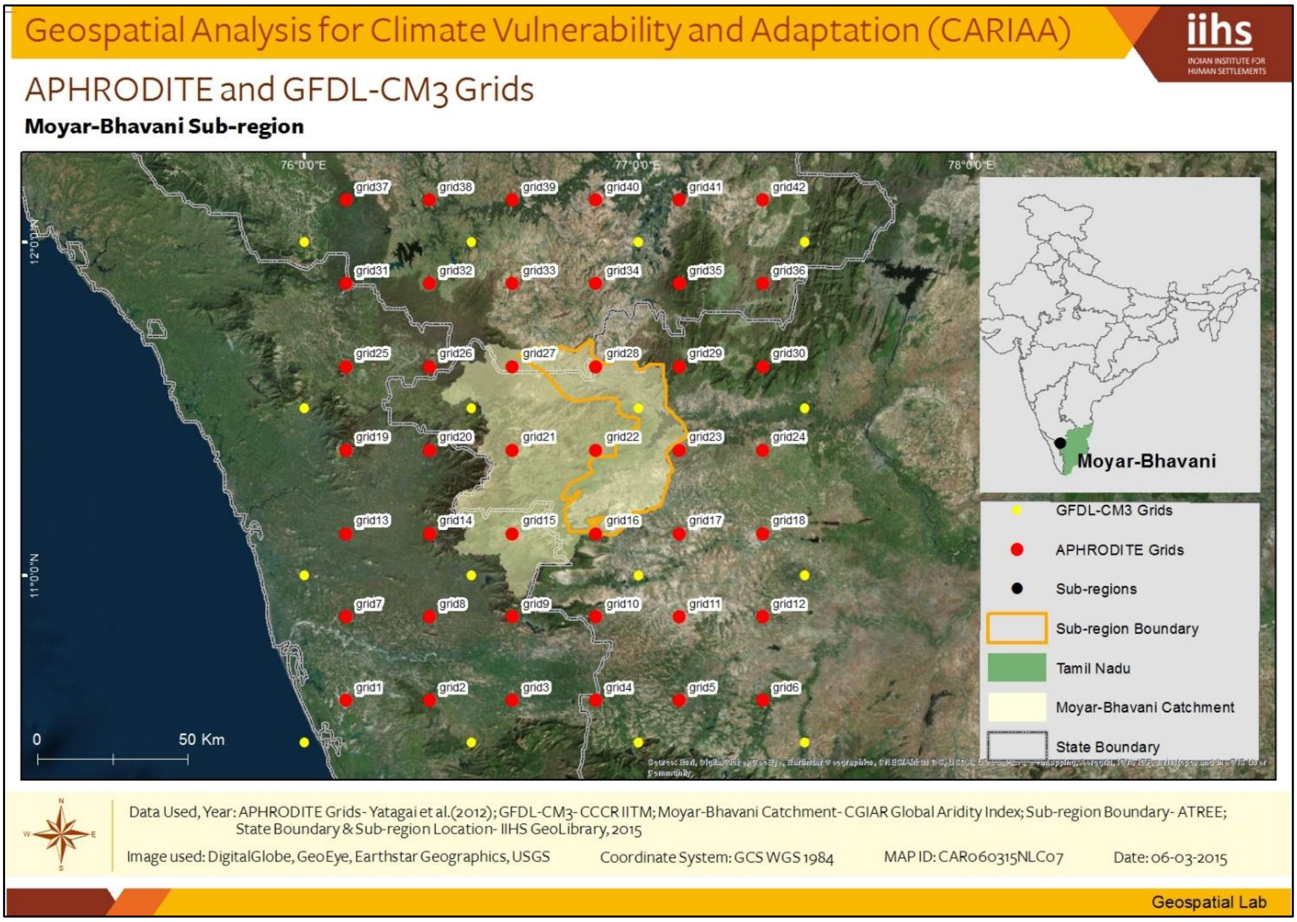
[1] The CSIRO GFDL-CM3 is a global coupled model developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) as a component of the Coupled Model Intercomparison Project-Phase 5 (CMIP5). For more detail please see: http://cmip-pcmdi.llnl.gov/cmip5/availability.html

Annexure 3

APHRODITE pixel corners (grids) used in the assessment of historical (1951-2007) precipitation trends in the Moyar-Bhavani sub-region envelope. The watershed (WS), semi-arid region (SAR) and pixel corners of the CSIRO-GFDL CM3 climate model (see footnote on previous page) have been shown for illustrative purposes.

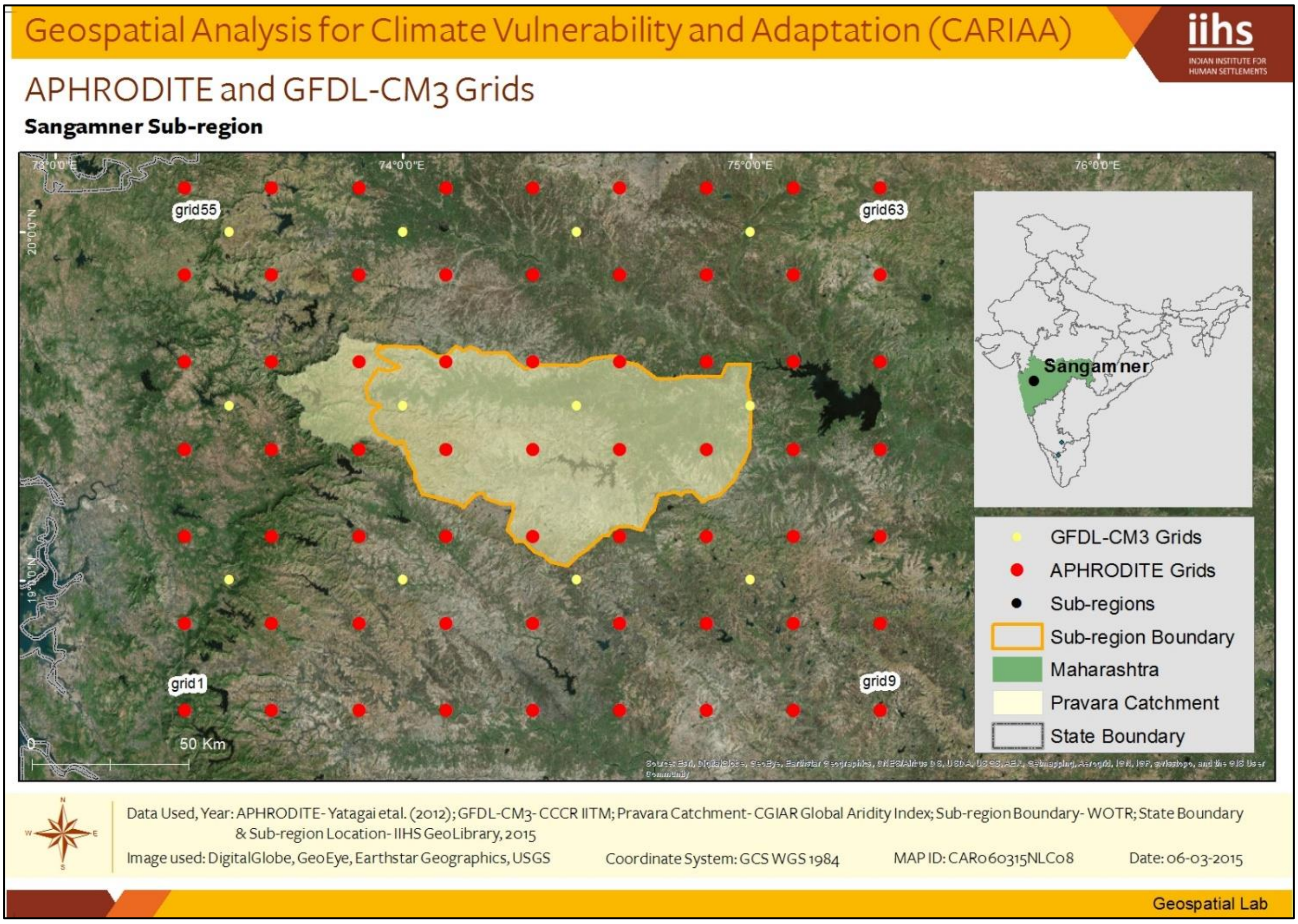


Data Used, Year: APHRODITE Grids- Yatagai et al.(2012); GFDL-CM3- CCCR IITM; Moyar-Bhavani Catchment- CGIAR Global Aridity Index; Sub-region Boundary- ATREE; State Boundary & Sub-region Location- IIHS GeoLibrary, 2015

Image used: DigitalGlobe, GeoEye, Earthstar Geographics, USGS Coordinate System: GCS WGS 1984 MAP ID: CAR060315NLC07 Date: 06-03-2015

Annexure 4

APHRODITE pixel corners (grids) used in the assessment of historical (1951-2007) precipitation trends in the Sangamner sub-region envelope. The watershed (WS), semi-arid region (SAR) and pixel corners of the CSIRO-GFDL CM3 climate model have been shown for illustrative purposes.



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APHRODITE and GFDL-CM3 Grids

Sangamner Sub-region

Data Used, Year: APHRODITE- Yatagai etal. (2012); GFDL-CM3- CCCR IITM; Pravara Catchment- CGIAR Global Aridity Index; Sub-region Boundary- WOTR; State Boundary & Sub-region Location- IIHS GeoLibrary, 2015

Image used: DigitalGlobe, GeoEye, Earthstar Geographics, USGS

Coordinate System: GCS WGS 1984

MAP ID: CAR060315NLC08

Date: 06-03-2015

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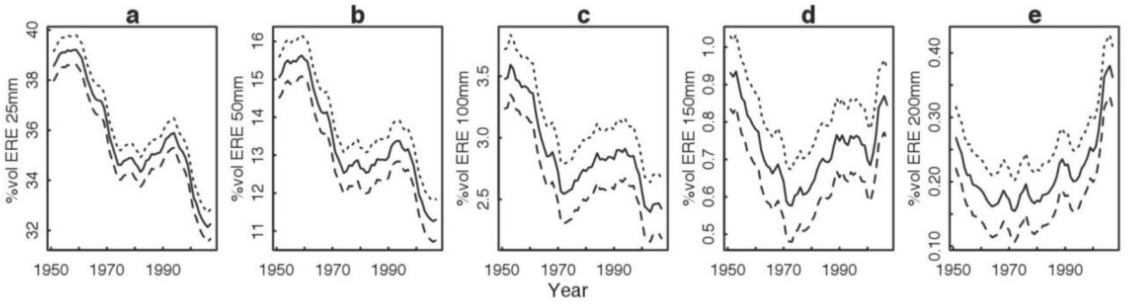
Annexure 5

Trends in percentage volume of rainfall (Jun-Nov) contributed by (a) 25 mm, (b) 50 mm, (c) 100mm, (d) 150mm and (e) 200mm extreme rain events (ERE) to the Indian monsoons (Krishnaswamy and Vaidyanathan unpublished).



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