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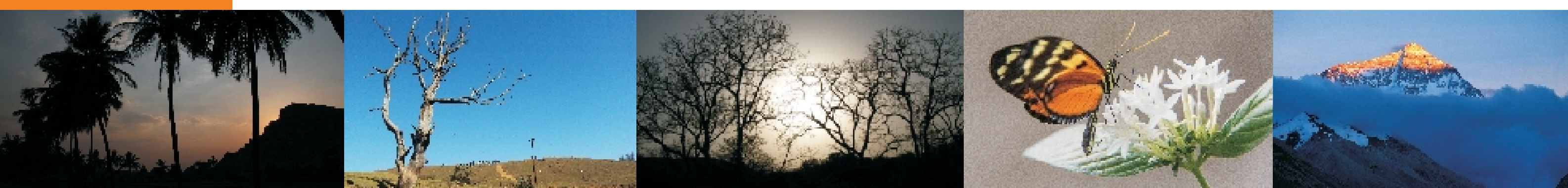
# Climate Change over INDIA

## An Interim Report




*Editors*

R. Krishnan, J. Sanjay

ESSO

Centre for Climate Change Research

ESSO-Indian Institute of Tropical Meteorology

Ministry of Earth Sciences, Govt. of India



**July 2017**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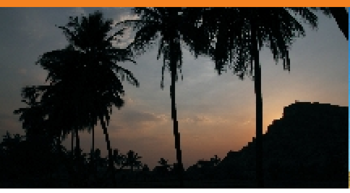

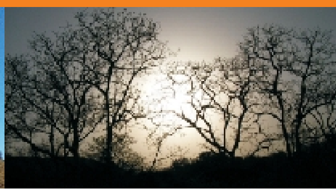
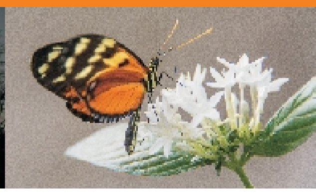
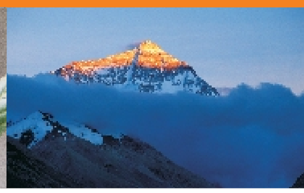

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# Climate Change over INDIA: An Interim Report

**Editors** R. Krishnan, J. Sanjay

**Cover Design and Layout** Abhay SD Rajput

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**Publication Date** July 2017

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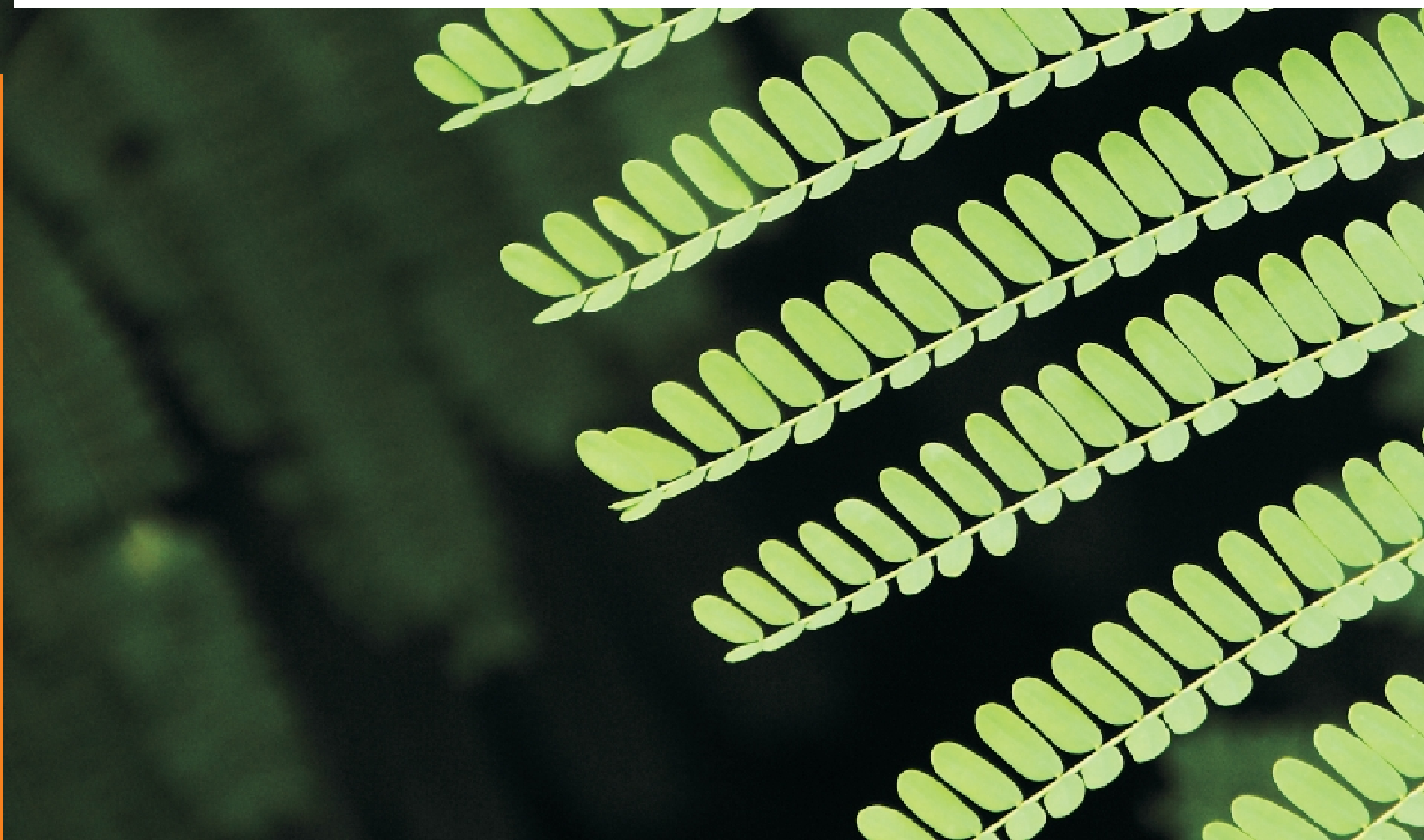
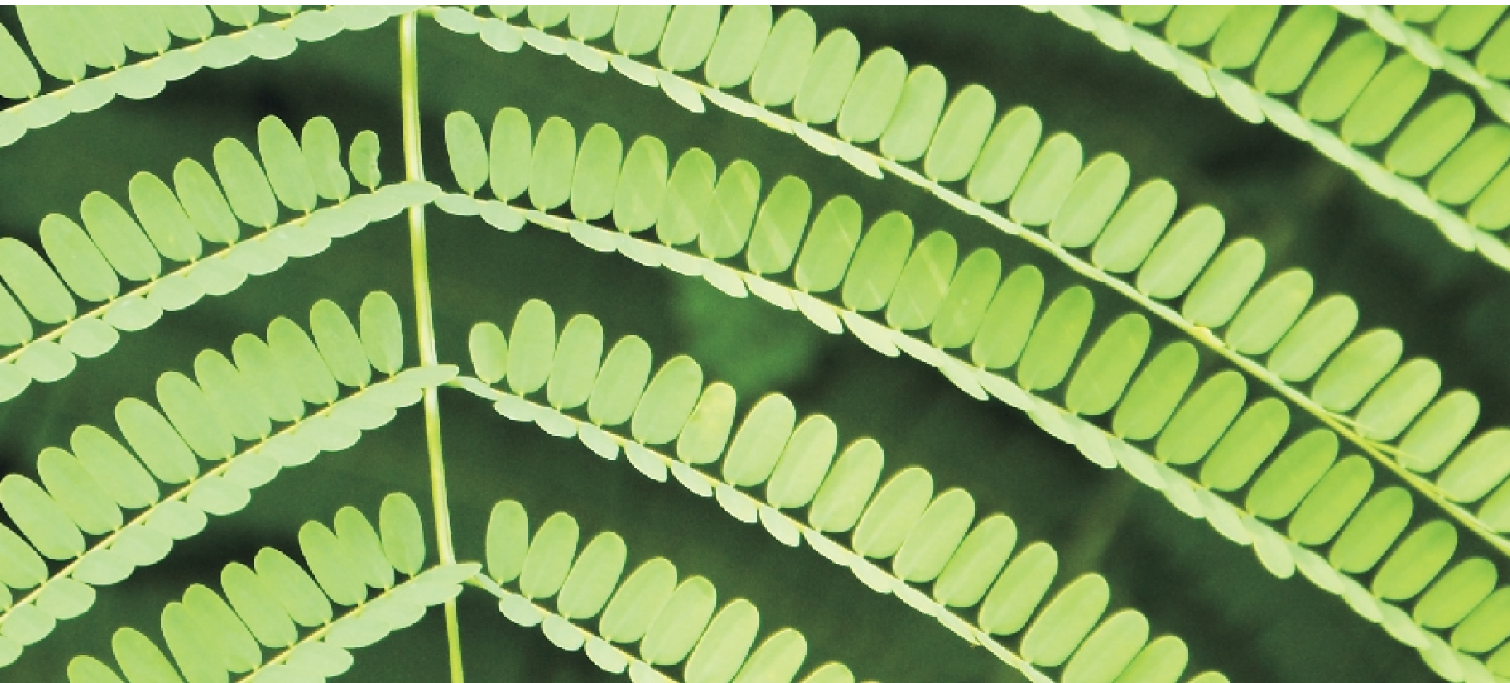


# Contents





# Introduction

Climate Change poses a major threat to the world today in view of its far-reaching implications for environment, agriculture, water availability, natural resources, ecosystems, biodiversity, economy and social well-being. The series of assessment reports of the United Nations Intergovernmental Panel on Climate Change (IPCC), with the Fifth Assessment Report (AR5) being the latest, provides clear scientific evidence to show that *"Human influence on the climate system is clear, and recent anthropogenic emissions of green-house gases (GHG) are the highest in history. Recent climate changes have had widespread impacts on human and natural systems. Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen (Climate Change 2013, IPCC)".*

As India pursues its development goals, there is need to balance social and economic imperatives with concerns on the front of climate variability and change. The Paris Agreement (2015) during the 21$^{st}$ Conference of Parties (COP21), called for Intended Nationally Determined Contributions (INDCs) to GHG emission reduction to limit global warming below 2°C and as close to 1.5°C as possible. In response, the Indian Government has ratified the deal in October 2016 for a reduction of emission intensity (emission per GDP) by up to 35% by 2030 relative to that in 2005, and create a terrestrial carbon sink of up to 3 Pg-CO2 (1 Pg = $10^{15}$ g) by 2030. The task of maintaining the necessary economic growth becomes even more pressing, given the country's dependence on climate-sensitive sectors such as agriculture and forestry. Pertinently, the National Action Plan on Climate Change outlines India's domestic plan for ecologically sustainable development. To tackle the grand challenging problems of global warming, it is essential to build human capacity in the country to address all fundamental issues relating to the science of climate change.

Although it is realized that increasing concentration of atmospheric GHGs over the last century has led to significant rise in the global mean surface temperature of the Earth, there are several uncertainties in understanding climate change and its impact at regional levels. Future climate projections over the Indian region based on the IPCC models, particularly the Indian monsoon rainfall which is the lifeline of the country, exhibit wide variations and uncertainties. Such uncertainties pose huge limitations in policy making for meeting the demands of adaptation to climate change. Advancing our understanding of the science of regional climate change requires a multidisciplinary and integrated approach. The challenges emanating from the rising trend of global warming have brought renewed focus on the fluctuating behaviour of monsoon in a changing climate.

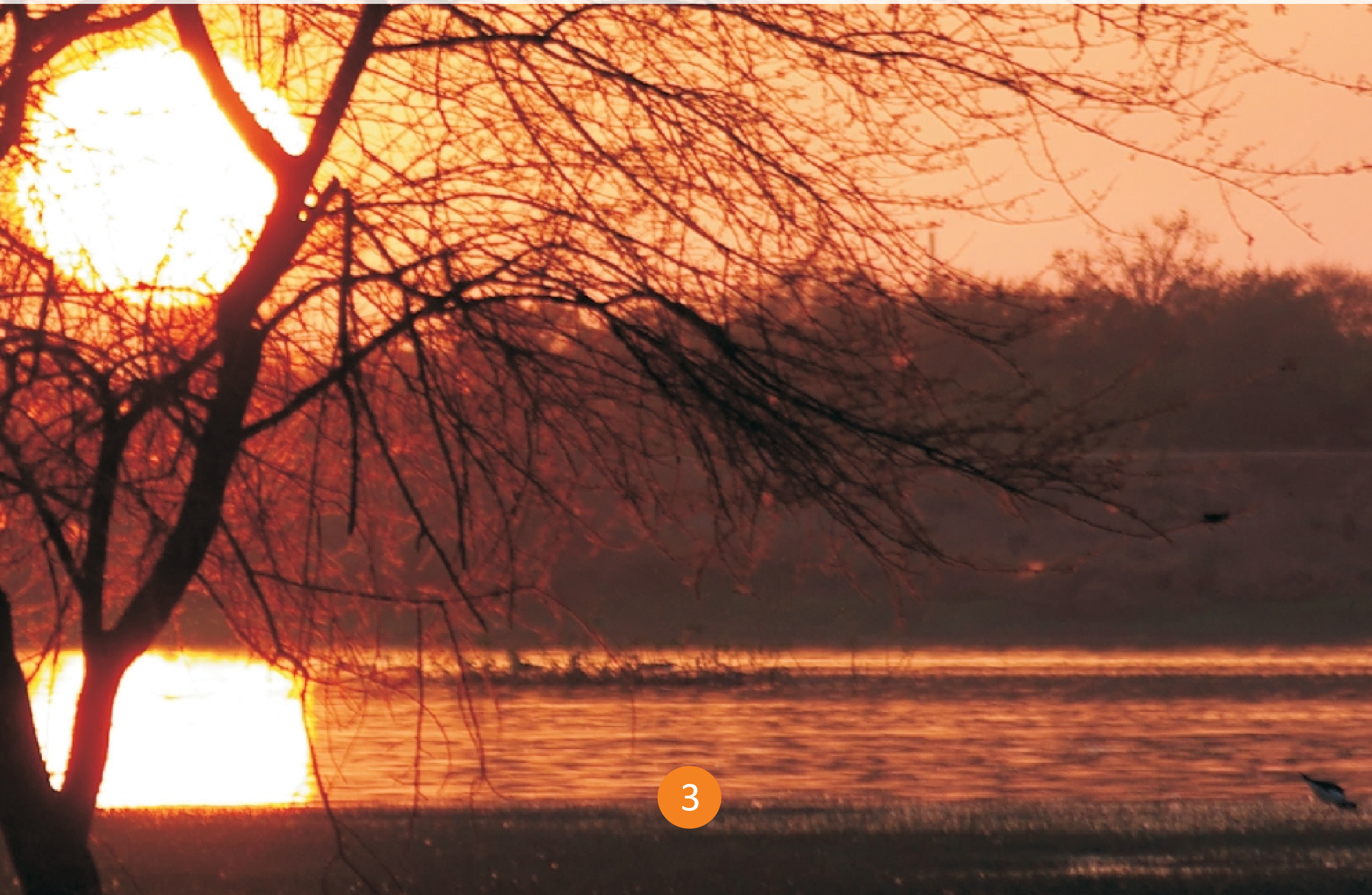
It is in this context that the role of the Centre of Climate Change Research (CCCR) becomes crucial. Launched in 2009 with the support of the Ministry of Earth Sciences (MoES), Government of India, the CCCR is part of the Indian Institute of Tropical Meteorology (IITM) located at Pune. The CCCR focuses on development of new climate modelling capabilities in India and South Asia to address issues concerning the science of climate change. This Interim Report on Climate Change over India is intended to provide a brief overview of ***(a)*** *Updated assessment of observed climate change over India* ***(b)*** *Future climate projections over India* ***(c)*** *Development of the IITM Earth System Model to better understand and quantify climate change and its regional impacts.* The three topics, which are among the core research activities of the CCCR at IITM, have been presented as three chapters in this Interim Report, and an updated report is planned to be submitted later next year.

Chapter 1

# Observed Climate Variability and Change over India

**Lead Author:** *Ashwini Kulkarni*
**Co-authors:** *Nayana Deshpande, D.R. Kothawale, S.S. Sabade, M.V.S. Ramarao, T.P. Sabin, Savita Patwardhan, M. Mujumdar and R. Krishnan*





## 1. Introduction

The recent IPCC report (AR5) has documented that there is unprecedented warming of the earth's atmosphere in last few decades, which can substantially impact the hydrological cycle and precipitation patterns over the globe. The global temperatures have shown an increase of 0.85° C during the period 1880-2012. The land temperatures over India have also shown unequivocal warming. The annual average temperatures over the Indian landmass have shown an increasing trend of about 0.6°C $(100 \text{ yrs})^{-1}$ during the period 1901-2010. The highest trend is observed in post monsoon season 0.79°C $(100 \text{ yrs})^{-1}$, and the lowest in the monsoon season 0.43° C $(100 \text{ yrs})^{-1}$.

Over the last thirty years there has been consistent warming over Indian landmass. It has been documented that the land-ocean thermal contrast and the monsoon circulation have weakened during the recent few decades, while the frequency of cyclonic disturbances, tropical cyclones and severe tropical cyclones has reduced over the Indian Ocean as well as Bay of Bengal during the monsoon and post monsoon seasons. The overall monsoon does not show any significant change mainly because the decreasing trend in moderate rain events has been compensated by an increasing trend in heavy rain events.

India receives almost 75% of the annual rainfall in the summer monsoon (southwest monsoon) season from June through September. The summer monsoon rainfall plays a vital role in agriculture, water resource management and power management. The survival of the large population as well as the economy of India depends highly on the quantity and distribution of rainfall received during the summer monsoon season. It depicts high variability on a variety of space-time scales, from diurnal to inter-annual to decadal. A large year-to-year variability is characterized by years of excess and deficit monsoons. Deficit monsoons have large adverse impact on crop production, while it is observed that good /excess monsoons do not compensate for the loss in crop yield during droughts. Hence, it is essential to examine the variability and changes in Indian rainfall based on the most recent data. This chapter provides a brief overview of the observed changes in temperature and precipitation over India. We also present analyses of extreme temperature and precipitation indices. Detailed descriptions of the observed climate variability and change over India are described in Rajeevan and Nayak (2016).

### Box 1.1 Data

*Gridded data from India Meteorological Department used in this chapter includes:*

- *The high resolution (1° x 1° long/lat) daily gridded maximum, minimum and mean temperature data for the period 1951-2015.*
- *The high resolution (0.25° x 0.25° long/lat) daily gridded precipitation data for the period 1951-2015.*

### Highlights

- *Annual mean, maximum and minimum temperatures averaged over the country as a whole show significant warming trend of 0.16°, 0.17° and 0.14° C per decade, respectively since 1981. Maximum warming trend is seen during the post-monsoon season. The annual average temperature over the Indian landmass has significantly increased in the region north of 20° N.*
- *The number of warm days and warm nights has significantly increased over the last 35 years.*
- *The annual as well as seasonal (June through September) monsoon rainfall over India shows significant decreasing trend over the core monsoon zone, north-eastern parts and southern parts of west coast.*
- *The total number of consecutive dry days with spell length more than five days has increased significantly, while the total number of consecutive wet days has shown significant decrease.*

## 2. Observed temperature and Rainfall variations

### 2.1. Temperature

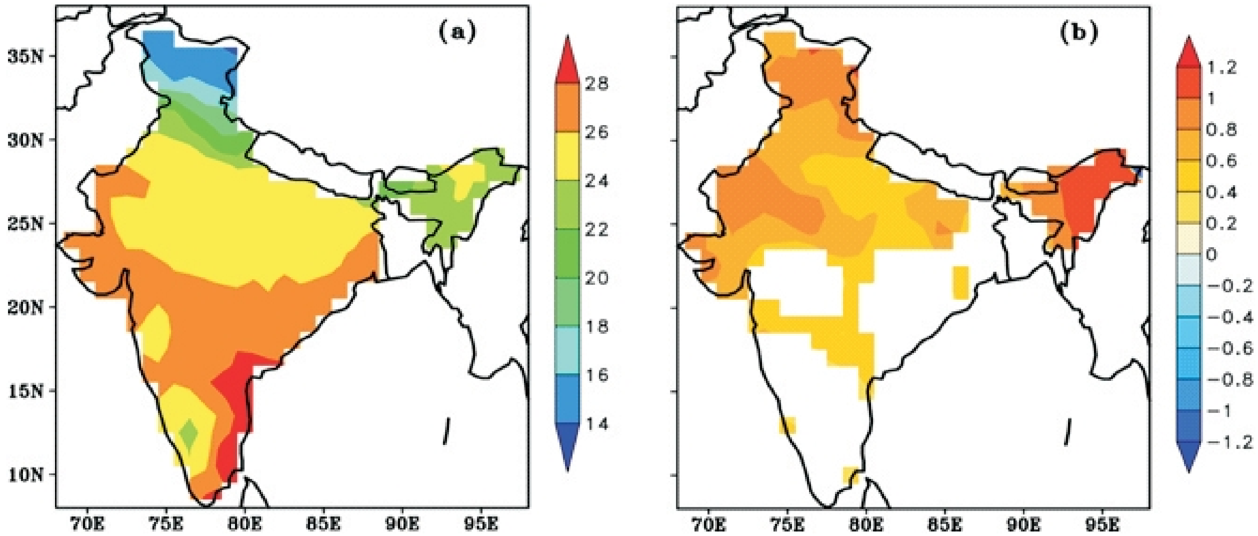



***Fig 1.1**: Spatial maps showing (a) Annual climatological mean temperature over the Indian landmass (b) Linear trend of annual temperature. The temperature data is for the period 1981-2015. Trends are expressed as change over 35 years and shading denotes significant trend. Note that the warming trends are significant in the region to the north of 20° N. Over northwest India the warming is more pronounced (~0.6°-1°C in the recent 35 years).*

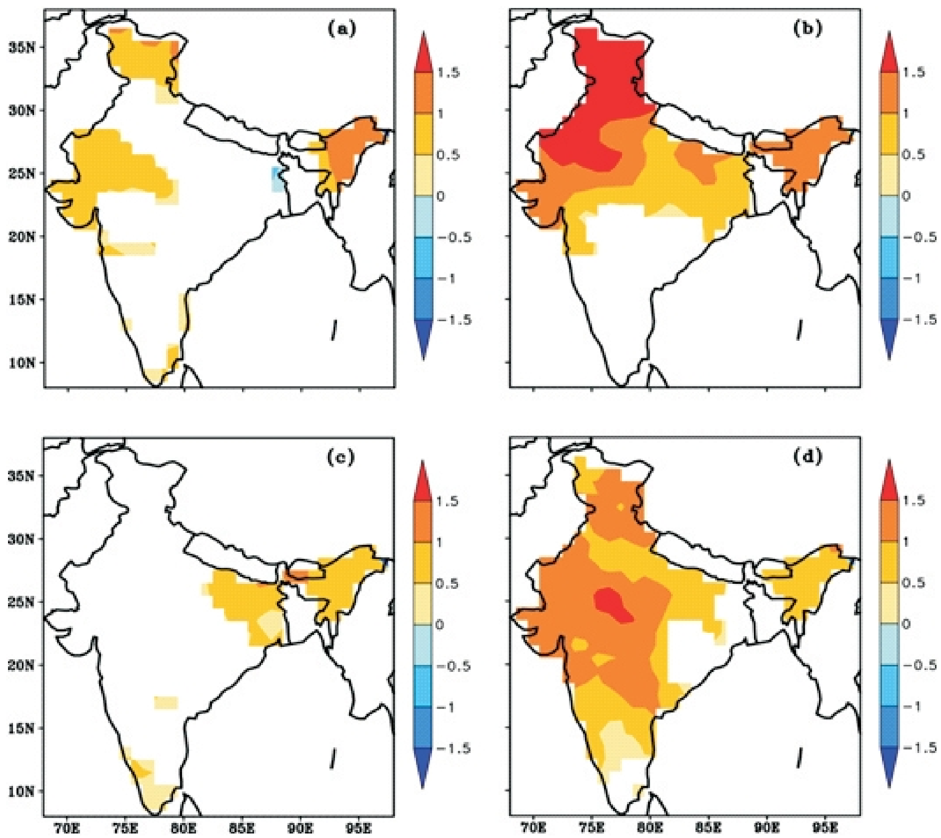



***Fig 1.2**: Spatial maps of linear trend in mean temperature for different seasons (a) Winter (Dec-Jan-Feb), (b) Pre-Monsoon (Mar-Apr-May), (c) Monsoon (Jun-Jul-Aug-Sep), (d) Post-Monsoon (Oct-Nov) during 1981-2015. Trends are expressed as change over 35 years and only significant grids are shaded. Note that maximum warming trends are observed during the pre-monsoon and post-monsoon seasons.*

***Table 1.1****: Trends in all-India average seasonal mean, maximum and minimum temperatures for two time periods 1951-2015 and 1981-2015 * indicates significance at 5% level.*

| | 1951-2015 | | | 1981-2015 | | |
|---|---|---|---|---|---|---|
| | Tmean | Tmax | Tmin | Tmean | Tmax | Tmin |
| Annual | 0.086 | 0.24 | -0.10 | 0.58* | 0.6* | 0.51* |
| DJF | -0.24 | -0.28* | -0.20 | 0.39* | 0.47* | 0.30* |
| MAM | -0.11 | 0.081 | -0.33* | 0.92* | 1.06* | 0.71* |
| JJAS | 0.24 | 0.53* | -0.076 | 0.37* | 0.32* | 0.38* |
| ON | 0.44* | 0.57* | 0.28* | 0.85* | 0.69* | 0.94* |

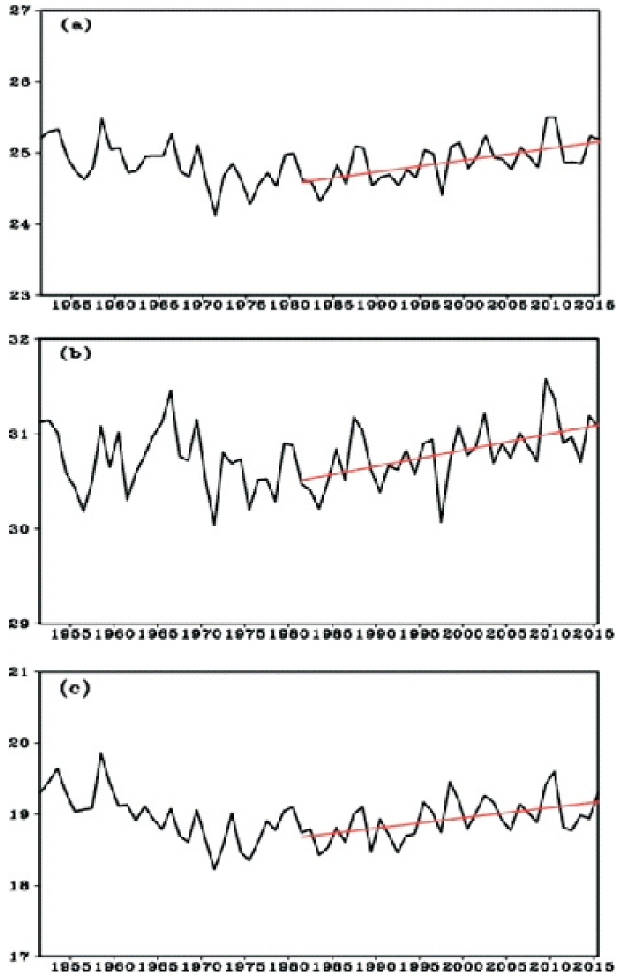



***Fig 1.3****: Time series of all-India averaged annual (a) Mean (b) Maximum (c) Minimum temperatures. The red line depicts linear trend based on 1981-2015. The trends in the mean, maximum and minimum temperatures for the period 1981-2015 are statistically significant with magnitudes corresponding to 0.58°C, 0.6°C and 0.5°C respectively. Season-wise trends in mean, maximum and minimum temperatures during the 35 year period are given in* ***Table 1.1****.*

## 2.2. Changes in temperature extremes

The Indian region experienced extreme weather events in recent years such as heat waves (Andhra Pradesh and Telangana, 2016); cold waves (Jammu and Kashmir, 2017), extremely heavy rain events (Mumbai, 2005, Uttarakhand 2013) and many others. These events happen to be more severe and more frequent in recent years, producing devastating impacts on human life, agriculture, water resources, health etc. In this section we examine changes and trends in some of the extreme indices.

The number of warm days averaged over the entire Indian landmass depict significant increasing trend ~ 4.5 days $(35\ years)^{-1}$ during the period 1981-2015, while the number of warm nights has also increased significantly ~ 3.5 days $(35\ years)^{-1}$ (Fig. 1.4). On the other hand, the number of cold days and cold nights do not show any significant trend (Fig. 1.4c, 1.4d). The occurrence of hot days and hot nights, particularly during the pre-monsoon (Mar-Apr-May) season, were significantly more during the recent 35 years as compared to the previous time epoch.

## 2.3. Precipitation

The climatological annual mean precipitation is of the order of 6-14 mm/day over west coast and northeastern parts of the country (Fig. 1.5a). Central India receives 4-6 mm/day, while the dry regions of northwest and peninsular India has only up to 3 mm/day. During summer monsoon season, central India is the core monsoon region which receives 6-12 mm/day. A significant decreasing trend in the summer monsoon precipitation is seen over the core monsoon region of north-central India and also over the west coast (Fig. 1.5d).

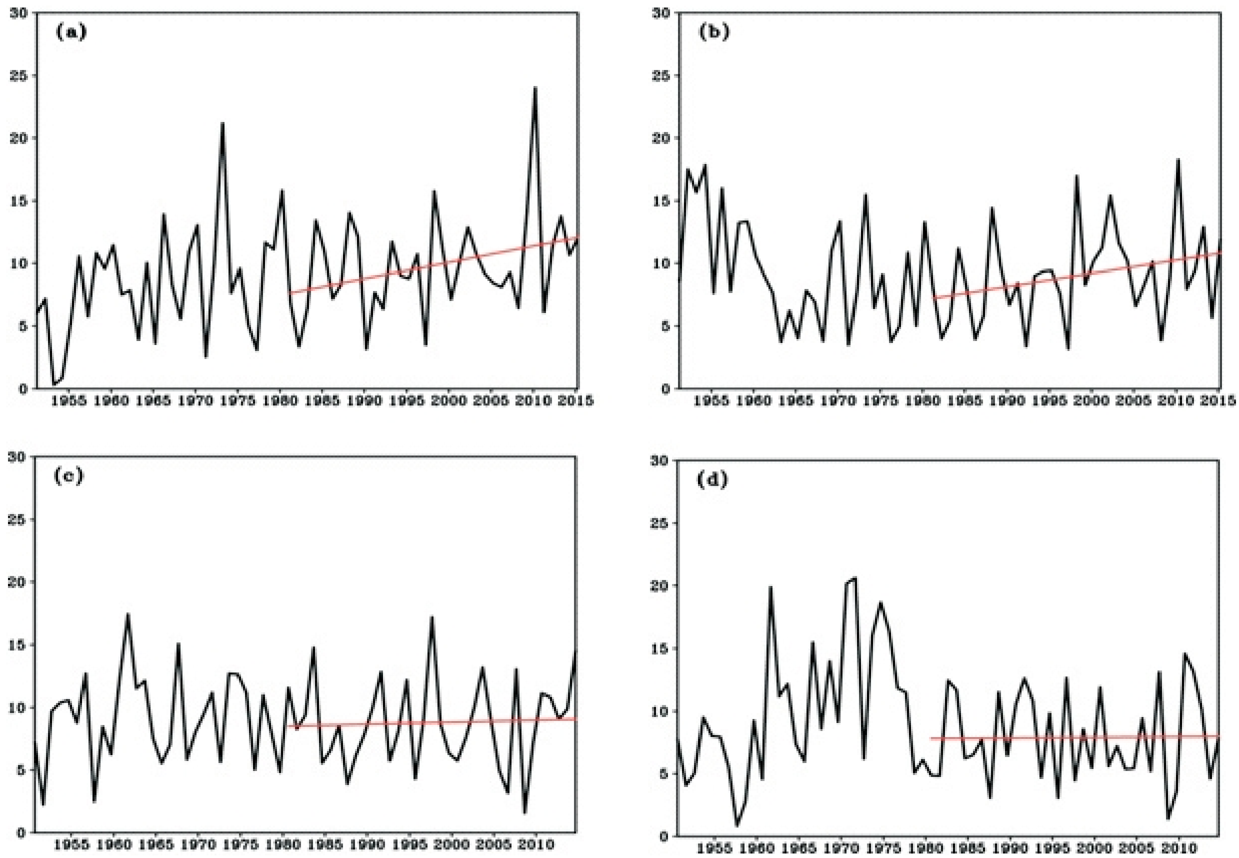



***Fig 1.4**: Inter-annual variability of (a) number of hot days and (b) hot nights during Mar-Apr-May and (c) cold days and (d) cold nights during Dec-Jan-Feb. The straight line indicates linear trend over 1981-2015.*

### Box 1.2 Temperature and precipitation extremes

*The Expert Team on Climate Change Detection and Indices (ETCCDI) defined a set of climate extreme indices based on daily maximum, minimum precipitation and temperature and daily precipitation amounts.*

*In this chapter, the temperature indices have been computed on $1^{\circ}$ x $1^{\circ}$ grid while the precipitation indices are computed on $0.25^{\circ}$ x $0.25^{\circ}$ grid based on the entire period 1951-2015.*

*To examine the observed changes and trend in extreme precipitation and temperature indices we select few from the 27 indices (see Table 1 in Sillmann et al. [2013]).*

*The percentile indices for temperature extremes considered are cold nights and days (during winter Dec-Jan-Feb) and warm nights and days (during Mar-Apr-May), which describe the threshold exceedance rate of days where minimum or maximum temperature is below the 10th or above the 90th percentile, respectively.*

*The extreme indices considered for precipitation are % contribution by moderate rain days (those between $70^{th}$ and $90^{th}$ percentile values) and by very heavy rain days (those exceeding $95^{th}$ percentile).*

*The number of consecutive dry-day index (CDD) represents the number of dry days (days with daily rainfall < 1 mm) in the spells where consecutive dry days are at least 5 (i.e., days with PR<1 mm) in a year. Similarly number of consecutive wet day index (CWD) is the number of wet days (days with daily rainfall > 1 mm) in the spells where consecutive wet days are at least 5 (ie days with PR > 1 mm) in a year.*

***Table 1.2**: Statistics for All-India rainfall.*

| | Winter | Pre-monsoon | Monsoon | Post-monsoon | Annual |
|---|---|---|---|---|---|
| Months | JF | MAM | JJAS | OND | |
| Mean (mm) | 36.4 | 128.5 | 858 | 119.1 | 1142.1 |
| % of Annual RF | 3.2 | 11.2 | 75.1 | 10.4 | 100 |
| Std Dev | 11.3 | 21.2 | 80.2 | 29.5 | 98.8 |
| CV(%) | 30.9 | 16.5 | 9.3 | 24.7 | 8.6 |
| Max RF (Year) | 59.3 (1954) | 209.2 (1990) | 1011.7 (1988) | 205.1 (1956) | 1359.6 (1990) |
| Min RF (Year) | 14.2 (1960) | 95.3 (1962) | 665.2 (1972) | 63.5 (2011) | 922.4 (1972) |

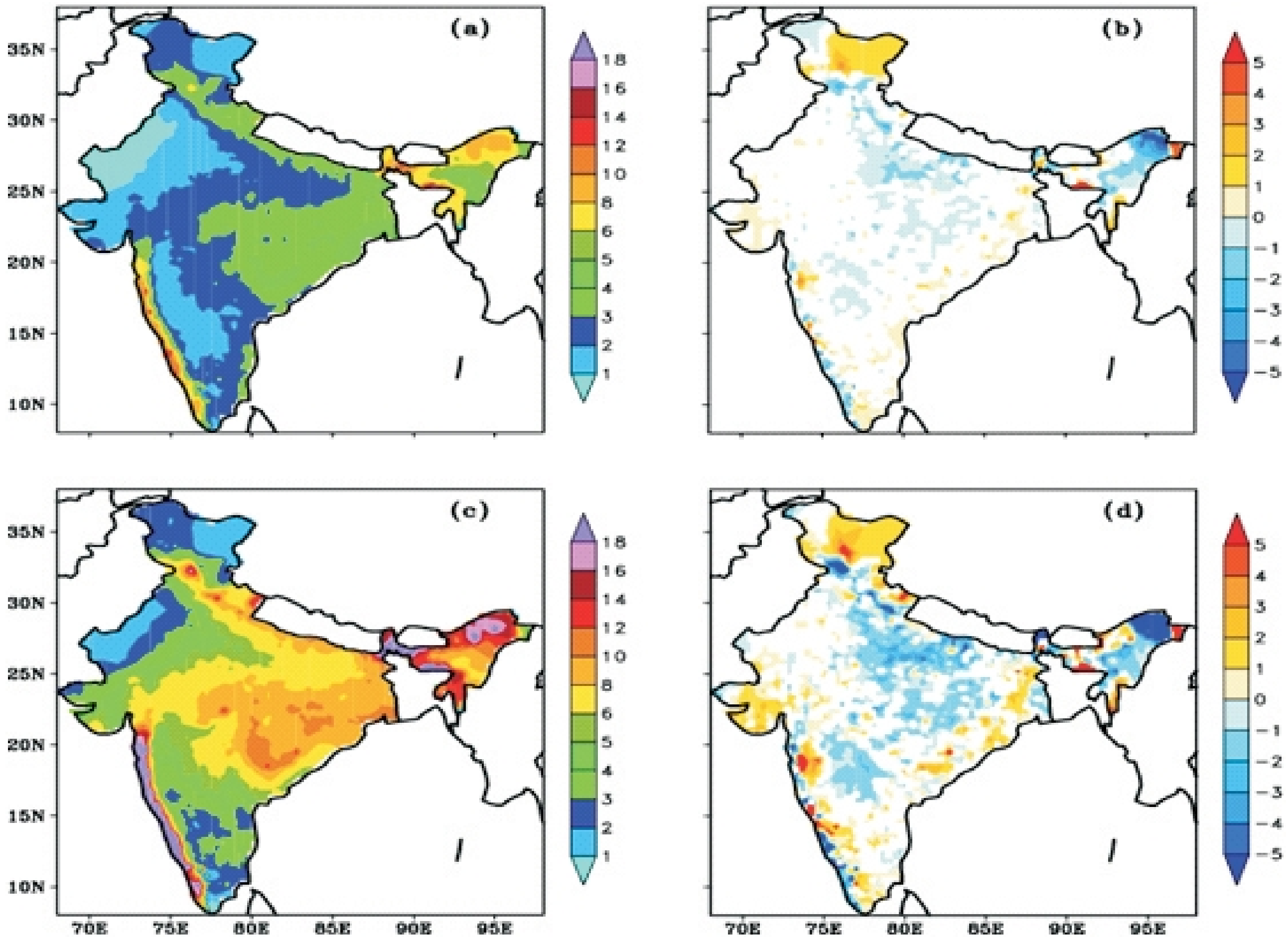



***Fig 1.5**: Spatial maps showing climatological mean and trends (a) Annual mean precipitation (b) Trend in annual precipitation (c) Jun-Jul-Aug-Sep (JJAS) precipitation (d) Trend in JJAS precipitation during the period 1951-2015. In (b) and (d), only statistically significant trends are shaded. The statistics for all-India rainfall for various seasons is given in Table 1.2.*

## 2.4. Changes in precipitation extremes

Here we present four extreme indices based on daily precipitation. The rainfall values between 70$^{th}$ and 90$^{th}$ percentile are said to be moderate and those more than 95$^{th}$ percentile are defined to be very heavy rain days. The moderate rainfall (%) shows significant decreasing trend over the 65 yr period (1951-2015) by approximately 10% (Fig. 1.6a), while the contribution due to very heavy rain days (Fig. 6b) shows a statistically significant increasing trend of around 4% in 65 years which is consistent with earlier studies (eg. Goswami et al 2006; Rajeevan et al. 2008).

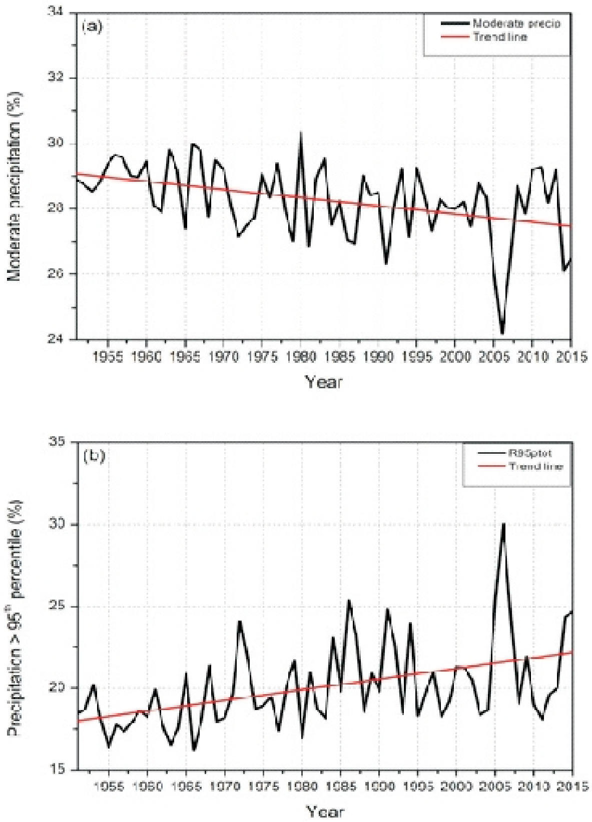



***Fig 1.6**: Time series of percentage contribution of (a) Moderate precipitation and (b) Very heavy precipitation to the total seasonal precipitation over central India. The red line shows the linear trend.*

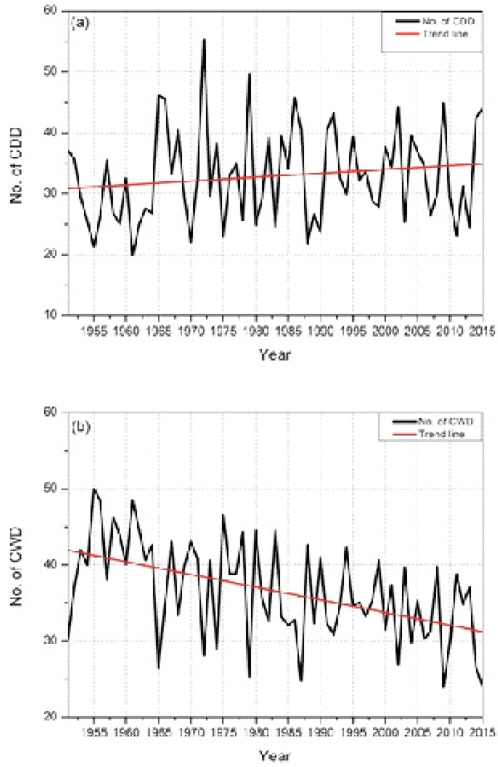



***Fig 1.7**: Time series of (a) number of dry days and (b) number of wet days with minimum spell length of 5 days over central India during JJAS. The red line shown linear trend. Note that the number of dry days with spell length at least five days exhibits an increasing trend. The number of consecutive dry days shows an increased by about 4 days in 65 years. The number of consecutive wet days with spell length more than five days shows a significant decrease of about 10 days in 65 years. Prolonged break (active) spell appear to be more (less) frequent in the last 65 years.*

## 3. References

Goswami BN, Venugopal V, Sengupta D, Madhusoodanan M.S, Xavier PK (2006) Increasing trend of Extreme Rain Events over India in a Warming Environment, ***Science***, 314, 5804, 1 December, 1442-1445.

Rajeevan M, Bhate J, Jaswal AK (2008) Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. Geophys Res Lett 35:L18707. doi:10.1029/2008GL035143

M.N. Rajeevan and S. Nayak (eds.) (2016) Observed Climate variability and change over the Indian region, Springer Geology, doi:10.1007/978-981-10-2531-0

Sillmann J, Kharin VV, Zwiers FW, Zhang X, Bronaugh D (2013) Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. J. Geophys. Res. Atmos., 118, 2473–2493, doi:10.1002/jgrd.50188.

Chapter 2

# Future Climate Change Projections over the Indian Region

**Lead Author:** *J. Sanjay*

**Co-authors:** *R. Krishnan, M.V.S. Ramarao, R. Mahesh, Bhupendra Singh, Jayashri Patel, Sandip Ingle, Preethi Bhaskar, J.V. Revadekar, T.P. Sabin, M. Mujumdar*

## 1. Introduction

Assessments of impacts of climate change and future projections over the Indian region, have so far relied on a single regional climate model (RCM) - eg., the PRECIS RCM of the Hadley Centre, UK. While these assessments have provided inputs to various reports (e.g., INCCA 2010; NATCOMM2 2012), it is important to have an ensemble of climate projections drawn from multiple RCMs due to large uncertainties in regional-scale climate projections. Ensembles of multi-RCM projections driven under different perceivable socio-economic scenarios are required to capture the probable path of growth, and provide the behavior of future climate and impacts on various biophysical systems and economic sectors dependent on such systems.

The Centre for Climate Change Research, Indian Institute of Tropical Meteorology (CCCR-IITM) has generated an ensemble of high resolution downscaled projections of regional climate and monsoon over South Asia until 2100 for the Intergovernmental Panel for Climate Change (IPCC)using a RCM (ICTP-RegCM4) at 50 km horizontal resolution, by driving the regional model with lateral and lower boundary conditions from multiple global atmosphere-ocean coupled models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The future projections are based on three Representation Concentration Pathway (RCP) scenarios (viz., RCP2.6, RCP4.5, RCP8.5) of the IPCC.

These high-resolution downscaled projections of regional climate over South Asia are generated as part of the International Programme called Coordinated Regional Downscaling Experiment (CORDEX) sponsored by the World Climate Research Programme. This chapter provides a synthesis of results from the CORDEX South Asia multi-RCM outputs, that allows us to interpret the strengths and limitations of future regional climate projections over India. This information is useful to reduce uncertainty of impact assessment estimates to an extent and provide a pan-Indian regional assessment for informed policy-making.

### Highlights

- *The all India mean surface air temperature change for the near-term period 2016–2045 relative to 1976–2005 is projected to be in the range of 1.08°C to 1.44°C, and is larger than the natural internal variability. This assessment is based on a reliability ensemble average (REA) estimate incorporating each RCM performance and convergence, and is associated with less than 16% uncertainty range (Table 2.1, Box 2.4).*
- *The all India mean surface air temperature is projected to increase in the far future (2066–2095) by 1.35 ± 0.23°C under RCP2.6, 2.41 ± 0.40°C under RCP4.5 and 4.19 ± 0.46°C under RCP8.5 scenario respectively. These changes are relative to the period 1976–2005. The semi-arid north-west and north India will likely warm more rapidly than the all India mean (Table 2.1, Fig. 2.1).*
- *Monthly increase in all India mean surface air temperature based on REA estimate is relatively higher during winter months than in the summer monsoon months throughout the 21$^{st}$ century under the three RCP scenarios (Fig. 2.3).*
- *The REA changes for all India annual minimum temperature of 4.43 ± 0.34°C is more pronounced than that of 3.94 ± 0.45°C and 4.19 ± 0.46°C increases estimated for the respective annual maximum and mean temperatures respectively the end of the 21st century under RCP8.5 scenario (Tables 2.1, 2.2 and 2.3).*
- *The models project substantial changes in temperature extremes over India by the end of the 21$^{st}$ century, with a likely overall decrease in the number of cold days and nights, and increase in the number of warm days and nights.*
- *Although the all India annual precipitation is found to increase as temperature increases, the REA assessment indicates that precipitation changes throughout the 21$^{st}$ century remain highly uncertain.*
- *The all India annual precipitation extremes are projected to increase with relatively higher uncertainty under RCP8.5 scenario by the end of the 21$^{st}$ century.*
- *The downscaled projections suggest that intensification of both dry and wet seasons is expected along the west coast of India and in the adjoining peninsular region.*

## 2. Future Projections of Climate over India

The focus of this chapter is on the summary of new and emerging knowledge since the IPCC AR5(IPCC 2013, 2014), with emphasis on material deriving from dynamical downscaling work under CORDEX South Asia (Sanjay et al., 2017), which is often of greater relevance for impact, adaptation and vulnerability (IAV) applications than the coarser resolution CMIP5 global climate model data used for AR5.The assessed downscaled historical and future projections of climate change till the end of the 21st century are based on six simulations with IITM-RegCM4 RCM and ten simulations with SMHI-RCA4 RCM for RCP4.5 and RCP8.5 scenarios (see list of CORDEX South Asia experiments in Table 2.1). While for RCP2.6 only a subset of available five simulations with SMHI-RCA4 runs are assessed. The changes are considered over the Indian land mass, by masking out the oceans and territories outside the geographical borders of India, and are expressed relative to the reference base line period: 1976–2005. The multi-RCM ensemble mean spatial patterns and all India averages are reported for the 30-year future periods: 2016–2045, 2036-2065 and 2066-2095 representing near-term, mid-term and long-term changes in future climate over India.

### 2.1 Projected Changes in Temperature

The projections of near-term change in the CORDEX South Asia multi-RCM ensemble mean annual mean surface air temperature relative to the reference period 1976-2005, show modest sensitivity to alternate RCP scenarios over Indian land area (see left panels of Fig. 2.1). The RCP2.6 scenario shows increase of less than 1°C over most of India except in some areas (eg.,Tamil Nadu in south and Jammu and Kashmir in north), where decreases of less than 1°C near-term change in surface temperature are projected. While under the RCP4.5 and RCP8.5 scenarios, the near-term changeshow similar increase of less than 2°C uniformly over the Indian land. The long-term projections of surface air temperature change over India for the end of 21st century are found to be dependent on the RCP scenarios (see right panels of Fig. 2.1). The geographical patterns of change for RCP2.6 scenario

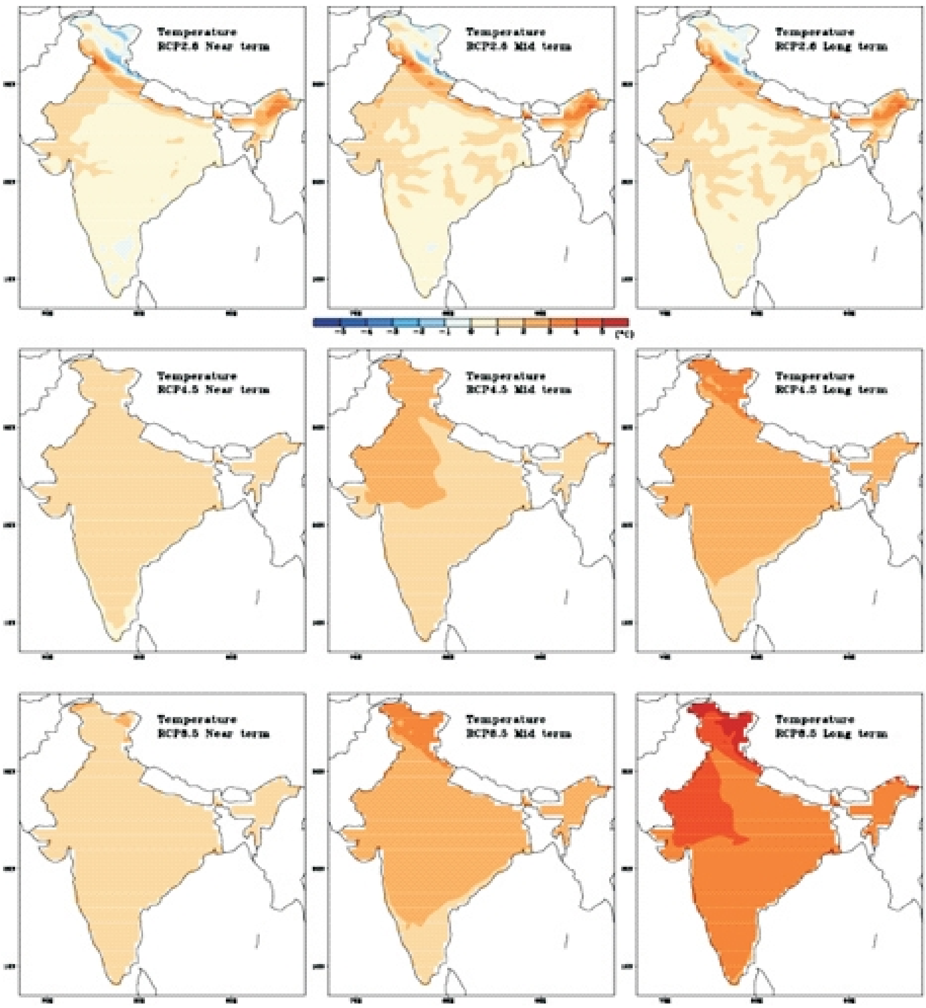



***Figure 2.1*** *CORDEX South Asia multi-RCM ensemble mean projections of annual average surface air temperature (°C) changes for near-term (2016-2045), mid-term (2036–2065) and long-term (2066–2095) climate under RCP2.6, RCP4.5 and RCP8.5 scenarios, relative to 1976–2005.*

**Table 2.1** List of the 16 CORDEX South Asia RCM simulations driven with 10 CMIP5 AOGCMs.

<table>
<tr><th>CORDEX South Asia RCM</th><th>RCM Description</th><th>Contributing CORDEX Modeling Center</th><th>Driving CMIP5 AOGCM (see details at https://verc.enes.org/data/enes-model-data/cmip5/resolution)</th><th>Contributing CMIP5 Modeling Center</th></tr>
<tr><td rowspan="6">IITM-RegCM4 (6 members)</td><td rowspan="6">The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4 (RegCM4; Giorgi et al., 2012)</td><td rowspan="6">Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM), India</td><td>CCCma-CanESM2</td><td>Canadian Centre for Climate Modelling and Analysis (CCCma), Canada</td></tr>
<tr><td>NOAA-GFDL-GFDL-ESM2M</td><td>National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory (GFDL), USA</td></tr>
<tr><td>CNRM-CM5</td><td>Centre National de RecherchesMe'te'orologiques (CNRM), France</td></tr>
<tr><td>MPI-ESM-MR</td><td>Max Planck Institute for Meteorology (MPI-M), Germany</td></tr>
<tr><td>IPSL-CM5A-LR</td><td>Institut Pierre-Simon Laplace (IPSL), France</td></tr>
<tr><td>CSIRO-Mk3.6</td><td>Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia</td></tr>
<tr><td rowspan="10">SMHI-RCA4 (10 members)</td><td rowspan="10">Rossby Centre regional atmospheric model version 4 (RCA4; Samuelsson et al., 2011)</td><td rowspan="10">Rosssy Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden</td><td>ICHEC-EC-EARTH</td><td>Irish Centre for High-End Computing (ICHEC), European Consortium (EC)</td></tr>
<tr><td>MIROC-MIROC5</td><td>Model for Interdisciplinary Research On Climate (MIROC), Japan Agency for Marine-Earth Sci. & Tech., Japan</td></tr>
<tr><td>NCC-NorESM1</td><td>Norwegian Climate Centre (NCC), Norway</td></tr>
<tr><td>MOHC-HadGEM2-ES</td><td>Met Office Hadley Centre for Climate Change (MOHC), United Kingdom</td></tr>
<tr><td>CCCma-CanESM2</td><td>CCCma, Canada</td></tr>
<tr><td>NOAA-GFDL-GFDL-ESM2M</td><td>NOAA, GFDL, USA</td></tr>
<tr><td>CNRM-CM5</td><td>CNRM, France</td></tr>
<tr><td>MPI-ESM-LR</td><td>MPI-M, Germany</td></tr>
<tr><td>IPSL-CM5A-MR</td><td>IPSL, France</td></tr>
<tr><td>CSIRO-Mk3.6</td><td>CSIRO, Australia</td></tr>
</table>

remain below 2°C above 1976-2005 levels over most parts of India throughout the 21st century, where the forced signal is typically smaller than the internal variability of the climate system (see top panels of Fig. 2.1). The multi-RCM ensemble mean annual mean surface air temperature mid-term change exceeds 2°C over the north-west and north India for RCP4.5 scenario, while in the long-term the change for this mid-scenario exceeds 2°C over most parts of India except the southern tip of the Indian peninsula (see middlepanels of Fig. 2.1). The spatial pattern and magnitude of the projected mid-term warming for the RCP8.5 scenario resembles that of the long-term change for the RCP4.5 scenario (see bottompanels of Fig. 2.1). The projected annual warmingexceeding 3°C over entire India is more rapid for this high-emission scenario by the end of 21st century, with relatively higher change exceeding 4°C projected in the semi-arid north-west and north India (see bottom right panel of Fig. 2.1).

The all India averaged annual surface air temperature anomalies(relative to 1976–2005) based on the India Meteorological Department (IMD) 1°longitude-latitude gridded data show steady long-term warmingwith interannual variations for the period 1970-2015 (Fig. 2.6). The CORDEX South Asia historical RCM simulations capture the observed the interannualvariationsand the warming trend reasonably well.A consistent and robust feature across the downscaled CORDEX South Asia RCMs is a continuation of warming over India in the 21st century for all the RCP scenarios (Fig. 2.2).The all India averaged annual surface air temperature increases are almost the same for all the RCPscenarios during the first decade after 2005.The warming rate depend more on the specified green house gas concentration pathway at longer time scales, particularly after about 2050. The multi-RCM ensemble mean under RCP2.6 scenario stays around 1.5°C above 1976-2005 levels throughout the 21st century, clearly demonstrating the potentialof mitigation policies.The ensemble mean annual India warming exceeds 2°C within the 21st century under RCP4.5, and the warming exceeds 4°C by the end of the 21st century under RCP8.5 scenario.The spread in the minimum to maximum range in the projected warming among the CORDEX South Asia RCMs for each RCP scenario (shown as shading in Fig. 2.2) provide a simple, but crude, measure of uncertainty.

A reliability ensemble averaging (REA) technique is used to provide a quantitative estimate of the associated uncertainty range of future climate change projections for India simulated by the RCMs under CORDEX South Asia.The viability of REA methodology in providing realistic future CMIP5 projections of the Indian summer monsoon by incorporating model performance and model convergence criteria was demonstrated by Sengupta and Rajeevan (2013) for two main variables, surface air temperature and precipitation. The results of applying REA methodology to the CORDEX South Asia multi-RCMs all India averaged annual surface air temperature changes under the three different RCP scenarios are summarized in Table 2.2.

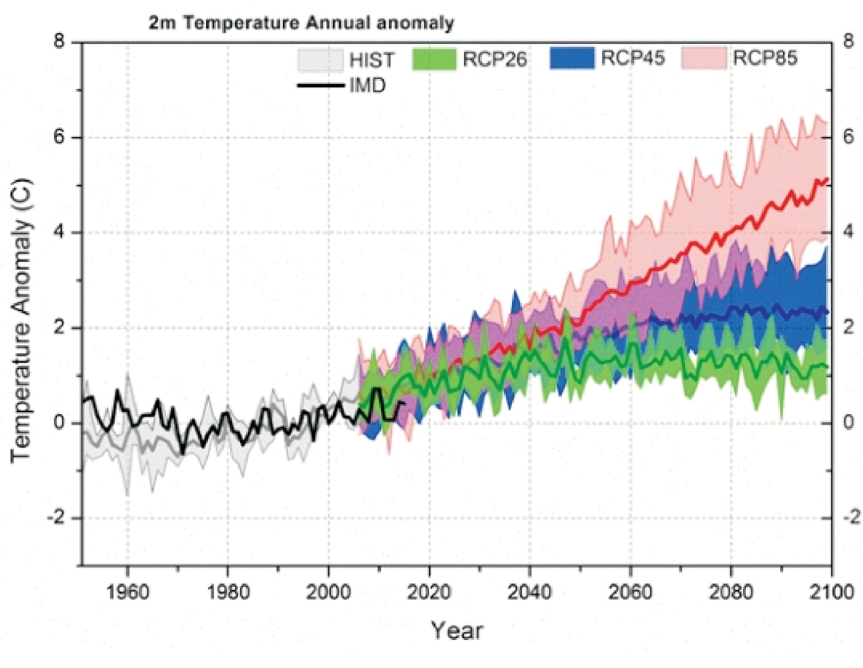



***Figure 2.2*** *Time series of Indian annual mean surface air temperature (°C) anomalies (relative to 1976–2005) from CORDEX South Asia concentration-driven experiments. The historical simulations (grey) and the downscaled projections are shown for RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red) scenarios for the multi-RCM ensemble mean (solid lines) and the minimum to maximum range of the individual RCMs (shading). The black line shows the observed anomalies during 1951-2015based on IMD gridded data.*

**Table 2.2** CORDEX South Asia multi-RCM reliability ensemble average (REA) estimate of projected changes in annual mean surface air temperature over India and the associated uncertainty range. The values in parenthesis show the uncertainty in percent for the REA estimate.

| Scenario | Annual Mean Temperature ( °C) | | |
|---|---|---|---|
| | 2030s | 2050s | 2080s |
| RCP2.6 | 1.08 ± 0.12 *(11.1%)* | 1.35 ± 0.18 *(13.3%)* | 1.35 ± 0.23 *(17.0%)* |
| RCP4.5 | 1.28 ± 0.20 *(15.6%)* | 1.92 ± 0.28 *(14.6%)* | 2.41 ± 0.40 *(16.6%)* |
| RCP8.5 | 1.44 ± 0.17 *(11.8%)* | 2.41 ± 0.28 *(11.6%)* | 4.19 ± 0.46 *(11.0%)* |

The REA near-term (2016-2045) warming are almost the same for all the RCP scenarios ranging between 1.08-1.44°C. The natural variability (computed following Sengupta and Rajeevan (2013)) in the observed all India annual mean surface air temperature (based on IITM India averaged monthly data) is 0.347°C, while the REA based temperature increases are well above this natural variability estimate. The uncertainty range defined by the root mean square difference varies in the near-term between 0.12°C to 0.20°C for the three RCP scenarios, with the RCP4.5 near-term warming of 1.28°C indicating the maximum uncertainty of 15.6% . The proper weighting of individual CORDEX South Asia RCMs based on their present day performance by the REA method has resulted in the REA warming under RCP2.6 scenario to be 1.35°C above 1976-2005 levels till the end of 21st century, which is lesser than that defined by multi-RCM ensemble mean shown in Fig. 2.2. However this estimate of annual warming well below 2°C by the end of 21st century for RCP2.6 is found to be associated with the highest uncertainty of 17% among all the RCP scenarios. The REA estimates of long-term (2066-2095) warming are 2.41±0.40°C and 4.19 ± 0.46°C under RCP4.5 and RCP8.5 scenarios respectively. The assessment of 4.19°C warming by the end of the 21st century under RCP8.5 scenario is highly reliable as it is associated with the lowest uncertainty (of 11%) among the three RCP scenarios.

The REA estimate of projected monthly changes for the CORDEX South Asia multi-RCMsof all India averaged monthly surface air temperature relative to the reference period 1976-2005 indicate relatively higher seasonal warming during winter months than in the summer monsoon months (Fig. 2.3). The annual cycle of the near-term change show least sensitivity to alternate RCP scenarios over Indian land area (see left panels of Fig. 2.3).The long-term monthly change over India for the end of 21st century show distinct annual cycle, particularly for the RCP8.5 scenario (see right panels of Fig. 2.3). The REA monthly change estimates are higher (lower) than the annual values (Table 2.2) in January (July) for the mid-term and long-term periods under the three RCP scenarios. The associated uncertainty range for the REA monthly changes (shading in Fig. 2.3) is seen to steadily increase from near-term to long-term, with the highest values for each month by the end of the 21st century under RCP8.5 scenario.

The forced signal of warming occurs not only in the annual mean of daily mean surface air temperature, but also in the annual means of daily maximum and daily minimum temperatures. The results of applying REA technique to the CORDEX South Asia multi-RCMs all India averaged annual means of daily maximum and daily minimum surface air temperature changes under the three different RCP scenarios are summarized in Table 2.3 and Table 2.4 respectively.

**Table 2.3** CORDEX South Asia multi-RCM reliability ensemble average (REA) estimate of projected changes in annual mean of daily maximum temperature over India and the associated uncertainty range. The values in parenthesis show the uncertainty in percent for the REA estimate.

| Scenario | Annual Maximum Temperature ( °C) | | |
|---|---|---|---|
| | 2030s | 2050s | 2080s |
| RCP2.6 | 0.99 ± 0.11 *(11.1%)* | 1.26 ± 0.16 *(12.7%)* | 1.27 ± 0.20 *(15.7%)* |
| RCP4.5 | 1.26 ± 0.20 *(15.9%)* | 1.81 ± 0.27 *(14.9%)* | 2.29 ± 0.36 *(15.7%)* |
| RCP8.5 | 1.36 ± 0.16 *(11.8%)* | 2.30 ± 0.31 *(13.5%)* | 3.94 ± 0.45 *(11.4%)* |

**Table 2.4** CORDEX South Asia multi-RCM reliability ensemble average (REA) estimate of projected changes in annual mean of daily minimum temperature over India and the associated uncertainty range. The values in parenthesis show the uncertainty in percent for the REA estimate.

| Scenario | Annual Minimum Temperature ( °C) | | |
|---|---|---|---|
| | 2030s | 2050s | 2080s |
| **RCP2.6** | 1.16 ± 0.17 *(14.7%)* | 1.44 ± 0.24 *(16.7%)* | 1.35 ± 0.25 *(18.5%)* |
| **RCP4.5** | 1.36 ± 0.18 *(13.2%)* | 2.14 ± 0.28 *(13.1%)* | 2.63 ± 0.38 *(14.4%)* |
| **RCP8.5** | 1.50 ± 0.16 *(10.7%)* | 2.60 ± 0.23 *(8.8%)* | 4.43 ± 0.34 *(7.7%)* |

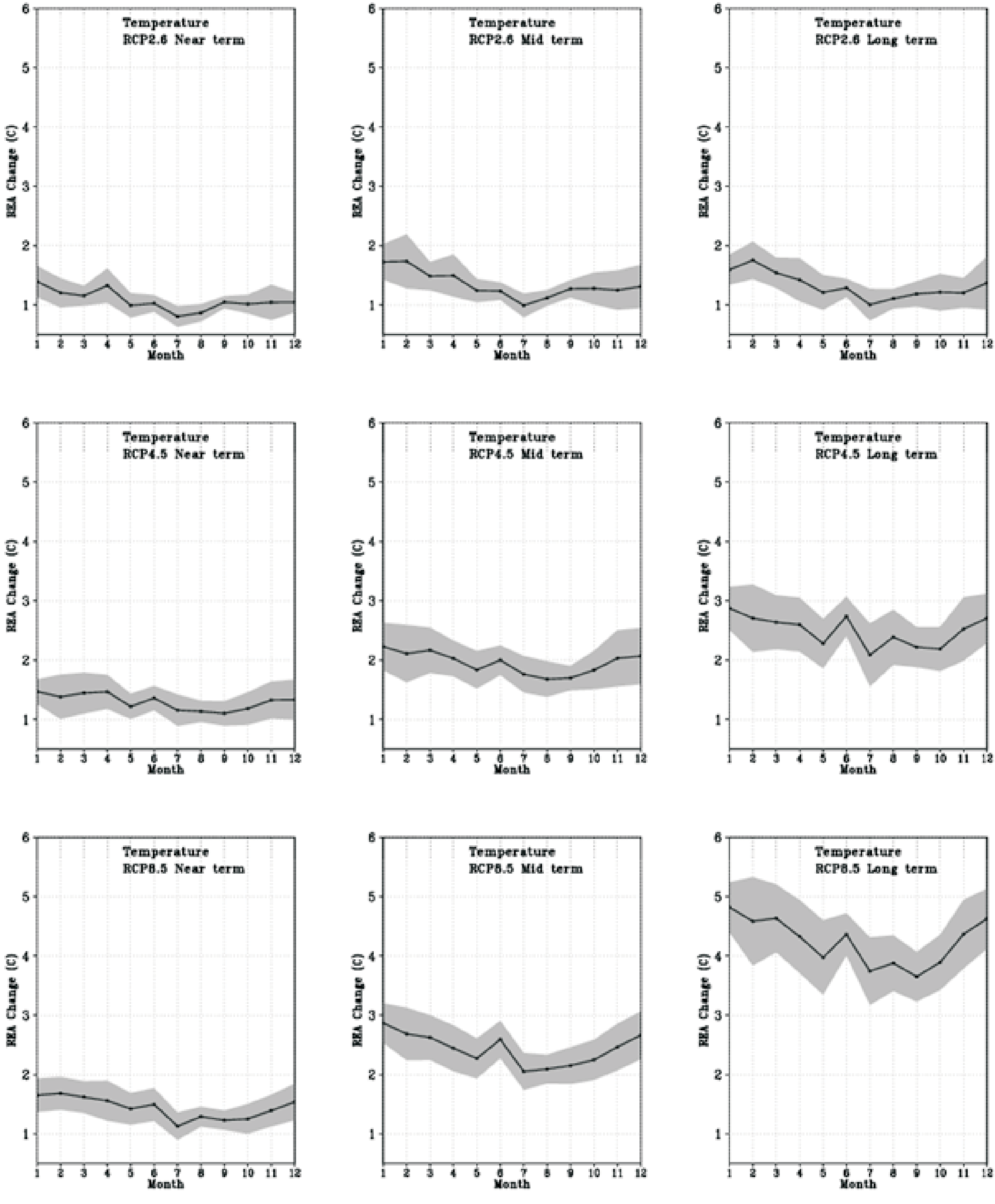
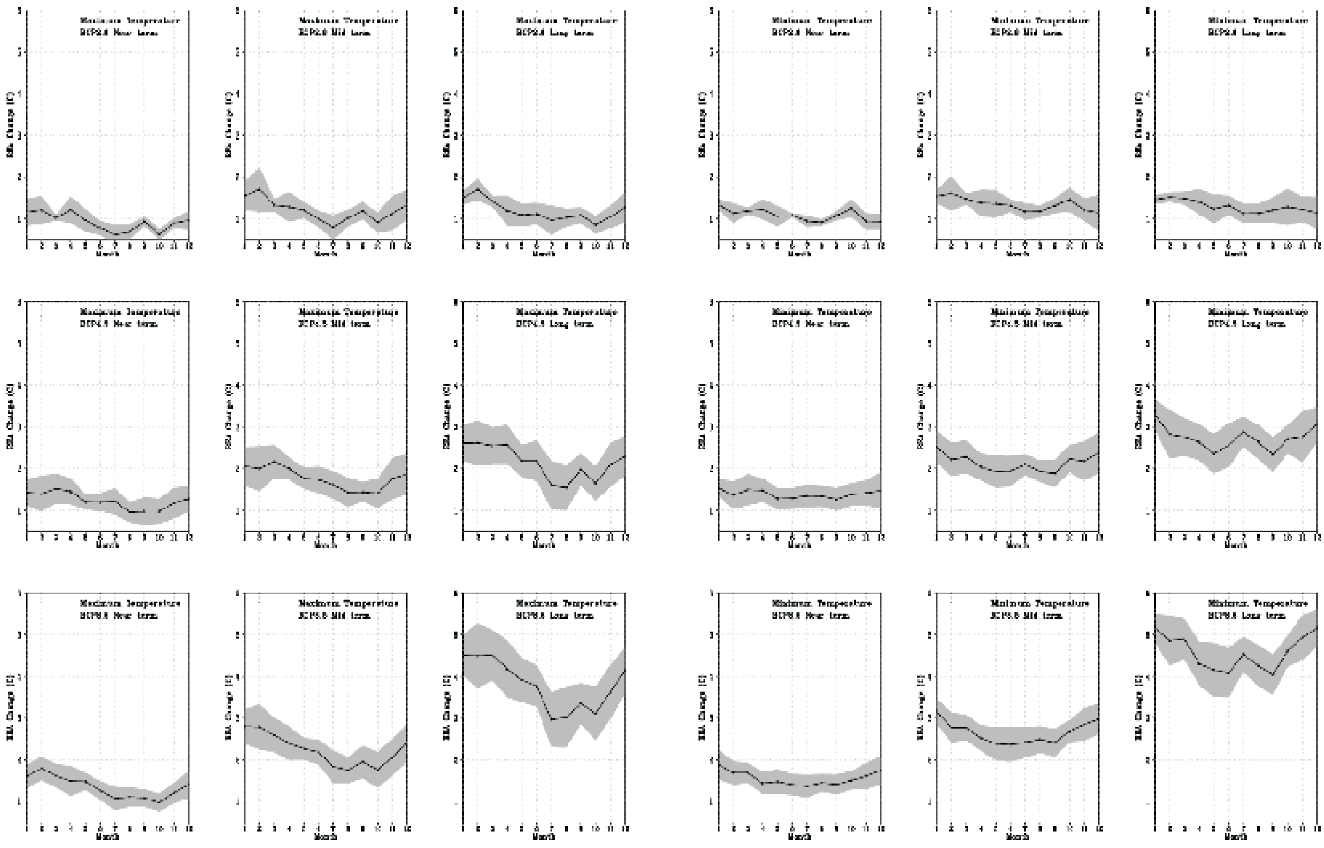



***Figure 2.3** CORDEX South Asia multi-RCM reliability ensemble average (REA) estimate of projected monthly change of all India averaged monthly surface air temperature (°C; solid lines) and the associated uncertainty range (shading)for near-term (2016-2045), mid-term (2036–2065) and long-term (2066–2095) climate under RCP2.6, RCP4.5 and RCP8.5 scenarios, relative to 1976–2005.*

The estimate of annual natural variability in the observed all India maximum and minimum surface air temperature (based on IITM India averaged monthly data) are 0.513°C and 0.213°C respectively, while the REA based annual mean maximum and minimum temperature increases are well above these natural variability estimates. The REA estimate of warming for the three 30 year future periods are lower (higher) for the annual means of daily maximum (minimum) temperature than the respective warming found earlier for the annual mean of daily mean temperature under all three RCP scenarios (Table 2.2). The REA changes for annual minimum temperature of 4.43 ± 0.34°Cis more pronounced than that of 3.94 ± 0.45°C and 4.19 ± 0.46°C increases estimated for all India annual maximum (Table 2.3) and mean (Table 2.4) temperatures respectively the end of the 21st century under RCP8.5 scenario. The assessment of 4.43°C warming for annual mean of daily minimum surface air temperature by the end of the 21stcentury under RCP8.5 scenario is highly reliable as it is associated with the lowest uncertainty (of 7.7%) among not only the three RCP scenarios for this variable but also for the annual mean and maximum statistic shown in Table 2.2 and Table 2.3.

Similar to the results obtained for the changes in the all India averaged monthly surface air temperature (Fig. 2.3), the REA estimate of projected monthly changes of maximum and minimum temperature relative to the reference period 1976-2005 indicate relatively higher seasonal warming during winter months than in the summer monsoon months (Fig. 2.4a and 2.4b). The REA estimate of the projected change in the all India minimum temperature for January and December months is likely to exceed 5°C by the end of 21st century under the RCP8.5 scenario (see bottom right panel of Fig. 2.4b).



(a) (b)

***Figure 2.4*** *CORDEX South Asia multi-RCM reliability ensemble average (REA) estimate of projected monthly change of all India averaged monthly (a) maximum and (b) minimum temperature (°C; solid lines) and the associated uncertainty range (shading)for near-term (2016-2045), mid-term (2036–2065) and long-term (2066–2095) climate under RCP2.6, RCP4.5 and RCP8.5 scenarios, relative to 1976–2005.*

## 2.2. Projected Changes in Precipitation

The sign, magnitude, andspatial extent of the projected CORDEX South Asia multi-RCM ensemble mean annual precipitation changes relative to the reference period 1976-2005 exhibit large variability (Fig. 2.5).The dominance of internal variability of the climate system for annual precipitation at sub-regional scales in India over the relatively smaller forced signal under RCP2.6 scenario leads to increasing and decreasing changes for multi-RCM ensemble meanin several parts of the country throughout the 21st century (see top panels of Fig. 2.5). The multi-RCM ensemble mean annual precipitation mid-term increase exceeds 10% over the west coast and the adjoining southern parts of the Indian peninsula for RCP4.5 scenario, while in the long-term the change for this mid-scenario exceeds 20% over the south-west coast and the adjoining Kerala State (see middle panels of Fig. 2.5). The precipitation changes are not significant over the remaining parts of India for this mid-scenario up to the mid 21$^{st}$ century, however in long-term increase exceed 10% over north-west and adjoining parts of the country. The long-term projected annual precipitation increase exceeds 10% over most parts of India except in Jammu and Kashmir under RCP8.5 scenario, with relatively higher increase exceeding 30% projected along the west coast of India for this high-emission scenario by the end of 21$^{st}$ century (see bottom right panel of Fig. 2.5).

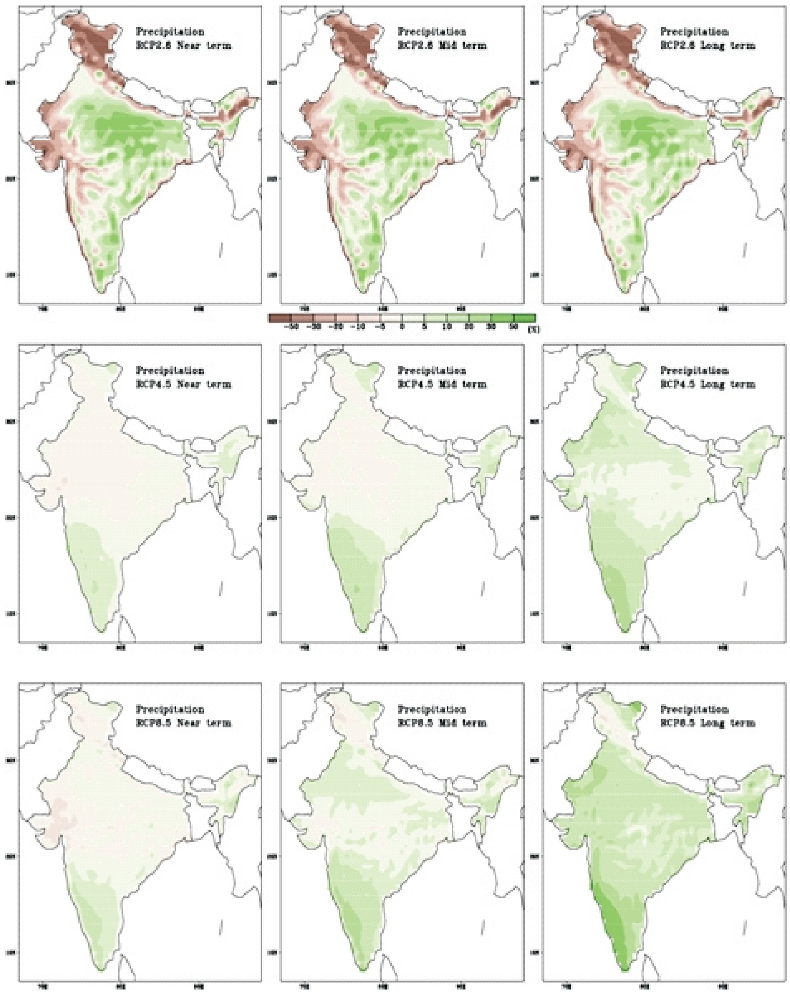



***Figure 2.5*** *CORDEX South Asia multi-RCM ensemble mean projections of average percent changes in annual mean precipitatio for near-term (2016-2045), mid-term (2036–2065) and long-term (2076–2095) climate under RCP2.6, RCP4.5 and RCP8.5 scenarios, relative to 1976–2005.*

The all India averaged annual precipitation anomalies based on IMD high resolution 0.25° longitude-latitude gridded data show interannual variationsduring 1951-2015 (Fig. 2.6). The CORDEX South Asia historical RCM simulations capture the observed interannualvariability. These downscaled projections continue to show interannual variations into the future without any consistent trend for all the RCP scenarios till mid 21$^{st}$ century, and a small increase at longer time scales under RCP8.5 scenario (Fig. 2.6). However the spread in the minimum to maximum range of the projected all India annual precipitation changeamong the CORDEX South Asia RCMs (shown as shading in Fig. 2.6) increases with time, particularly for RCP8.5 scenario, indicating large uncertainty.The results of applying REA methodologyto provide a quantitative estimate of the associated uncertainty range of future climate change projections for Indiaunder the three different RCP scenarios are summarized in Table 2.5.

The natural variability in the observed all India annual mean precipitation (based on IITM India averaged monthly data) is 0.205mm $d^{-1}$, while the REA based precipitation increases are below this natural variability estimate, except in long-term for RCP4.5, and by mid-term for RCP8.5 scenarios. The associated uncertainty range defined

**Table 2.5** CORDEX South Asia multi-RCM reliability ensemble average (REA) estimates of projected changes in annual mean precipitation over India and the associated uncertainty range. The values in parenthesis show the uncertainty in percent for the REA estimate.

| Scenario | Annual Mean Precipitation (mm day $^{-1}$) | | |
|---|---|---|---|
| | 2030s | 2050s | 2080s |
| **RCP2.6** | 0.16 ± 0.12 *(75%)* | 0.15 ± 0.17 *(113%)* | 0.14 ± 0.13 *(93%)* |
| **RCP4.5** | 0.07 ± 0.14 *(200%)* | 0.15 ± 0.19 *(127%)* | 0.30 ± 0.21 *(70%)* |
| **RCP8.5** | 0.15 ± 0.15 *(100%)* | 0.27 ± 0.19 *(70%)* | 0.55 ± 0.32 *(58%)* |

by the root mean square difference is also very high for the three RCP scenarios, with the RCP8.5 long-term precipitation increase of 0.55 mm $d^{-1}$ indicating the minimum uncertainty of 58%. Thus the assessment of all India annual precipitation changes throughout the 21st century remains highly uncertain.

The REA estimate of projected monthly changes for the CORDEX South Asia multi-RCMs of all India averaged monthly precipitation relative to the reference period 1976-2005 indicate relatively higher seasonal increase during summer monsoon months than in the winter months (Fig. 2.7). The long-term monthly change over India by the end of 21st century show distinct annual cycle, particularly for the RCP8.5 scenario (see right panels of Fig. 2.7).Although the REA estimate indicates that the projected increase in the all India precipitation during July to October months are expected to exceed 1 mm $d^{-1}$by the end of the 21st century under RCP8.5 scenario, the associated uncertainty range for the REA monthly changes (shading in Fig. 2.7) are also found to be the highest for these months(see bottom right panel of Fig. 2.7).

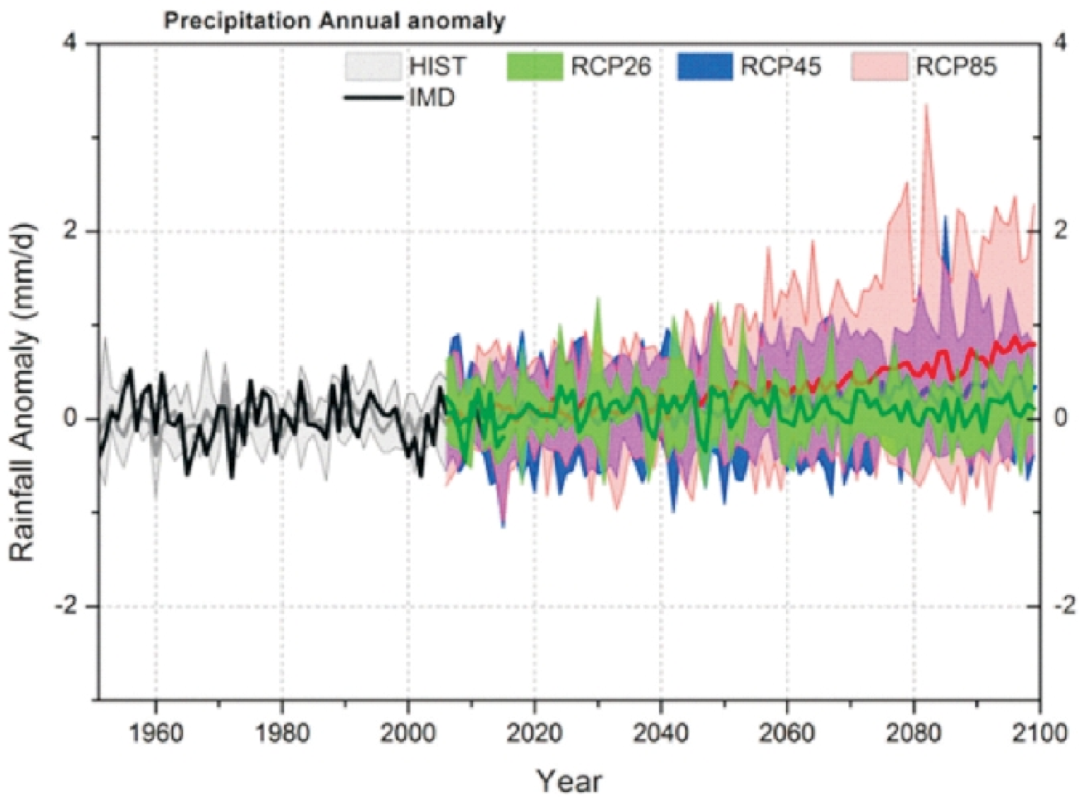



***Figure 2.6*** *Time series of Indian annual mean precipitation (mm $d^{-1}$) anomalies (relative to 1976–2005) from CORDEX South Asia concentration-driven experiments. The historical simulations (grey) and the downscaled projections are shown for RCP2.6 (green), RCP4.5 (blue) and RCP8.5 (red) scenarios for the multi-RCM ensemble mean (solid lines) and the minimum to maximum range of the individual RCMs (shading). The black line shows the observed anomalies during 1951-2015 based on IMD gridded data.*

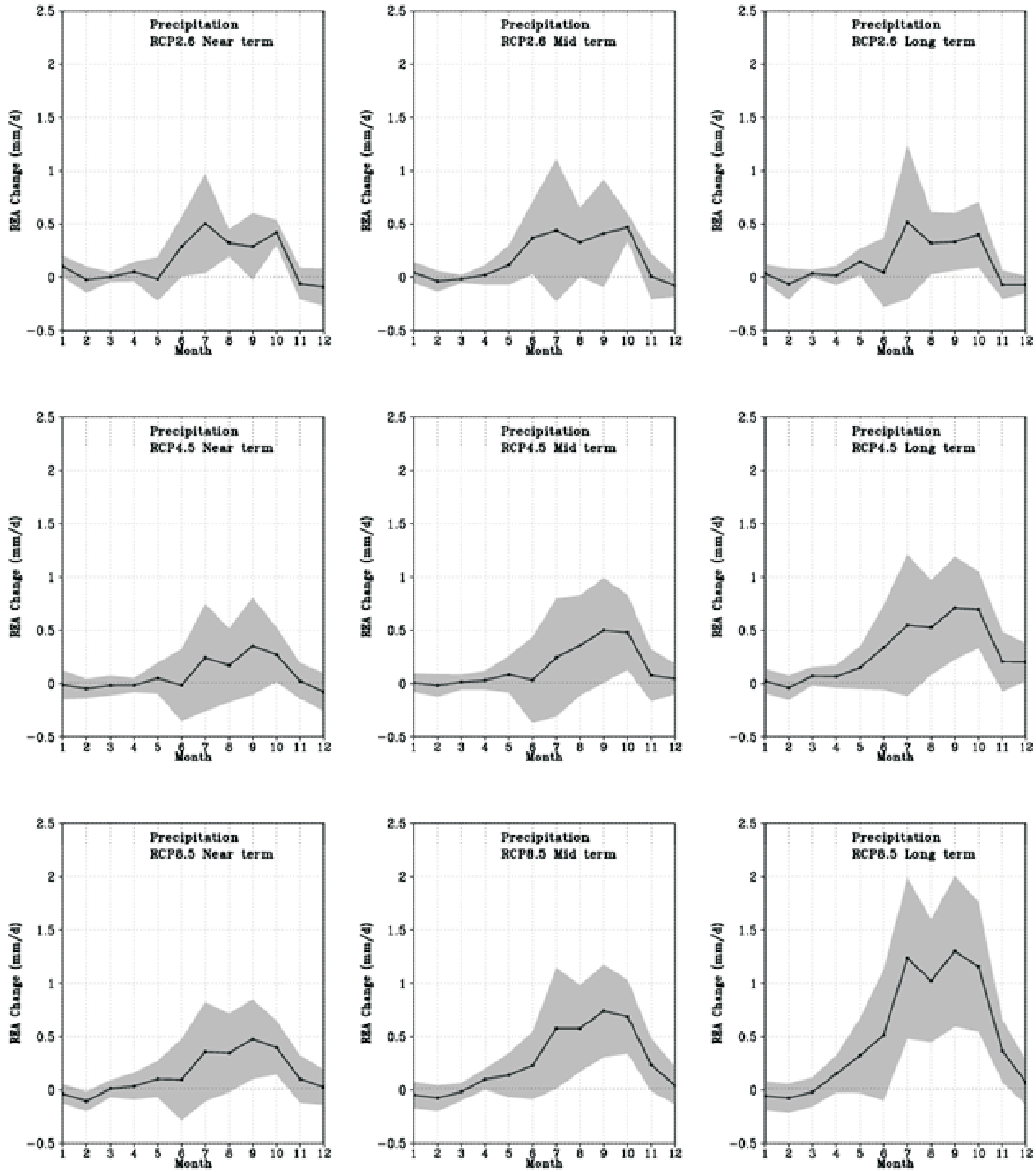



***Figure 2.7*** *CORDEX South Asia multi-RCM reliability ensemble average (REA) estimate of projected monthly change of all India averaged monthly precipitation (mm* $d^{-1}$*; solid lines) and the associated uncertainty range (shading)for near-term (2016-2045), mid-term (2036–2065) and long-term (2066–2095) climate under RCP2.6, RCP4.5 and RCP8.5 scenarios, relative to 1976–2005.*

## 3. Projected Changes in Climate Extremes over India

The previous section provided information on the projected changes in multi-year averages of annual or monthly climate over India. The climate change vulnerability and impacts result mainly from extreme climate events. The IPCC Special Report on Extremes (SREX; Intergovernmental Panel onClimate Change (IPCC), 2012) assessment concluded that future increases in the number of warm days and nights and decreases in the number of cold days and nights are virtually certain on the global scale.It is also likely that since about 1950 the number of heavy precipitation events over land has increased in more regions than it has decreased (Sillmann et al., 2013).Thissection assessselected temperature- and precipitation-based climate extremes indicesdefined by the Expert Team on Climate Change Detection and Indices (ETCCDI; see details in Box 2.1), which are computed with a consistent methodologyfor climate change simulations using different emission RCP scenarios in the CORDEX South Asia multi-RCM ensemble. The changes in the indices are analysed over Indian land region during 1951 to 2099relative to the reference period 1976–2005.

**Box 2.1 Temperature and Precipitation Climate Extreme Indices**

*The Expert Team on Climate Change Detection and Indices (ETCCDI) has defined a set of climate change indices to facilitate the investigation of observed and projected changes in temperature and precipitation extremes,focusing on extreme events. These indices in general describe moderate extreme events with a re-occurrence time of 1 year or less (Zhang et al., 2011). The indices are based on daily minimum and maximum of near surface temperature and daily precipitation amounts (TN, TX, and PR, respectively).A subset of the available 27 indices (see Table 1 in Sillmann et al. (2013))are selected for analysis in this chapter, which give a comprehensive overview of the projected changes in temperature and precipitation extremes across RCMs and scenarios. The calculations are performed with the Climate Data Operators (CDO) package as documented at https://code.mpimet.mpg.de/projects/cdo.*

*The percentile indices for temperature extremes considered are cold nights and days (TN10p and TX10p, respectively) and warm nights and days (TN90p and TX90p, respectively), which describe the threshold exceedance rate of days where TN or TX is below the 10th or above the 90th percentile, respectively. The thresholds are based on the annual cycle of the percentiles calculated for a 5 day sliding window centered on each calendar day in the base period 1976-2005. Sillmann et al. (2013) discussed that these percentile indices are better suited for the tropical regions than absolute temperature indices as they show the highest increase in the tropical regions where inter-annual temperature variability is relatively small. Therefore, small shifts in the mean of the temperature distribution can lead to larger changes in the exceedance rates than in the high variability extra-tropical regions. Since ecosystems and human infrastructure in the tropics are adapted to relatively small temperature variations, small changes in the extremes can have relativelylarge impacts, such as alteration of ecosystems and species extinction.*

*The ratio of extreme precipitation expressed by very wet days (R95p) to the total wet-day precipitation (PRCPTOT) represents the annual contribution of very wet days to the total annual wet-day precipitation (R95PTOT), which is relevant for societal impacts (Sillmann et al. 2013).The CDO based R95p computes the percentage of wet days (PR ≥ 1mm) with daily precipitation amount greater than the 95th percentile of all wet days during the climate base reference period: 1976-2005.This index based on a percentile threshold takes into account the respective precipitation climatologies of different regions.The simple daily intensity index (SDII) describes the daily precipitation amount averagedover all wet days in a year.The maximum 5 day precipitation index (RX5day) describes the monthly or annual maximum of 5 day precipitation accumulations. This index is often used to describe changes in potential flood risks as heavy rain conditions over several consecutive days can contribute to flood conditions.The consecutive dry-day index (CDD) represents the length of the longest period of consecutive dry days (i.e., days with PR<1 mm) in a year ending in that year. If a dry spell does not end in a particular year and spans a period longer than 1 year (as may happen in very dry regions), then CDD is not reported for that year and the accumulated dry days are carried forward to the year when the spell ends.*

## 3.1 Temperature Extremes

The observations based on IMD daily gridded data over India since 1951indicate that there is evidence of changes in some climate-related extremes. Figure 2.8 shows that there is an overall decrease in the number of cold nights (TN10p) and cold days (TX10p), and an increase in the number of warm nights (TN90p) and warm days (TX90p).There is a consistent decrease in cold nights (TN10p)and cold days (TX10p) from the late 20th to the 21st century in all RCP scenarios (Figures 2.8a and 2.8b). The mean decrease is generally more pronounced for TN10pthan for TX10p. TN10p decreases to near 0% and TX10p to 2% by the end of 21$^{st}$ century for RCP4.5 scenario. Thus there will be virtually no cold nights or days over India as defined for the 1976–2005 reference base periods under the future projections. The spread among the RCMs (shading in Fig. 2.8) generally becomes smaller as the projection approaches the zero exceedancerates as more models simulate fewer cold nights and days. The warm nights (TN90p) and warm days (TX90p)over India show a general increase in the exceedance rate toward the end of the 21st century (Figures 2.8c and 2.8d). The increase is more pronounced for TN90p than for TX90p. The mean increase in TN90p and TX90p for RCP8.5 scenario is from about 10% in 1976–2005 to 80% and 65% by the end of $21^{st}$ century, respectively. The smallest increases in TN90p and TX90p,to 25% and 22% respectively, occur for RCP2.6 scenario, followedby greater respective increases to 50% and 40% forRCP4.5 scenario.

The changes in the percentile indices based on minimum temperature (TN10pand TN90p) are more pronounced than those based onmaximum temperature (TX10p and TX90p).The largest decreases in TN10p and largest increases in TN90p projected over India are typical for tropical regions that are characterized by small day-to-day temperature variability so that changes in mean temperature are associated with comparatively larger changes in exceedance rates below the $10^{th}$and above the $90^{th}$percentiles.

The spatial pattern of the projected multi-RCM ensemble mean of the annual frequency of temperature indices shows that more rapid decreases in cold nights (TN10p) and cold days (TX10p) are expected along the west coast and the adjoining peninsular region than in other parts of India by mid $21^{st}$ century for RCP4.5 and RCP8.5 scenarios (Fig. 2.9a and 2.9b). The increase in annual frequency of warm nights (TN90p) and warm days (TX90p) are also projected to be higher over these same regions by mid $21^{st}$ century for RCP4.5 and RCP8.5 scenarios (Fig. 2.9c and 2.9d).

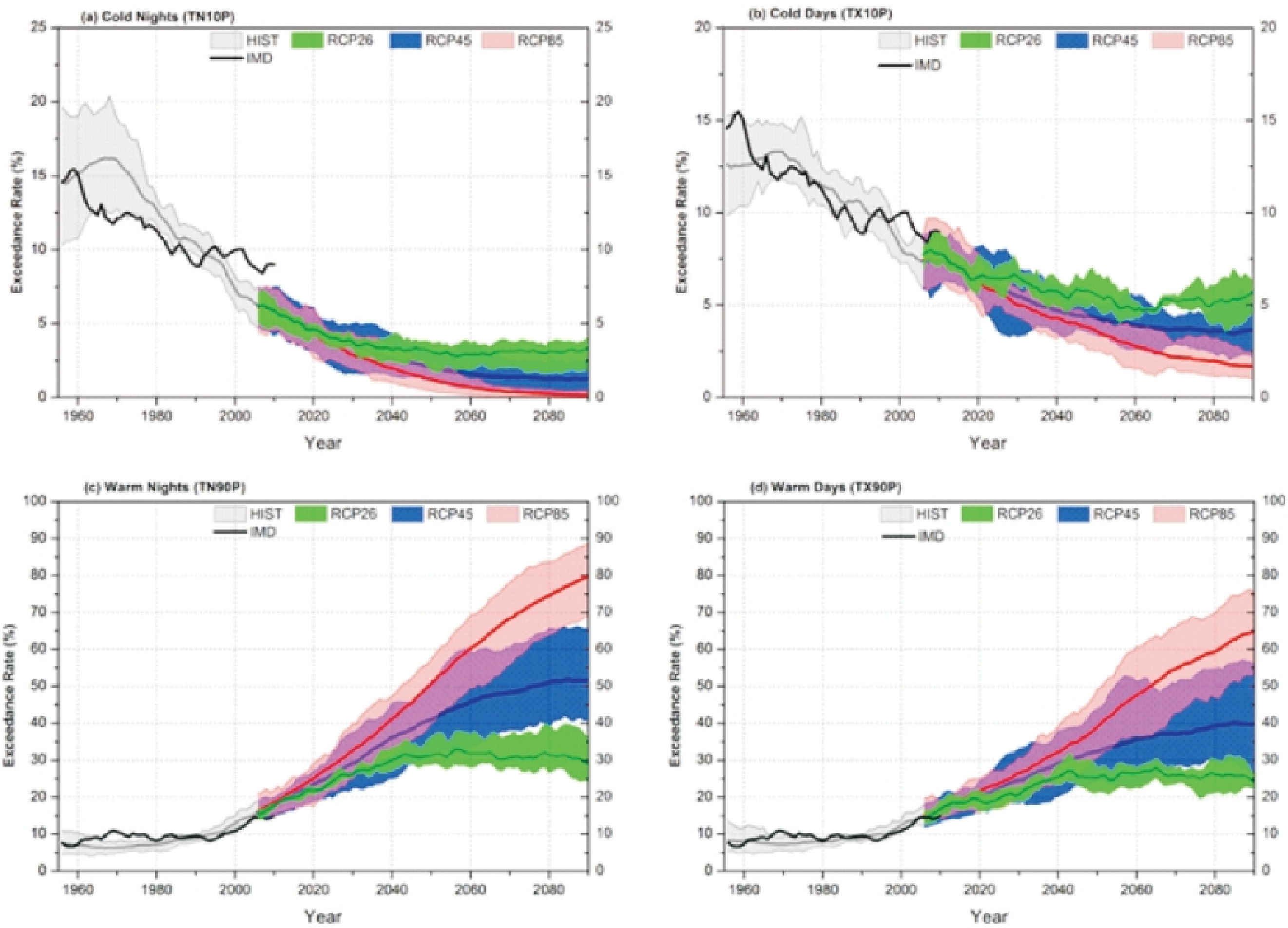



***Figure 2.8*** *India averages of temperature indices over land as simulated by the CORDEX South Asia multi-RCM ensemble (see Table 2.1) for the RCP2.6 (green), RCP4.5 (blue), and RCP8.5 (red) displayed for the percentile indices (a) cold nights (TN10p), (b) cold days (TX10p), (c) warm nights (TN90p), and (d) warm days (TX90p). Changes are displayed as absolute exceedance rates (in %). By construction the exceedance rate averages to about 10% over the base period 1976-2005. Solid lines show the ensemble mean and the shading indicates the range among the individual RCM. The black line show the observed indices based on IMD gridded data. Time* series are smoothed with a 20 year running mean filter.

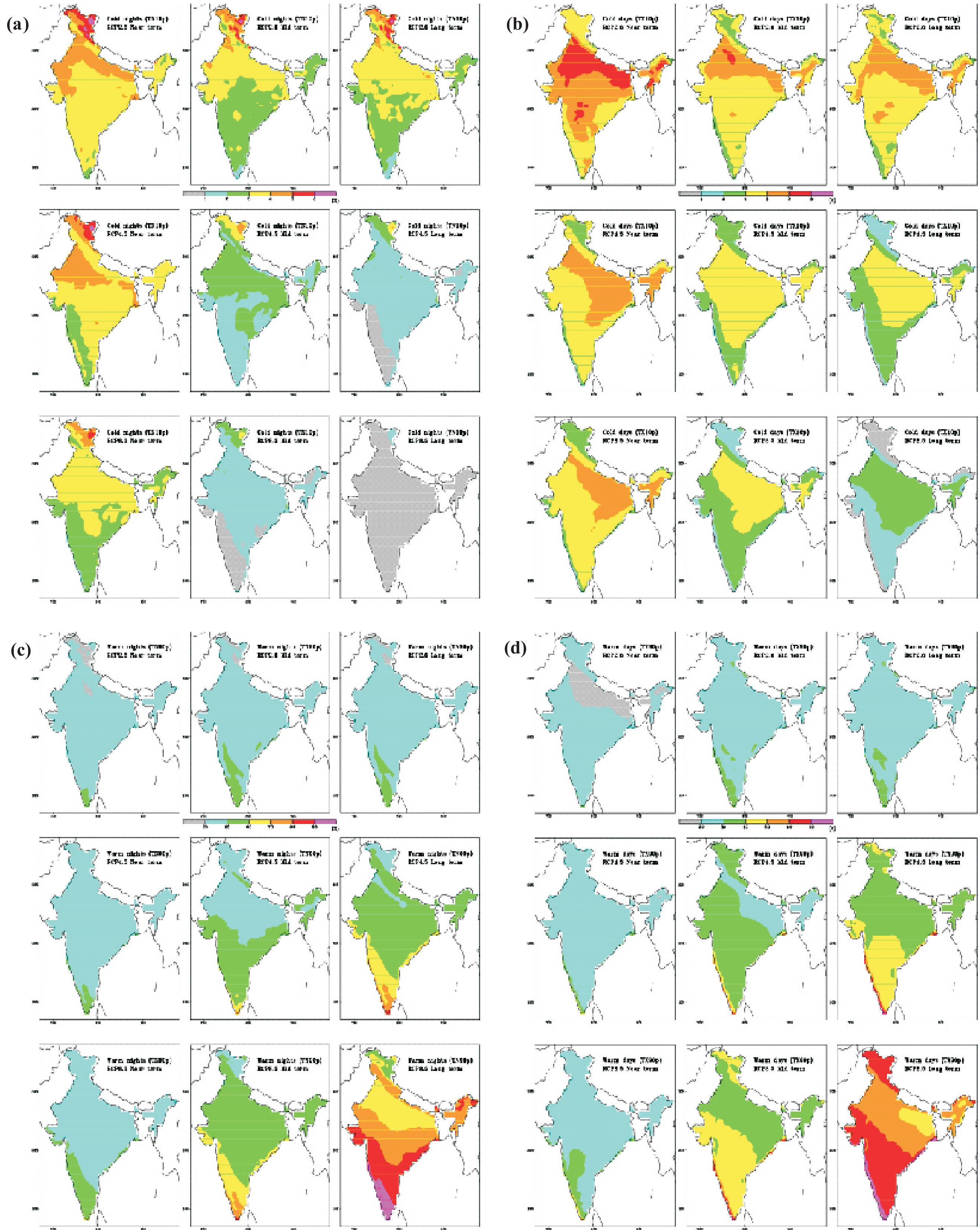


***Figure 2.9*** *CORDEX South Asia multi-RCM ensemble mean of the annual frequency of (a) cold nights (TN10p), (b) cold days (TX10p), (c) warm nights (TN90p), and (d) warm days (TX90p), temporally averaged for near-term (2016-2045), mid-term (2036–2065) and long-term (2066–2095) climate under RCP2.6, RCP4.5 and RCP8.5 scenarios, as absolute values of the exceedance rate (in %). By construction the exceedance rate averages to about 10% over the base period 1976–2005.*

## 3.2 Precipitation Extremes

Changes in the selected precipitation indices (see details in Box 2.1) relative to the 1976–2005 reference period are expressed in percentage terms. Indian land averaged precipitation indices areprojected to increase in the 21st century (Fig. 2.10). Relative increases in maximum 5-day precipitation (RX5day; Fig. 2.10c), which represents a more extreme aspect of the precipitation distribution, are greaterover time than those for the contribution of very wet days to total wet day precipitation (R95PTOT; Fig. 2.10a) and the simple daily intensity index (SDII; Fig. 2.10b). In RCP8.5, R95PTOT and SDII are projected toincrease by 15% and 21%, respectively, by year 2100, whereasRX5day is projected to increase by 38%. However the spread among the CORDEX South Asia individual RCMs (shading in Fig. 2.10) is highest for RCP8.5 scenario, and remain overlapping with RCP4.5 scenario throughout the 21st century for these precipitation extreme indices. The all India averaged temporal evolution of maximumconsecutive dry days (CDD) is not shown here as the temporaland spatial variability of this index over Indian land area is verylarge.

The spatial pattern of the projected multi-RCM ensemble mean of the precipitationextreme indices shows that relatively higher increase in the contribution of very wet days to total wet day precipitation (R95PTOT; Fig. 2.11a), the daily intensity (SDII; Fig. 2.11b), and in the maximum 5-day precipitation (RX5day; Fig. 2.11c) are expectedalong the west coast and the adjoining peninsular region than in other parts of India by mid $21^{st}$ century for RCP4.5 and RCP8.5 scenarios. The striping plotted in Fig. 2.11 indicates where more than 70% of the RCM realizations concur on an increase (vertical) or decrease (horizontal) in theextreme precipitation indices for the RCP scenarios.The striping is not plotted for R95PTOT as the RCM realizations have more than 70% consensus for increase over entire India for the three RCP scenarios. Although the maximum number of consecutive dry days (CDD; Fig. 2.11d) is projected to increase over many parts of India, the RCM consensus is generally found only in parts of the Indian peninsular region throughout the $21^{st}$ century for RCP8.5 scenario. The increases in CDD combined with increases in RX5day indicates an intensification of both dry and wet seasons along the west coast and the adjoining peninsular region over India.

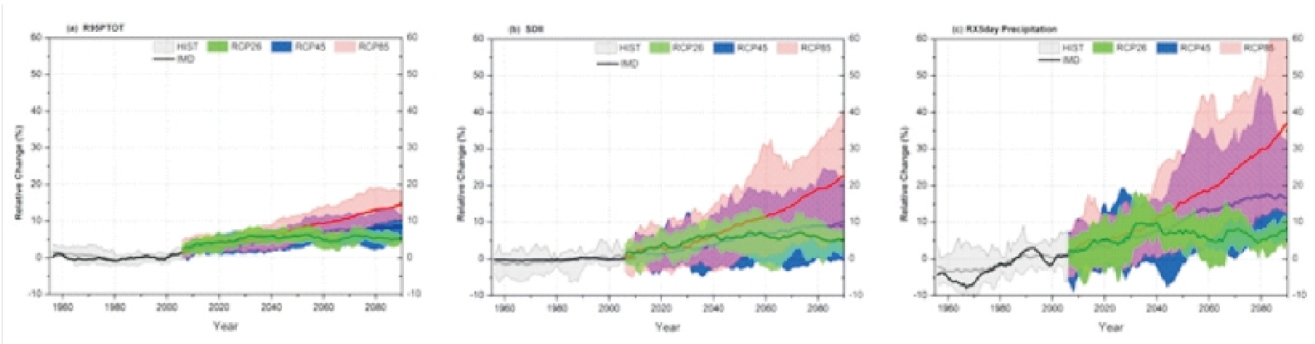



***Figure 2.10*** *India averages of precipitation indices over land as simulated by the CORDEX South Asia multi-RCM ensemble (see Table 1) for the RCP2.6 (green), RCP4.5 (blue), and RCP8.5 (red) displayed for the absolute indices (a) contribution of very wet days to total wet day precipitation (R95PTOT), (b) maximum 5-day precipitation (RX5day), (c) simple daily intensity index (SDII), and (d) maximum number of consecutive dry days (CDD). Changes are displayed relative to the reference period 1976-2005 (in %). Solid lines show the ensemble mean and the shading indicates the range among the individual RCMs. Time series are smoothed with a 20 year running mean filter.*

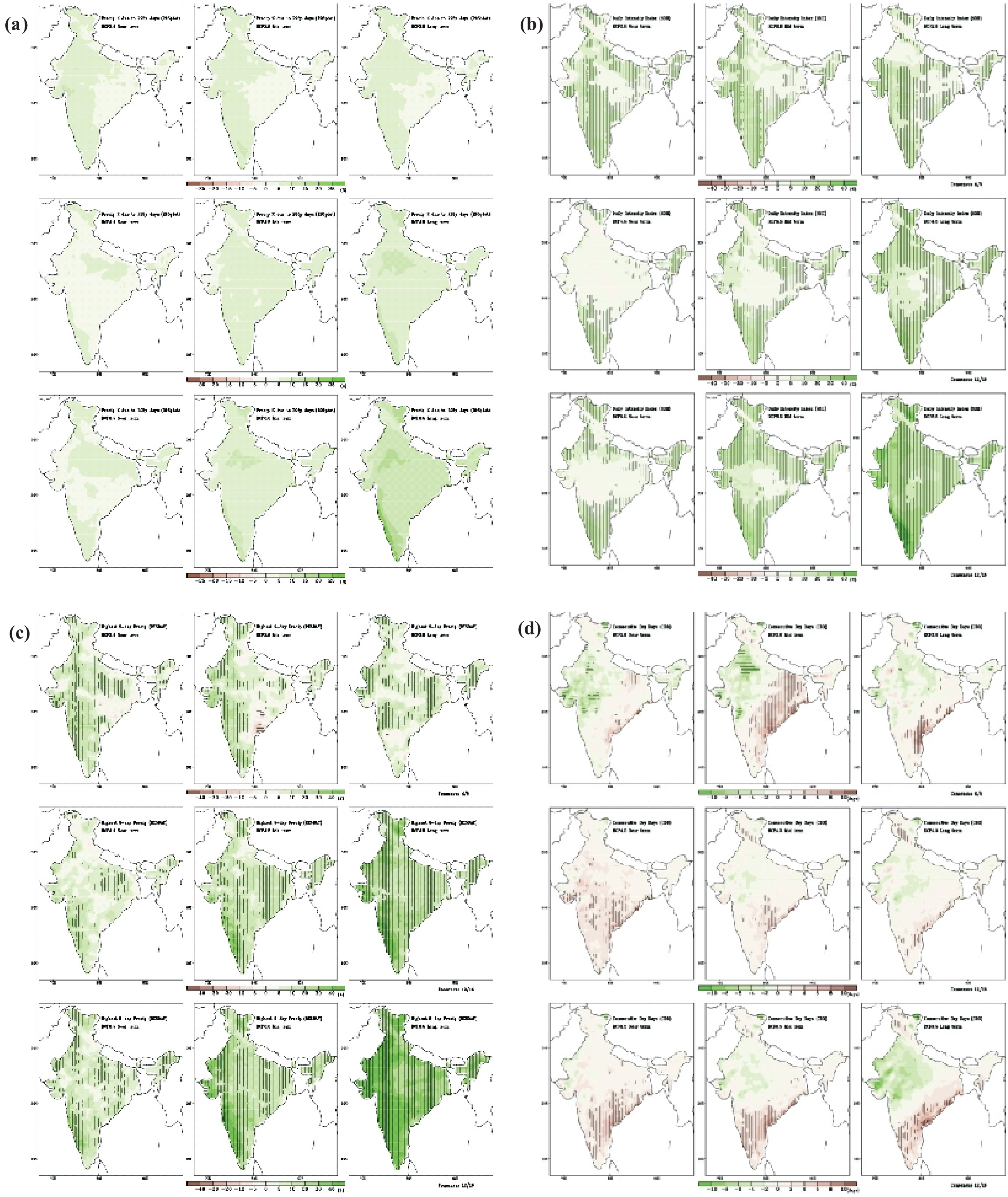



***Figure 2.11** CORDEX South Asia multi-RCM ensemble mean for the absolute precipitation indices (a) contribution of very wet days to total wet day precipitation (R95PTOT), (b) simple daily intensity index (SDII), (c) maximum 5-day precipitation (RX5day), and (d) maximum number of consecutive dry days (CDD), temporally averaged for near-term (2016-2045), mid-term (2036–2065) and long-term (2066–2095) climate under RCP2.6, RCP4.5 and RCP8.5 scenarios, displayed as changes relative to the reference period 1976-2005 (in %). Striping indicates where at least 70% of the RCM realizations concur on an increase (vertical) or decrease (horizontal) in the future scenarios. The striping is not plotted for R95PTOT as the RCM realizations have more than 70% consensus for increase over India for the three RCP scenarios.*

## 4. Acknowledgments

The IITM-RegCM4 simulations were performed using the IITM Aaditya high power computing resources. The Director, IITM is gratefully acknowledged for extending full support to carry out this research work. IITM receives full support from the Ministry ofEarth Sciences, Government of India. The World Climate Research Programme's Working Group onRegional Climate, and the Working Group on Coupled Modelling, former coordinatingbody of CORDEX and responsible panel for CMIP5 are sincerely acknowledged. The climatemodeling groups (listed in Table 2.1) are sincerely thanked for producing and making availabletheir model output. The Earth System Grid Federationinfrastructure (ESGF; http://esgf.llnl.gov/index.html) is also acknowledged. The Climate Data Operatorssoftware (CDO; https://code.zmaw.de/projects/cdo/) and the Grid Analysis and Display System (GrADS; http://iges.org/grads/) were extensively used throughout this analysis.

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## Chapter 3

# The IITM Earth System Model (IITM ESM)

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## 1. Introduction

Earth System Models (ESM) are important tools that allow us to understand and quantify the physical, chemical & biological mechanisms governing the rates of change of elements of the Earth System, comprising of the atmosphere, ocean, land, cryosphere and biosphere (terrestrial and marine) and related components. ESMs are essentially coupled numerical models which incorporate processes within and across the different Earth system components and are expressed as set of mathematical equations. ESMs are useful for enhancing our fundamental understanding of the climate system, its multi-scale variability, global and regional climatic phenomena and making projections of future climate change. In this chapter, we briefly describe the salient aspects of the Indian Institute of Tropical Meteorology ESM (IITM ESM), that has been developed recently at the IITM, Pune, India, for investigating long-term climate variability and change with focus on the South Asian monsoon.

Observations of the climate system based on direct measurements and remote sensing from satellites and other platforms indicate that the warming of the climate system has been unequivocal since the 1950s, many of the observed changes are unprecedented over decades to millennia (Stocker et al. 2013). Long-term climate model simulations, that took part in the Intergovernmental Panel for Climate Change (IPCC) fifth assessment report (AR5), provide very high confidence in interpreting the observed global-mean surface temperature trends during the post-1950s; as well as the human influence on the climate system which is clearly evident from the increasing concentration of greenhouse gases (GHG) in the atmosphere, positive radiative forcing and the observed global warming (Stocker et al. 2013). On the other hand, there are major challenges in comprehending the impacts of climate change at regional levels. For example, the 20th century simulations and future projections of the South Asian monsoon rainfall based on the IPCC models exhibit a wide range of variations and uncertainties *[Ref: Turner and Annamalai, 2012; Sharmila et al., 2014; Saha et al 2015; Krishnan et al. 2016],* which pose huge challenges to policy makers and development of adaptation strategies.

The Coupled Modeling Intercomparison Project (CMIP3; [*Meehl et al.*, 2007], CMIP5; [*Taylor et al.*, 2012]) coordinated by the World Climate Research Programme (WCRP) form the basis of the climate projections in the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. The CMIP models have convincingly demonstrated the role of anthropogenic forcing on the rising trend of global mean temperatures [*Flato et al.*, 2013], however there are challenges in quantifying the response of regional monsoon precipitation to climate change [*eg., Turner and Annamalai*, 2012; *Sperber et al.*, 2013; *Kitoh*, 2017].

The underlying philosophy behind the IITM ESM is based on developing a global modeling framework to address the science of climate change, including detection, attribution and future projections of global

### Highlights

- ***IITM-ESMv1:*** *Successful development of the first version of IITM ESM at CCCR, IITM, Pune by transforming a seasonal prediction model (CFSv2) into a long term climate model (Ref: Swapna et al. 2015). This development was achieved by incorporating a new ocean model component (MOM4p1, including ocean biogeochemistry) in CFSv2. Major improvements in the IITM-ESM relative to CFSv2 include:*
  - *Significant reduction of cold bias of global mean sea surface temperature (SST) by ~0.8°C*
  - *Robust simulations of drivers of natural modes of global climate variability [eg., El Nino/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)] well-captured in IITM-ESMv1*
  - *Teleconnections between ENSO and the Indian monsoon rainfall well captured in IITM-ESMv1*
- ***IITM-ESMv2:*** *Successful development of the second version of IITM ESM at CCCR, IITM, Pune by incorporating various refinements and improvements in the first version. The IITM-ESMv2 is a radiatively balanced global climate modeling framework that has the capability to address key scientific questions relating to long-term climate change.*
- ***IITM-ESMv2 to participate in CMIP6:*** *The IITM-ESMv2 would be first climate model from India to contribute to the Coupled Model Intercomparison Project Sixth Phase (CMIP6) for the IPCC sixth assessment report (Ar6).*

climate, with special emphasis on the South Asian monsoon. With this view, the first version (IITM ESM version 1) was developed by transforming a state-of-the-art seasonal prediction model, Climate Forecast System version 2 (CFSv2, [*Saha et al.*, 2010], into a model suitable for long-term climate [*Swapna et al. 2015*]. Subsequently an updated version of the IITM Earth System Model (IITM ESM version 2) has been developed at the CCCR-IITM, Pune, by incorporating various refinements leading to a radiatively balanced global climate modeling framework appropriate for addressing the science of climate change.

## 2. A brief description of the IITM-ESM

The IITM-ESMv2 configuration includes ***(a)*** A atmosphere general circulation model [global spectral model with triangular truncation of 62 waves (T62, grid size ~200 km) and 64 vertical levels with top model layer extending up to 0.2 hPa ***(b)*** A global ocean component based on the Modular Ocean Model Version 4p1 (MOM4p1) (*Griffies*, 2009) having a zonal resolution of ~100 km and the meridional resolution ~ 35 km between 10°S and 10°N and coarser grid ~100 km poleward of 30° latitude in both Hemispheres and with 50 levels in the vertical ***(c)*** A land surface model (Noah LSM) with four layers ***(d)*** A dynamical sea-ice model known as the Sea Ice Simulator (SIS) (*Winton*, 2000). A schematic of the IITM-ESMv2 is shown in Figure 3.1. Here we present highlights of the IITM-ESMv2 simulations, which include multi-century runs corresponding to the pre-industrial and future climatic conditions following the Coupled Model Intercomparison Project Phase 6 (CMIP6) protocols. The IITM-ESMv2 would be the first climate model from India contributing to the CMIP6 experiments for the Intergovernmental Panel for Climate Change (IPCC) sixth assessment report (AR6) to be released in 2021.

## 3. Salient features of the IITM-ESMv2

The IITM-ESMv2 has capabilities for conducting long-term climate change studies. The salient features of the IITM-ESMv2 include:

***a. Radiatively balanced framework:*** *Global balance of net radiative fluxes at the top-of-the-atmosphere (TOA), surface of the Earth (surface)*

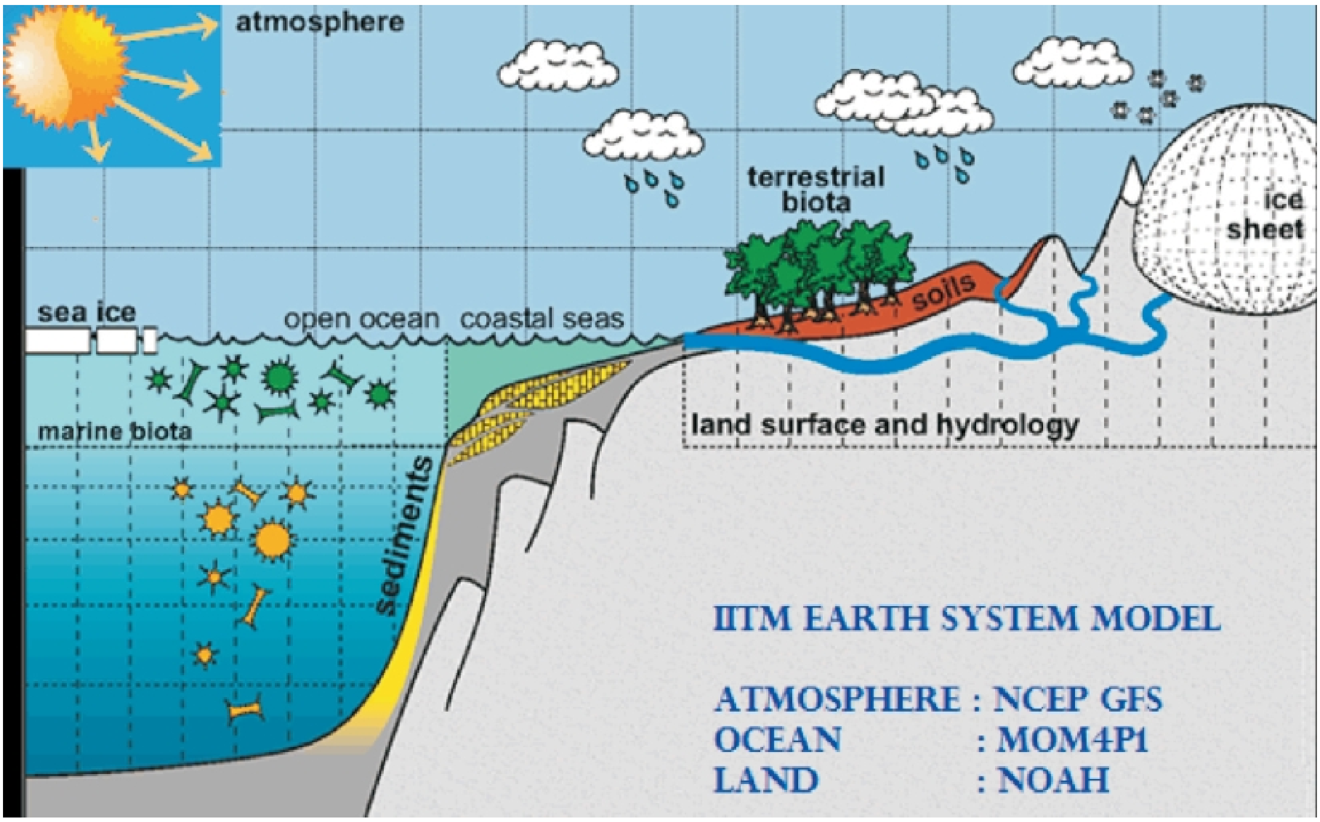



**Figure 3.1** Schematic showing different components of the IITM Earth System Model.

*and atmosphere. This is an essential criterion to be met by climate models in order to make reliable assessments of the impacts of the radiative effects from anthropogenic forcing (eg., GHG, aerosols, …) on the climate system (Figure.3.2). The IITM-ESMv2 exhibits fidelity in capturing the global and tropical climatic features (Figures.3.3-3.4)*

b. ***South Asian Monsoon:*** *Improved simulation of time-mean monsoon precipitation over South Asia (Figure.3.5). Given that the Indian Monsoon (a.k.a South Asian Monsoon) is the lifeline of the regional socio-economic activities, there is strong emphasis at CCCR, IITM to make reliable assessments of changes in the Indian monsoon precipitation under climate change. Keeping this in view, the model developmental efforts at CCCR, IITM focused on refining the representations of both the global climate as well as the regional monsoon phenomenon in the IITM-ESMv2.*

c. ***Marine biogeochemistry:*** *IITM-ESMv2 incorporates interactive ocean biogeochemistry and ecosystem processes. This allows us to investigate the impacts of climate variability and climate change on marine primary productivity and mechanisms that control the ocean carbon cycle (Figure.3.6).*

d. ***Polar sea-ice distribution:*** *Sea-ice distribution in polar region is an important component of the climate system. The IITM-ESMv2 shows a realistic representation of time-mean distribution of polar sea-ice, as compared to IITM-ESMv1 which severely underestimated the sea-ice cover (Figure 3.7).*

e. ***Atlantic Meridional Overturning Circulation (AMOC):*** *A significant outcome of improving polar sea-ice distribution is manifested by a realistic simulation of AMOC in the IITM-ESM. The AMOC, which is a deep ocean circulation driven by large-scale density (temperature & salinity) gradients in the ocean interior, is a major driver of global climate variability. Global warming impacts are projected to affect the strength of AMOC through their influence on polar ice caps (both over sea and land). These impacts can affect the global climate as well as the Asian monsoon by altering the atmospheric and oceanic circulation patterns.*

f. ***Aerosol forcing:*** *IITM-ESMv2 incorporates the radiative effects of aerosols, both natural (eg., dust, sea-salt, volcanic emissions…) and anthropogenic (sulfate, nitrate, organic carbon, black carbon, …), on the climate system. Atmospheric aerosols affect climate through scattering and absorption of the incoming solar radiation (direct effect) and through modification of cloud properties (indirect effect). Rapid industrialization during the last 5-6 decades has increased atmospheric aerosol loading [IPCC 2013]. Recent studies have pointed to the role of anthropogenic aerosol forcing on radiation, monsoon rainfall and regional climate [eg., Ramanathan et al. 2005, Bollasina et al. 2011, Krishnan et al. 2016]. Unlike GHGs, the space-time variability of aerosols is large. Furthermore, monsoon precipitation variability over South Asia* ***is*** *strongly influenced by monsoon internal dynamics. Therefore, reliable attributions of aerosol forcing on regional precipitation changes have been challenging. The IITM-ESMv2 serves as a valuable tool to address these scientific problems.*

g. ***Land use and land cover changes:*** *The IITM-ESMv2 has capabilities to address the effects of land use and land cover changes (LULC) on the climate system. This is of considerable interest to the Asian region which has undergone major changes in forest cover, agricultural land and vegetation types since pre-industrial times. The IITM-ESMv2 provides a great opportunity to investigate the role of LULC on the regional monsoon precipitation pattern.*

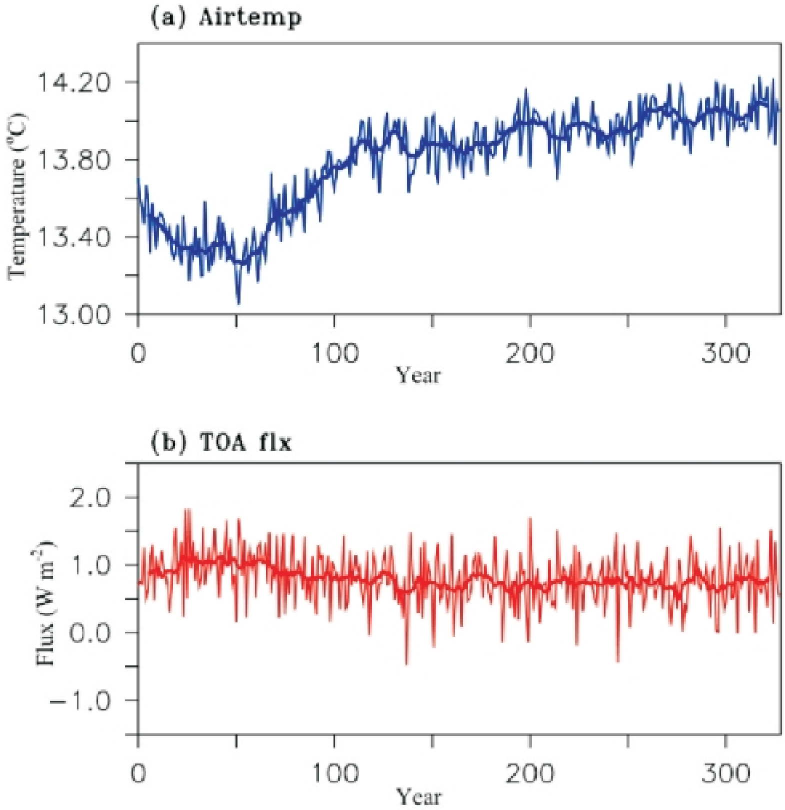



***Figure 3.2*** *Time-series plots from the Pre-Industrial (PI) control simulation of IITM ESM2* ***(a)*** *Global mean surface air-temperature (°C)* ***(b)*** *Net radiation flux at the top-of-atmosphere (TOA). The PI control experiment is a multi-century simulation uses GHG, aerosols, land-use & land-cover and other forcing corresponding to 1850. The PI control experiment of IITM ESM2 has completed more than 300 years of simulation on the IITM HPC and will continue for a few more centuries. It can be noticed that the time-series tend towards quasi-equilibrium with mean values of global mean surface-air-temperature ~14°C and TOA net radiation flux ~ 0.8 $Wm^{-2}$.*

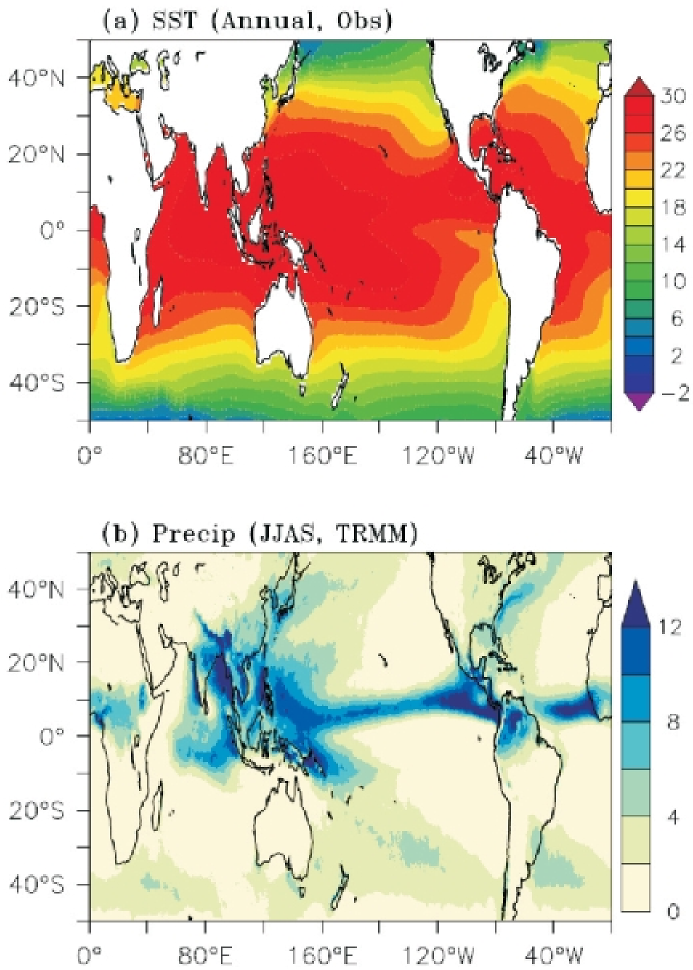



***Figure 3.3*** *Spatial map of the observed climatology (a) Annual mean sea surface temperature (SST °C) (b) Mean precipitation (mm $day^{-1}$) during the June-July-August-September (JJAS) boreal summer monsoon season. The SST data is based on Hadley Centre dataset (HadISST, Rayer et al. 2003) and the precipitation data is estimated from the Tropical Rainfall Measurement Mission (TRMM, Huffman et al., 2010) satellite. The warm pool region in the tropical eastern Indian Ocean and western Pacific Ocean are associated with SST > 29°C, while cooler SSTs prevail in the eastern equatorial Pacific (< 22°C) giving rise to a strong east-west gradient in the tropical Pacific Ocean. Cold SSTs (< 18°C) are seen in the extra-tropical oceanic areas. The boreal summer monsoon precipitation is dominated by tropical precipitation over the Indian subcontinent, Southeast and East Asia, Tropical Eastern Indian Ocean and Western Pacific, the Inter-Tropical-Convergence-Zone (ITCZ) over the equatorial Pacific and Atlantic, Central and Latin America, equatorial Africa. Extra-tropical precipitation is seen over the East Asian region including eastern China, Korea and Japan, and the east coast of North America.*

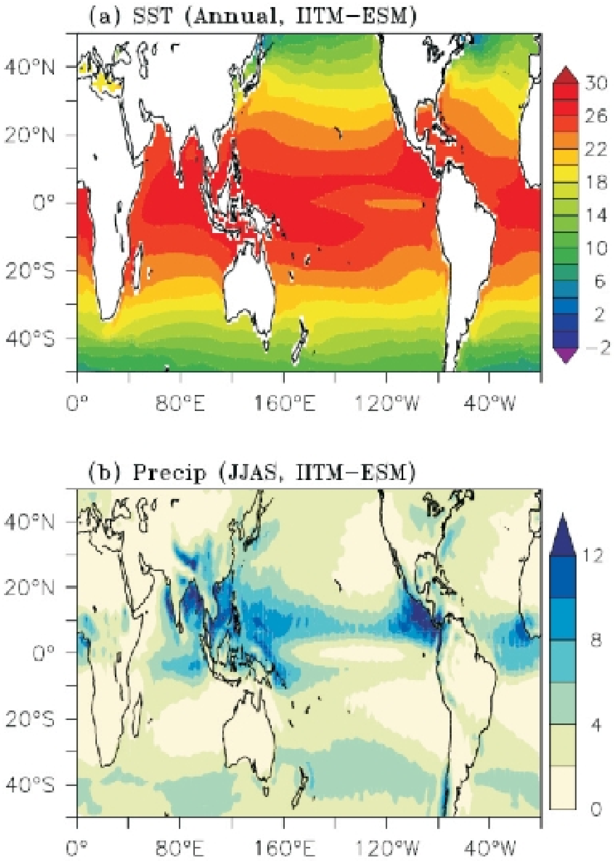



***Figure 3.4*** *Spatial map of climatological (a) Mean SST (°C) (b) Mean JJAS precipitation (mm day[-1]) simulated by the IITM-ESMv2 from the PI control simulation. The mean values are based on the last 100 years of the PI Control simulation. The broad spatial patterns of the simulated SST and rainfall are consistent with the observed patterns. The magnitude of the simulated SST and rainfall in the tropical Indo-Pacific warm pool are underestimated as compared to observations.*

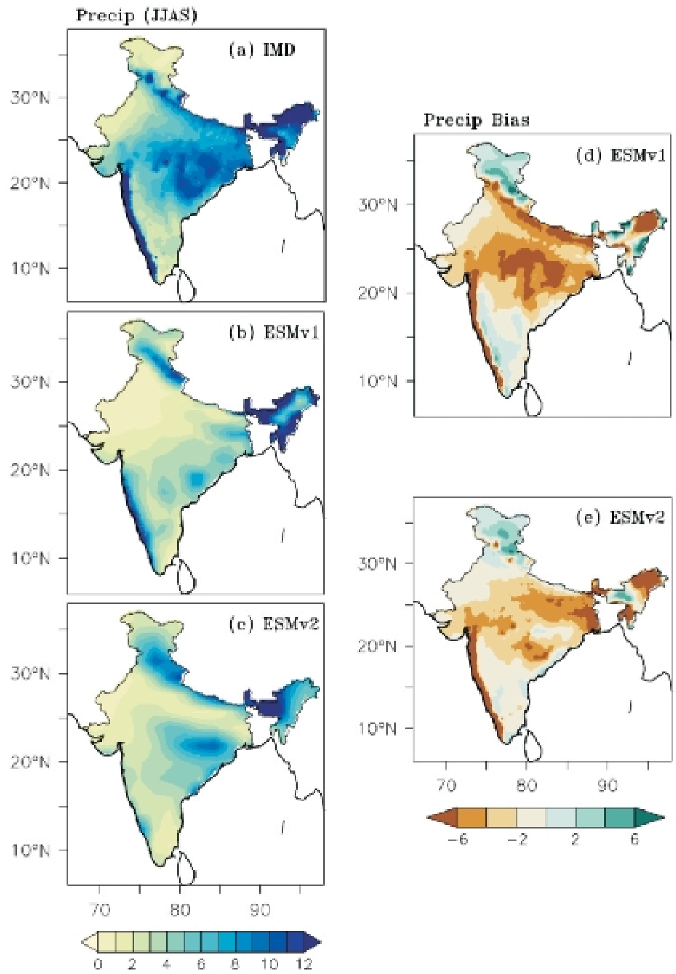



***Figure 3.5*** *Spatial map of mean boreal summer monsoon (JJAS) precipitation (mm day[-1]) over India* ***(a)*** *Observed precipitation from the India Meteorological Department (IMD) based on the Pai et al. (2015) dataset* ***(b)*** *Simulated precipitation from IITM-ESMv1* ***(c)*** *Simulated precipitation from IITM-ESMv2* ***(d)*** *Difference (IITM-ESMv1 minus IMD observation) shows the systematic bias in the IITM-ESMv1 simulation* ***(e)*** *Difference (IITM-ESMv2 minus IMD observation) shows the systematic bias in the IITM-ESMv2 simulation. It can be noticed that the IITM-ESMv1 has a large dry bias over north-central India. The magnitude of the negative bias in precipitation has been reduced in the IITM-ESMv2 simulation.*

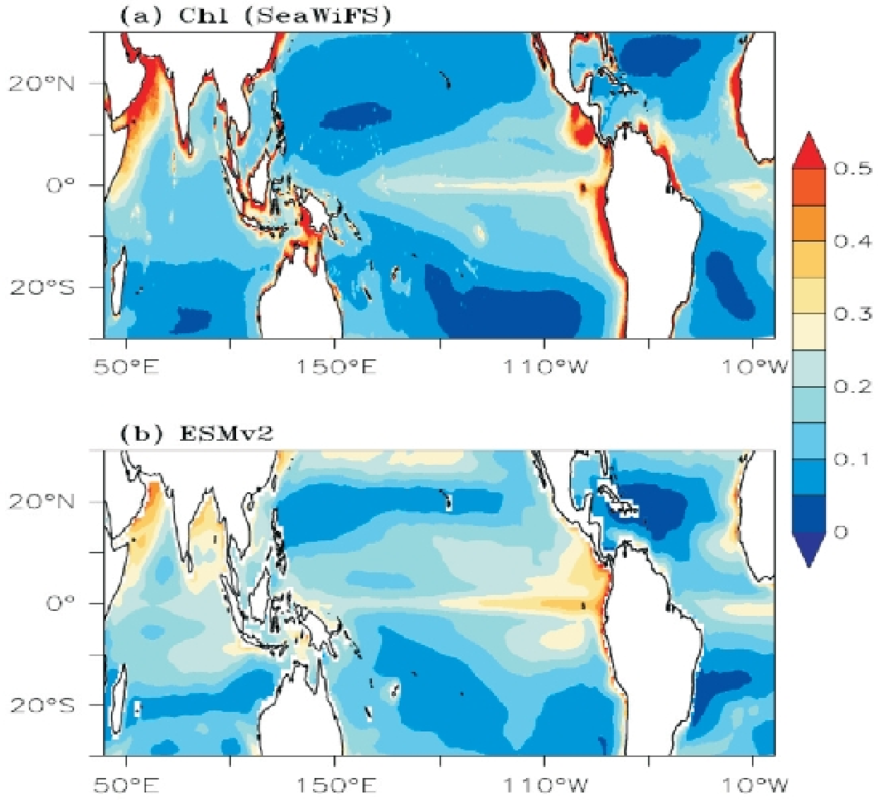



***Figure 3.6*** *Spatial maps of climatological mean chlorophyll concentration (mg m$^{-3}$)* ***(a)*** *Satellite estimates (SeaWifs)* ***(b)*** *IITM-ESMv2 simulation. High chlorophyll concentrations off the Somali Coast and Arabian Sea, and the eastern Pacific are associated with oceanic upwelling. The IITM-ESMv2 captures the high-chlorophyll patterns in the northern Indian Ocean and eastern Pacific, although the magnitudes are somewhat underestimated in the Arabian Sea. Also the simulated chlorophyll in the Pacific Ocean extends far westward from the Eastern to the Central Pacific, as compared to observations.*

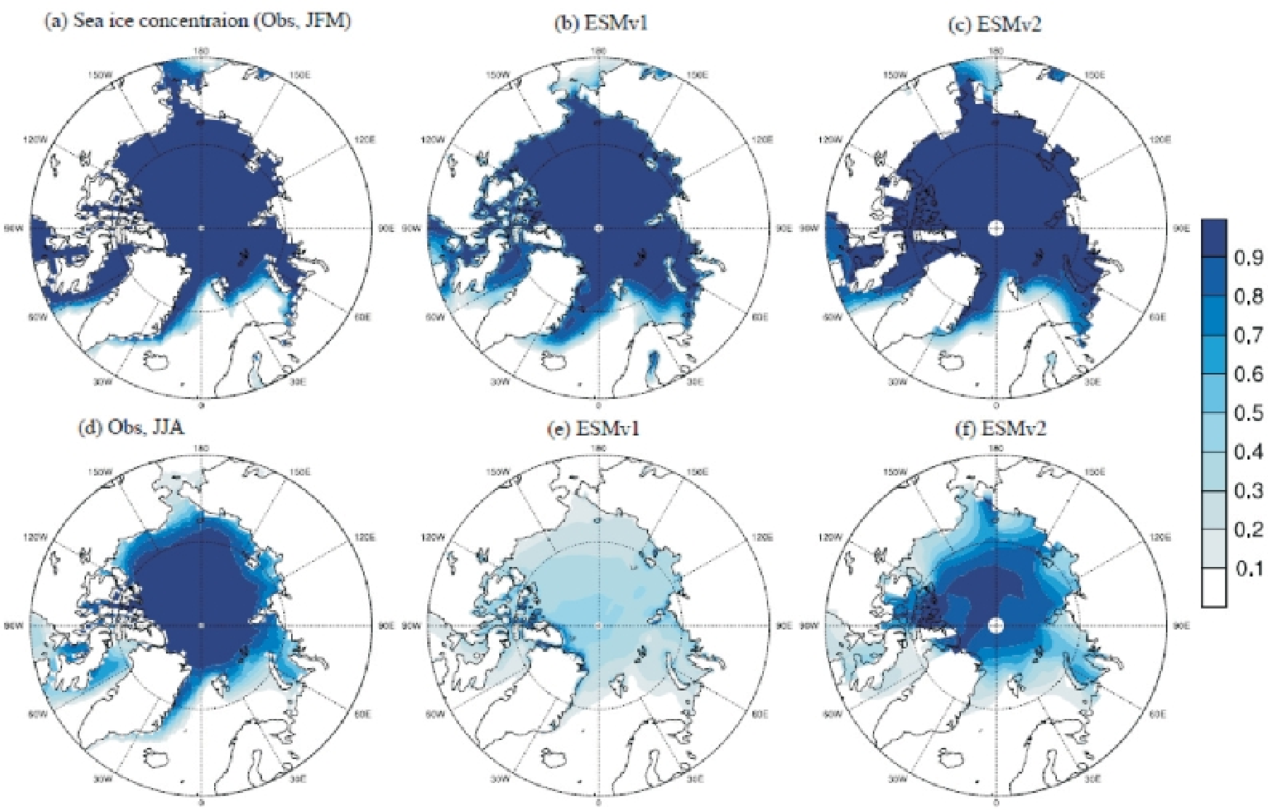



***Figure 3.7*** *Spatial map of mean sea-ice concentration (%) over the Arctic from observations (Hadley Centre) and IITM-ESMv1 and IITM-ESMv2 simulations* ***(a-c)*** *Winter and early Spring (Jan-Feb-Mar)* ***(d-f)*** *Northern Summer (Jun-Jul-Aug). The IITM-ESMv1 shows severely depleted sea-ice concentration during the northern summer as compared to observations. This bias in the sea-ice cover simulation is significantly remedied in IITM-ESMv2.*

## Box 3.1 Ongoing work and future plans

- Pre-Industrial (PI) control experiment of IITM-ESMv2 following the CMIP6 protocols is ongoing using the High Performance Computing (HPC) at IITM, Pune. This is a multi-century (> 500 years) simulation based on the pre-industrial conditions of GHG, aerosols, land-use & land-cover and other forcing. In addition special experiments are planned to understand long-term climate variability and trends during the 20th century and future projections (Figures 3.8, 3.9) as part of CMIP6 (please see list below). Completion of all the experiments, analysis of results, assessment and scientific publications of the CMIP6 simulations are targeted from 2017 through 2020.

    - PI Control (> 500 years)
    - Historical simulation (1850-2014)
    - AMIP Historical simulation forced with observed SST and sea-ice (1979-2014)
    - Transient climate sensitivity experiments by increasing $CO_2$ at 1% per year until quadrupling
    - Abrupt $CO_2$ quadrupling experiment
    - Future projection for 21st century (2015-2100) as per the CMIP6 protocols,
    - Global Monsoon MIP (Model Intercomparison Project) for the period 1850-2014.

- The CMIP6 data will be disseminated to all users using the Earth System Grid Federation (ESGF) node that has been setup at CCCR, IITM, Pune (Figure 3.10). The dissemination of CMIP6 data is targeted from 2019 through 2020.

- The development of next generation IITM ESM, which would include interactive aerosols and chemistry and improved physical processes, is planned in the next 5 years. In addition, we plan to generate very high-resolution (grid size ~ 27 km) climate change simulations and future projections using the atmospheric-only component of the IITM ESMv2 in the next 3-4 years. The high-resolution climate change projections are important for assessment of changes in weather and climate extremes.

- **High-resolution 20th century simulations and 21st century projections:** In addition to the IITM-ESMv2 Research and Development activities, the CCCR has generated high-resolution simulations of 20th century climatic variations and future projections using a global atmospheric model with telescopic zooming (~ 35 km in longitude x 35 km in latitude) over the South Asian region (Ref: Sabin et al. 2013, Krishnan et al. 2016). These high-resolution projections are useful to understand changes in monsoon rainfall, precipitation extremes, heat waves, droughts and floods, changes in cyclonic weather systems, hydrological cycle etc. Model outputs of the rainfall and temperature from the high-resolution simulations are made available for downloads http://cccr.tropmet.res.in/home/workshop/sept2014/index.html

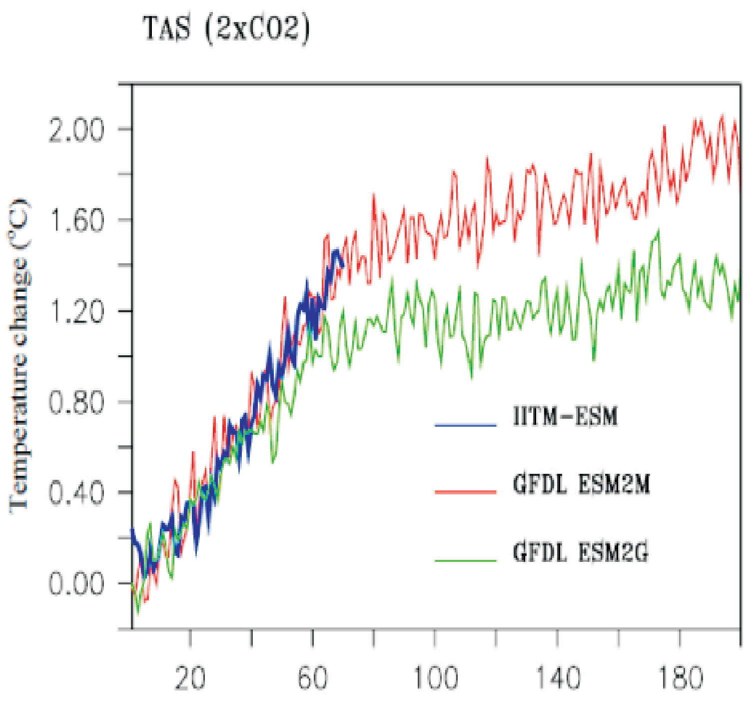
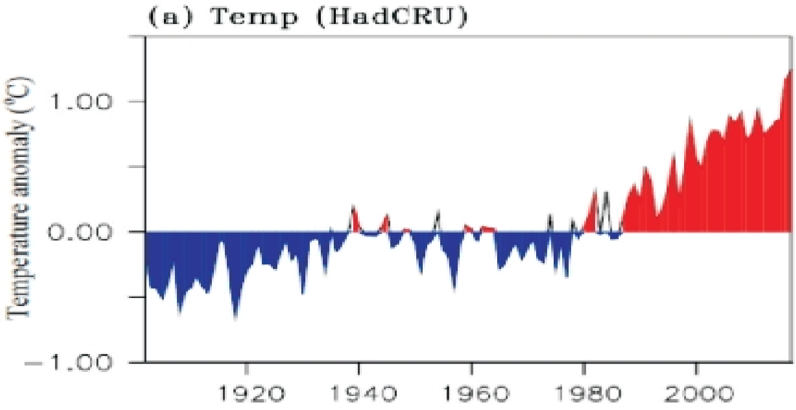



**Figure 3.8** Time-series of simulated global mean surface temperature (°C) anomalies based on the transient climate sensitivity experiments of the IITM-ESMv2 and the Geophysical Fluid Dynamics Laboratory (GFDL, USA) models (ESM2M and ESM2G) shown for comparison. The temperature anomalies are with respect to the PI control experiment. In the transient climate sensitivity experiment, CO2 is increased at a rate of 1% per year until doubling and thereafter it is kept constant. It can be noticed that the temperature increase in the IITM-ESMv2 is comparable with that of the GFDL-ESM2M, whereas the GFDL-ESM2G shows lower climate sensitivity. The IITM-ESMv2 and GFDL-ESM2M use the same ocean component, so that the oceanic heat uptake is similar in the two models, which may explain the similar response of global temperatures to increasing $CO_2$.



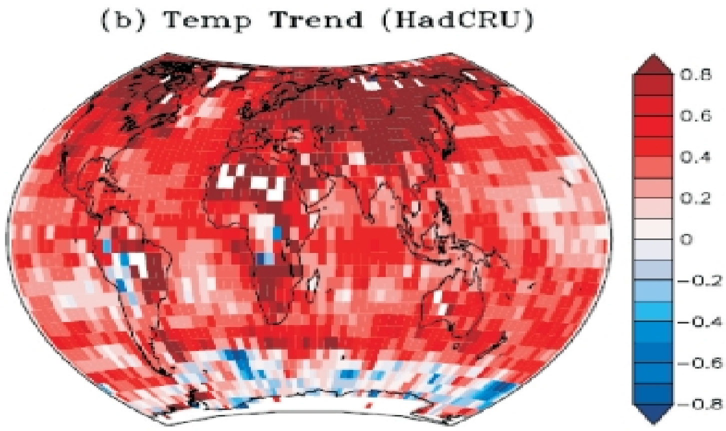




***Figure 3.9 (a)*** *Time-series of the observed global mean surface temperature (°C) anomalies for the period 1900-2016. A clear increasing trend [~ 0.85°C (116 years)$^{-1}$] in the global mean temperatures can be noted* ***(b)*** *Spatial map of linear trend in surface temperature over the period (1900-2016). Notice that the spatial pattern of warming is not uniform. The warming trend is stronger over the extra-tropical regions of North America, Europe, Asia, South America, Africa and Australia, and relatively smaller in magnitude over the tropical and near-equatorial areas. Special modeling experiments are included as part of the CMIP6 activity for detection, attribution and future projection of spatio-temporal variability of the climate change signal.*

***Figure 3.10 Dissemination of CMIP6 and CORDEX South Asia datasets from CCCR, IITM, Pune:*** *The Earth System Grid Federation (ESGF) maintains a global system of federated data centers that allow access to the largest archive of climate data world-wide. The ESGF Data Node at CCCR-IITM is focused on supporting CCCR-IITM climate model datasets (eg., CORDEX-South Asia and CMIP6).*

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