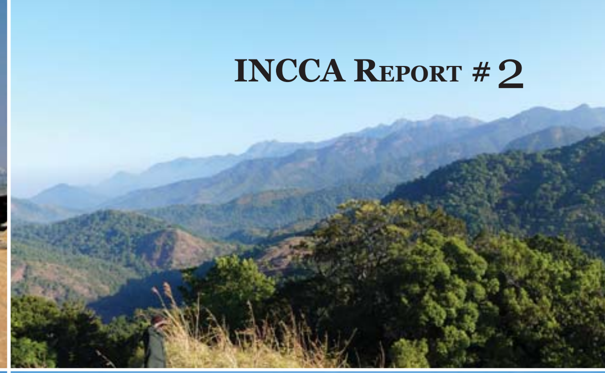
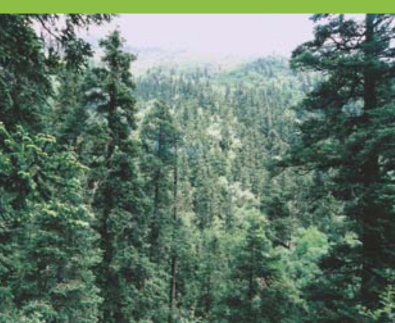
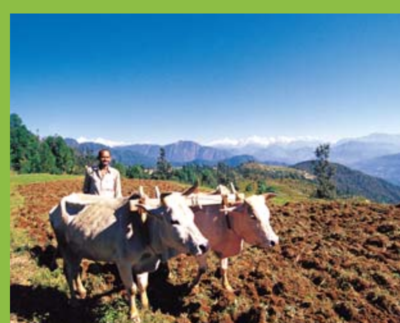
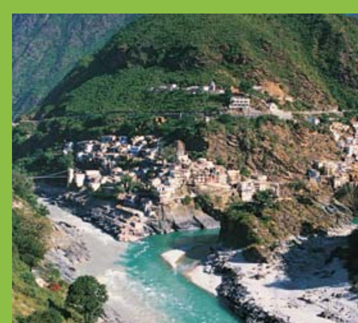
INCCA Report # 2

Climate Change and India: A 4x4 Assessment

A sectoral and regional analysis for 2030s



INCCA: Indian Network for Climate Change Assessment

November 2010

सत्यमेव जयते

Ministry of Environment & Forests
Government of India

Climate Change and India: A 4x4 Assessment

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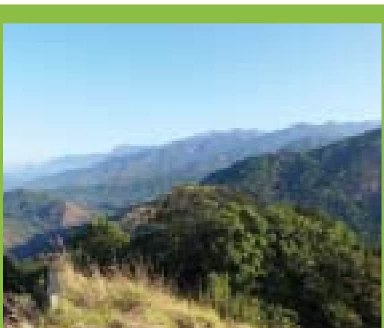

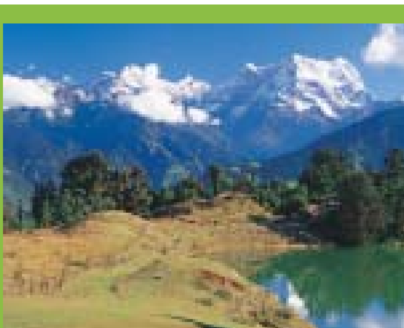

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Acknowledgement

The Indian Network for Climate Change Assessment (INCCA) is a network-based programme of the Ministry of Environment & Forests, which consists of over 120 institutions and over 250 scientists country wide. The Ministry takes the opportunity to acknowledge the work of a large number of scientists and experts on various aspects of climate change, particularly those who have contributed to the INCCA Assessments. Understandably, the contributions of various scientists/ experts associated with this assessment have also in turn received assistance from various institutions and agencies. The Ministry appreciates and acknowledges their cooperation and support.

Contents

Foreword

I have great pleasure in introducing the report "***Climate Change and India: A 4X4 Assessment A sectoral and regional analysis for 2030s***", prepared by the Indian Network for Climate Change Assessment (INCCA). This report provides an assessment of impact of climate change **in 2030s on four key sectors** of the Indian economy, namely *Agriculture, Water, Natural Ecosystems & Biodiversity and Health* in four climate sensitive regions of India, namely the *Himalayan region, the Western Ghats, the Coastal Area and the North-East Region*. It is for the first time that such a comprehensive, long term assessment has been undertaken based on rigorous scientific analysis. It is also for the first time that an assessment has been made for the 2030s (all previous assessments were for the 2070s and beyond).

As I have said in the past, **no country in the world is as vulnerable, on so many dimensions, to climate change as India.** Whether it is our long coastline of 7000kms, our Himalayas with their vast glaciers, our almost 70million hectares of forests (which incidentally house almost all of our key mineral reserves) – we are exposed to climate change on multiple fronts. Rigorous science based assessments are therefore critical in designing our adaptation strategies.

It was in this context that we formally launched the Indian Network of Climate Change Assessment (INCCA) last year. **INCCA is a network-based programme that brings together over 120 institutions and over 220 scientists from across the country to undertake scientific assessments of different aspects of climate change assessment.** As I have stated earlier, we need to make the "3 M's" – **Measure, Model and Monitor** – the foundation of our decision-making and we need to build indigenous capacity for this. We should not be dependent on external studies to tell us for example about the impact of climate change on our glaciers, on our monsoons, and indeed even on sea level rise. Indeed, recent evidence suggests the "scientific consensus" on many of these is debatable.

We need to build our own independent and credible research capacity on these issues. This report is a step in this direction. In particular, the knowledge and understanding of impacts as deduced from the Global Circulation Models and Regional Climate Models are not adequate to assess the impacts and implications for India. A need has been felt for comprehensive national as well as state level impact assessment. This assessment is an attempt to use PRECIS (providing climate investigation studies) based on HadRM (Hadley Regional climate Model) to generate climate change scenario for 2030s.

This is the third major publication of INCCA and I look forward to many more. I congratulate the scientists and experts associated with this Study.

Jairam Ramesh
Minister of State for Environment & Forests
(Independent Charge),
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1

The Context

Climate change is recognized as a significant man-made global environmental challenge. It is also treated as a threat. International efforts to address climate change began with the adoption of the United Nations Framework Convention on Climate Change in 1992. The importance and significance of the vulnerability of natural and human systems to climatic changes and adaptation to such changes is increasingly being realized. Consequently, there is now a growing recognition of the vulnerability and impacts of climate change on the key sectors of economic development. The Intergovernmental Panel on Climate Change (IPCC) has clearly concluded that the impact of human activities on climate is unequivocal (IPCC< 2007). The debate is the extent and magnitude of climate change. The 4th Assessment of the IPCC provides the latest understanding on the science, impacts, vulnerabilities, adaptation and mitigation of climate change.

The state of knowledge available at the global level is at the continental level and the details at the regional and sub-regional levels are rather inadequate. Wide ranging implications and adverse impacts due to climate change have been projected on developing countries. The assessment emphasizes the need for more comprehensive studies and information at the regional, national, at sub-national levels and at climate sensitive regions wherein the climate of a region is locally driven by topography, location, its proximity of the area to the sea and oceans.

1.1 The Indian Network for Climate Change Assessment

The knowledge and understanding of implications of climate change at the national level is inadequate and fragmentary. The Minister for Environment and Forests on October 14, 2009 announced the launch of the Indian Network for Climate Change Assessment (INCCA), which has been conceptualized as a Network-based Scientific Programme designed to:

- Assess the drivers and implications of climate change through scientific research
- Prepare climate change assessments once every two years (GHG estimations and impacts of climate change, associated vulnerabilities and adaptation)
- Develop decision support systems
- Build capacity towards management of climate change related risks and opportunities

It is visualized as a mechanism to create new institutions and engage existing knowledge institutions already working with the Ministry of Environment and Forests as well as other agencies (MoEF, 2009). Currently, the institutions of the various Ministries such as that of Ministry of Environment & Forests, Ministry of Earth Sciences, Ministry of Agriculture, Ministry of Science & Technology, Defence Research and Development Organisation etc., along with the research institutions of the Indian Space Research Organisation, Council of Scientific and Industrial Research, Indian Council of Agriculture Research, Department of Science & Technology, Indian Council of Medical Research, Indian Institute of Technology, Indian Institute of Management and prominent state and central Universities, and reputed Non-Governmental Organisations and Industry Associations are working in the various studies on climate change. The scope of the programmes under INCCA has been developed on the basis of the fundamental questions that we ask ourselves for climate proofing systems and the society dependent on climate and include, *inter alia*:

- Short, medium and long-term projections of climate changes over India at sub-regional scales
- The impact of changes in climate on key sectors of economy important at various regional scales
- The anthropogenic drivers of climate change i.e. greenhouse gas and pollutants emitted from various sectors of the economy
- The processes through which GHGs and pollutants interact with the climate system and change the biophysical environment

The mandate of INCCA would continue to evolve to include the new science questions that confront humanity including the population living within the Indian region. The aim of scientific research under INCCA is envisaged to encompass research that will develop understanding on the regional patterns of climate across India, how it is changing over time and likely to behave in the future. Consequently, INCCA will also focus on the impacts of the changing climate on regional eco-system hotspots, human systems and economic sectors. When INCCA was launched in October 2009, the following programmes were contemplated to be carried out under the aegis of INCCA:

- A provisional assessment of the Green House Gas emission profile of India for 2007 [Published in March 2010]
- An assessment of the impacts of climate change on water resources, agriculture, forests and human health in the Himalayan region, North-Eastern region, Western Ghats and Coastal regions of India [presented in this document].
- Undertake an assessment of black carbon and its impact on eco-systems.
- Undertake a long-term ecological, social, and economic monitoring of eco-systems to identify patterns and drivers of change that influence the sustainability of livelihoods dependent on these systems across India.
- Build capacity through thematic workshops and training programmes and
- Synthesize information thus generated in appropriate communication packages for informed decision making

Climate change may alter the distribution and quality of India's natural resources and adversely affect the livelihoods of its people. With an economy closely tied to its natural resources such as agriculture, water, and forestry, India may face major threat because of the projected changes in climate (NAPCC, 2007).

1.2 The 4x4 assessment

Climate change has enormous implications to the natural resources and livelihoods of the people. The available knowledge suggests adverse implications to key sectors of the economy. Accordingly, a 4x4 assessment has been devised to ascertain the impacts in 2030's. The choice of the sectors and regions is in conformity with the significance and importance of the climate sensitive sectors of the economy that cover the well being and livelihoods of the large population residing in these regions. The present assessment attempts to bring together what is known as four major regions in India, namely, Himalayan region, the North-Eastern region, the Western Ghats and the Coastal Region in regard to observed climate and climate change projections for the year 2030s on 4 key sectors such as the agriculture, water, natural ecosystem, biodiversity and health.

The report has been organized into 9 chapters, namely, (1) Context; (2) The Key Sectors and Regions; (3) The

A schematic representation of the programmes in INCCA is shown in figure 1.1.

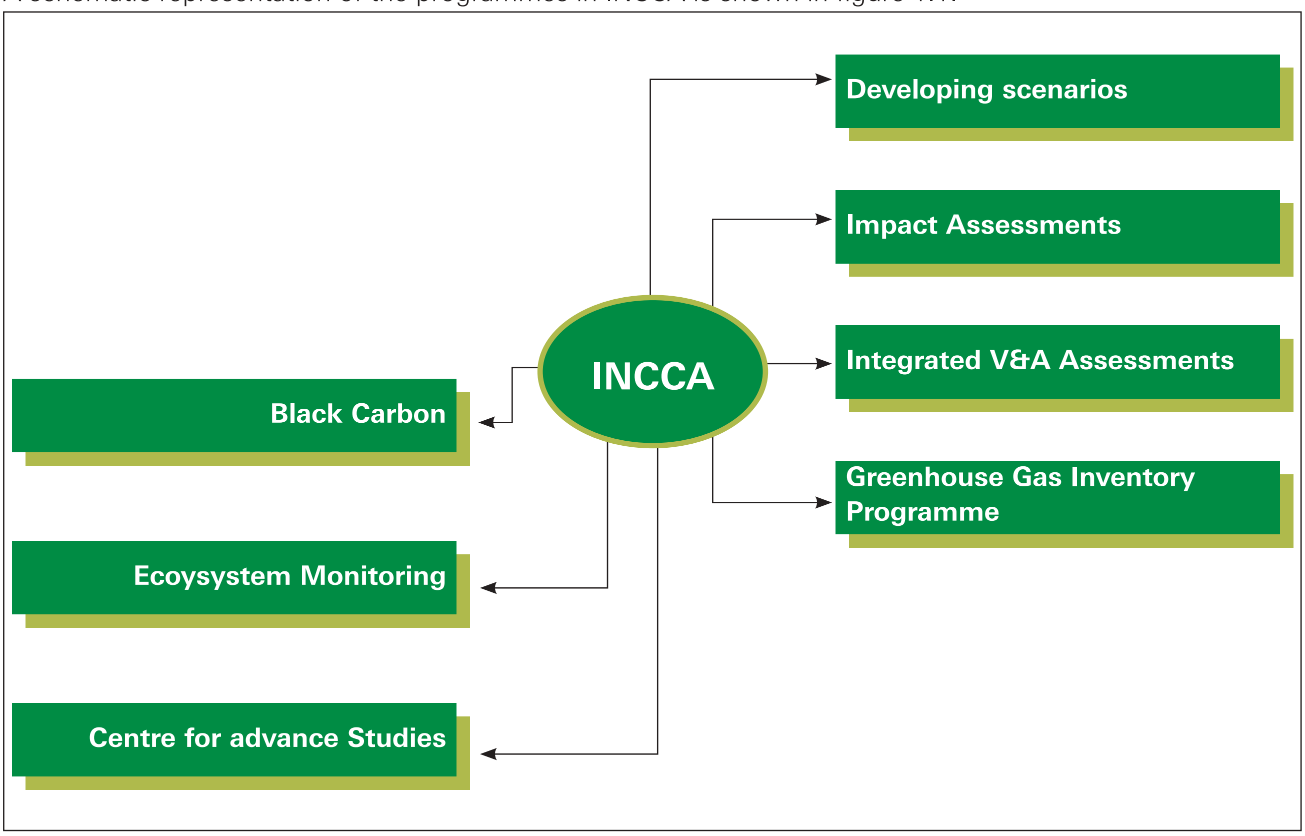


Figure 1.1: Programmes envisaged under INCCA

observed climate and climate change projections; (4) Observed Sea-level Rise, Extreme Events and Future projections; and then impacts of climate change on (5) Agriculture; (6) Natural ecosystems and biodiversity; (7) Human health; (8) Water and the last chapter deals with the (9) Salient findings, Challenges of the Assessment and Way Forward. A brief description of the coverage in the various chapters is provided in the following:

Chapter 2- Key sectors and regions: The assessment is unique in nature as the focus is on the 4 eco- sensitive regions of the country, namely, the Himalayan region, the North-Eastern region, the Western Ghats and the Coastal regions, each having a very distinctive bio-diversity. This chapter provides a description of these areas, its extent, its unique bio-diversity and socio-economic features. The other sections of this chapter briefly describe the methodology used for developing the regional climate scenarios including the scenarios of extreme events using the regional climate model PRECIS run on A1B socio-economic scenario. It further briefly describes the approach of assessing the impacts of climate change on sea-level rise and associated extreme events such as cyclones and storm surges. These projections then form the inputs to assessing the impacts of climate change on (a) agriculture; (b) Natural Ecosystems and Forests, (c) Human Health and (d) on Water yields in the different river basins that are a part of the 4 regions under focus.

Chapter 3- The observed climate and climate change projections: This chapter examines the long-term trends in observed annual and seasonal temperature, precipitation and pattern of extreme events over India using a century long data. It exclusively describes the observations for the four regions, which are in focus in this document. The projected climate in 2030's (average of 2021-2050) over India and over its sub-regions has been generated using regional climate model PRECIS – a version of the regional climate model HadRM3, developed by UK. The Greenhouse gas scenario is driven by the A1B socio-economic scenario developed by the IPCC that assumes significant innovations in energy technologies including renewables, which improve energy efficiency and reduce the cost of energy supply. The chapter describes the changes in projected climate in 2030's with respect to the observed climate of the 1970's (average of 1961-1990). Changes in frequency and intensity of extreme rainfall events have also been examined.

Chapter 4 - Observed Sea-level Rise, Extreme Events and Future projections: This chapter presents the long term trends of sea-level rise across the Indian coast, based on tide gauge records available from Mumbai, Kochi, Visakhapatnam and Diamond Harbour. Further, the chapter describes the frequency distribution of tropical cyclones in the Arabian sea, Bay of Bengal and the North Indian sea. Using the outputs of the regional climate change model PRECIS, the assessment discusses the future projections of sea-level rise across the Indian coast. In terms of, (a) the near-tem projections up to 2020, which are a result of, committed climate change and (2) the long-term projections of sea-level rise, which are in line with the global projections.

Further, it describes the frequency distribution in the future climate (2071 to 2100) using A2 socio-economic scenario which assumes a self-reliant nation, with continuously increasing population, regionally oriented economic development and slower and more fragmented technological changes. This chapter also analyses the frequency of occurrence and intensity of storm surges in the Bay of Bengal region using a storm surge model developed for the baseline scenario and future climate scenario for the period 2071-2100. Further, the chapter explores the extent of inundation due to a sea-level rise of 1m and 2m, in 2 low lying areas along the Eastern coast and one along the western coast that are sensitive to changes in sea level. These regions are Nagapattinam in Tamil Nadu; Paradeep in Orissa; and Kochi, a low-lying region characterized by the presence of backwaters.

Chapter 5- Agriculture: Agriculture in the four ecologically significant regions under consideration in this document is multi-dimensional, ranging from rice-based agriculture, horticultural crops, plantations, fisheries and dairy. The projected changes in climate such as increase in temperature, change in frost events and glacier melt are likely to influence the hill agriculture. Sea-level rise is another climate change related threat, which has potential influence on the coastal agriculture. Keeping in mind these potential threats, efforts have been made in this assessment to identify the impacts of climate change in the 2030's on important crops of these regions, fisheries in the coastal regions and on dairying. The information provided here is largely based on simulation modeling of impacts such as the InfoCrop model used for generating the impacts on crop productivity, but also supported by literature survey.

Chapter 6- Natural ecosystems and Biodiversity: Climate is one of the most important determinants of global vegetation patterns and has significant influence on the distribution, structure and ecology of natural eco-systems including forests. Changes in climate alter the configuration of forest eco-systems. Based on a range of vegetation modelling studies, IPCC (2007) suggests significant forest dieback towards the end of this century and beyond, especially in tropical, boreal and mountain areas. So far, several studies have been carried out that assess the impacts of climate change on forests by the end of the century in India. However, considering the policy relevance of developing adaptation strategies to ensure a sustained flow of ecosystem services, including conservation of biodiversity from the forests, a need was felt for a more near-term projection for 2030's.This chapter makes an attempt to assess the impact of climate change on Indian forest vegetation type by feeding the climate scenario outputs of the PRECIS forced by A1B socio-economic scenario onto a dynamic forest vegetation model IBIS. The assessment is of course made for the four eco-sensitive regions Western Ghats, the Himalayas, the Coastal regions, and the North-Eastern regions of India.

Chapter 7- Human health: Human health depends on people having enough food and safe water, a decent home protection against disasters, a reasonable income and good social and community relations. Climate change is projected to have mostly negative and large health impacts on many population groups, especially the poorest, in large areas in the four regions. These could include direct health impacts such as heatstroke, and indirect impacts such as increased diarrhoea risk from water contamination via flooding, or higher risk of mortality from the impact of large-scale loss of livelihoods. The chapter qualitatively describes the major public health risks that are associated with climate change and associated changes in the eco-systems. Also, it defines the malaria transmission windows in terms of temperature and temperature plus humidity and uses the same to project the changes in occurrence of malaria in the various regions under consideration in 2030's with respect to the 1970's. The projected climate parameters are derived from the PRECIS run on A1B socio-economic scenario at 50km x 50 km resolution.

Chapter 8- Water: This chapter first reviews the water resources in India, and the studies carried out so far to assess the impact of climate change on water resources by the end of the 21st century. In the subsequent sections it gives the description of changes in water yield in 2030's with respect to 1970's in river basins that are a part of the 4 regions under focus. Climate outputs from PRECIS regional climate model run on A1B IPCC SRES socio-economic scenario form the inputs to the hydrologic model SWAT (Soil and Water Assessment Tool - see chapter 8 for details of the tool) to assess not only the potential impacts of climate change on water yield but also other hydrologic budget components such as evapo transpiration and sedimentation yields. Further, the outputs from the hydrological model have been used to assess the impact of the climate change on the river basins for the same regions in terms of occurrence of droughts and floods. Soil moisture index developed to monitor drought severity has been developed using SWAT output to understand the spatial variability of agricultural drought severity.

Chapter 9- Salient findings, Challenges of the assessment and Way Forward: This chapter first synthesizes the salient findings emerging from the earlier chapters that highlight the impacts of climate change in 2030's on agriculture, natural ecosystems and biodiversity, human health and water in the Himalayan region, the North-Eastern region, the Western Ghats and on the Coastal region. Further, the chapter discusses the challenges, data gaps and uncertainties associated with the modeling aspects of the assessment. Subsequently, the way forward has been discussed which will make the assessments more scientifically rigorous and relevant to policy making. It addresses the issues of data gaps, undertaking systematic observations for developing critical country/region-specific inputs to the models, reducing uncertainties in climate change assessment through access to a larger number of regional models, and building capacity to undertake such measures has been suggested. Also, the way forward section of the chapter suggests undertaking further assessments at all the climatic zones and at state levels to bridge the gap between policy and science.

2

Key Sectors and Regions

The Climate Change Assessment Reports brought out by the Intergovernmental Panel on Climate Change since 1990 have progressively tracked the development and build-up of the knowledge and understanding of the science, impacts and mitigation of climate change at the global level as well as at the regional level. However, the observed changes at the physical and bio-physical are not very comprehensive. There is a need for more comprehensive studies at regional and sub-regional levels. The impact of climate change in short and medium term on key sectors of economy will be required to be studied at the national and provincial levels.

The present assessment attempts to bring together what is known as four major regions in India, namely, Himalayan region, the North-Eastern region, the Western Ghats and the Coastal Region in regard to observed climate and climate change projections for the year 2030 on the 4 key sectors such as the Agriculture, Water, Natural ecosystem and biodiversity and Human health.

2.1 Observed climate and climate change projections

Constructing climate change scenarios for the future is the first step of any assessment, as this drives the changes in the impacts on natural resources. In order to do so, examination of the current trends of climate is also essential. This assessment examines the trends in observed seasonal temperature and precipitation over India using a century long data. This is done in the context of the changes in climate that are being observed globally. Since one of the drivers of climate is the greenhouse gases and their concentration, the chapter reviews the current knowledge about the changes in global and regional and national climate in the very near future i.e 2030's. The nature of the models available for projecting global and regional climate have been discussed.

With the availability of a hierarchy of coupled atmosphere-ocean-sea-ice-land-surface global climate models (AOGCMs), having a resolution of 250-300 km, it has been possible to project the climate change scenarios for different regions in the world. The present assessment first describes the changes in climate in 2030's with respect to 1970's for the South Asian region. The projected climate change over this region for 2030's is an average of projections for the period 2021 to 2050 and is made using selected models from Coupled Model Inter-comparison Project 3 (CMIP3).

India has a unique climate system dominated by the monsoon, and the major physio-graphic features that drive this monsoon are its location in the globe, the Himalayas, the central plateau, the western and eastern ghats and the oceans surrounding the region. The global models fail to simulate the finer regional features, including the changes in the climate arising over sub-seasonal and smaller spatial scales. Keeping these limitations in view, the assessment describes the simulations and projections of climate for 2030's at a sub-regional scale, such as the Himalayan region, the North-East, the Western Ghats and the Coastal regions that are the focus of consideration in this assessment, using a regional model PRECIS developed by the Hadley centre, UK having a resolution of 50 km by 50 km. The GHG forcing for the future on the climate models is derived from the IPCC A1B socio-economic scenario (see chapter 4 for description of the scenario) that assumes significant innovations in energy technologies including renewables, which improve energy efficiency and reduce the cost of energy supply.

2.2 Sea level rise, extreme events and projections

India has a long coastline of more than 7500 km. The impacts of climate change at the coast occur at long-term scales. Sea-level rise and changes in the occurrence of frequency and intensity of storm surges are the consequences of climate change in the coastal sector. While sea-level rise is a global phenomenon, occurrence of storm surges is of particular concern to time scales, which are generally assessed for the turn of the century.

This chapter studies the long-term trends of sea-level rise across the Indian coast, based on long-term tide gauge records (more than 50 years) available from Mumbai, Kochi, Visakhapatnam and Diamond Harbour These estimates are corrected for vertical land movements, caused by glacial isostatic adjustment. The assessment also discusses the future projections of sea-level rise across the Indian coast. The projections are mostly available at a global scale and for the end of the 21st century. Near-term projections up to the 2020's are also available which are a result of committed climate change. The regional variations in sea-level rise with respect to global sea-level rise are manifestations of tectonic changes and ocean density. Since the future changes in these conditions have not been integrated in the projections, near as well as long-term changes in sea level across the Indian coastline are taken to be the same as the global projections.

Simulations of the Regional climate model (PRECIS) for the north Indian Ocean region have been analysed to determine the frequency distribution of tropical cyclones in the Bay of Bengal. The Bay of Bengal region has been chosen for the analysis as a significant number of cyclones have been observed to have occurred in the last 100 years in Bay of Bengal as compared to the Arabian Sea. The frequency distribution in the future climate scenario has been generated using A2 socio-economic scenario for the period 2071 to 2100. The A2 scenario assumes self-reliant nations, with continuously increasing population, regionally oriented economic development and slower and more fragmented technological changes and improvements to per capita income.

Besides the changes in mean sea level, changes in extreme sea level occur through storm surges, in particular along the east coast. This chapter makes extreme sea level projections using a storm surge model developed for the Bay of Bengal for the baseline scenario and future climate scenario for the period 2071-2100. The model is forced by wind fields and surface atmospheric pressure obtained from PRECIS run on A2 scenario with a sea-level rise of 4 mm/year since 1990. This is in consonance with the projected increase in the A1B scenario.

Further, inundation of land area for 1m to 2m sea-level rise have been analysed for three regions along the Eastern coast that are sensitive to changes in sea level. These regions are Nagapattinam in Tamil Nadu, which is characterized by a flat onshore topography, Paradeep in Orissa, an area with frequent occurrence of storm surges and Kochi, a low-lying region characterized by the presence of backwaters. The study helped in identifying potential vulnerable zones in areas characterized by different topographical features. Inundation maps prepared for a 1m and 2m sea-level rise indicate that these regions are highly vulnerable to sea-level rise and extreme events.

2.3 The four regions

2.3.1 The Himalayan Region

For the purposes of this assessment, the Himalayan Region comprises of the highest mountain system of the world, the Himalayas (Sanskrit: literally 'abode of snow') and the North-Eastern hill states. The region lies between 21°57′ and 37°5′ N latitudes and 72°40′ and 97°25′ E longitudes covering an area of 5,33,000 km2 (16.2% of the total geographical area of the country). It stretches over 2,500 km from Jammu & Kashmir in the west to Arunachal Pradesh in the

Index Map of Himalayan Region

Fig 2.1: Indian Himalayan Region

east, covering partially/ fully twelve states of India (Fig. 2.1), but its width varies from 150 km to 600 km at different places. From the foothills, the Himalayas rise rapidly northwards to over 8,000 m within a short distance and cover about 500, 000 sq. km. The heights are covered with perpetual snow, which feeds the valley glaciers, but the greater part of the Himalayas lies below the snow-line and is dissected by fluvial erosion. Being the youngest and loftiest mountain chain (more than 30 peaks exceeding 7,600 m in elevation) of the world and still rising, the Himalayan region is naturally unstable and fragile.

The Himalayas influence the climate of the Indian sub-continent by sheltering it from the cold air mass of Central Asia. The range also exerts a major influence on monsoon and rainfall patterns. They prevent frigid and dry arctic winds from blowing south into the subcontinent keeping South Asia much warmer when compared to regions located between corresponding latitudes throughout the globe. They are a barrier for the moisture-laden monsoon winds, preventing them from travelling further northwards and thus facilitating timely and heavy precipitation in the entire Northern India. Within the Himalayas, climate varies depending on elevation and location.

Natural vegetation too is influenced by the climate and elevation. Tropical, moist deciduous forest at one time covered all of the Sub-Himalayan area. With few exceptions, most of this forest has been cut for commercial lumber or agricultural land. The Himachal region, which at one point housed many species of pine, oak, rhododendron, poplar, walnut and larch, has been almost completely deforested. Forest cover remains only in a few inaccessible areas and on steep slopes. Below the timberline, the Himadri contains valuable forests of spruce, fir, juniper, cypress and birch.

Administratively it covers 10 states entirely i.e., Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, Meghalaya and two states partially i.e. the hill districts of Assam and West Bengal. More than 65% of its geographical area is under forests, representing one-third of the total forest cover and nearly half (46%) of the very good forest cover of the country. The forests of the region provide life supporting, provisioning, regulating, and cultural 'eco-system' services to millions of local as well as downstream people. Over 9,000 Himalayan glaciers and high altitude lakes form a unique reservoir storing about 12000 km^3 of fresh water.

The Himalayas are divided into three parallel or longitudinal zones, each with definite orographical features:

1. **Himadri** (the Great Himalaya) – It is the northern-most range with an average elevation of 6,000 m. The width of this zone, composed largely but not entirely of gneiss and granite, is about 24 km. It remains one of the few remaining isolated and inaccessible areas in the world today, although some high valleys are occupied by small clustered settlements. Musk deer, wild goats, sheep, wolves and snow leopards are some of the commonly found animals in this region. Extremely cold winters and a short growing season limit the farmers to one crop a year, most commonly potatoes or barley. The formidable mountains have limited the development of large-scale trade and commerce despite the construction of highways across the mountains linking Nepal and Pakistan to China.
2. **Himachal** (the Lesser/ Middle Himalaya) – It lies to the south of Himadri with a more or less uniform elevation of about 1830-3050 m. Some of the ranges contained in this zone are the Mahabharat, the Pir Panjal and Nag Tibba. It is a complex mosaic of forest-covered ranges and fertile valleys. Except for the major valley centers such as Srinagar, Kangra and Kathmandu and hill towns such as Shimla, Mussoorie and Darjeeling, the region is moderately populated. Within the Himachal, the intervening ranges tend to separate the densely populated valleys. The numerous gorges and rugged mountains make surface travel in any direction difficult. As a result of extensive deforestation, there is little animal life in this region.
3. **Siwalik** (Outer Himalayas) – It is the southernmost and lowest zone which forms the foothills of the Himalayas. A characteristic feature of this region is the large number of long, flat-bottomed valleys known as duns, which are usually spindle-shaped and filled with gravelly alluvium. South of the foothills lies the Tarai and Duars plains, the southern part of these are heavily farmed. Animals such as leopards, tigers, rhinoceroses and many varieties of deer once inhabited the forested areas of this region, but as a result of deforestation of their habitats, most of the wildlife has been destroyed. Major crops grown include maize, wheat, millet and mustard.

Nearly 40 million people inhabit the Himalayas (3.8% of the total population of the country). The economy of the Himalayas as a whole is poor with low per-capita income. Much of the Himalayan area is characterized by a very low economic growth rate combined with a high rate of population growth, which contributes to stagnation in the already low level of per-capita gross national product. Most of the population is dependent on agriculture, primarily subsistence agriculture; modern industries are lacking. Mineral resources are limited. The Himalayas have major hydroelectric potential, but the development of hydroelectric resources requires outside capital investment. The skilled labour needed to organize and manage development of natural resources is also limited due to low literacy rates. Most of the Himalayan communities face malnutrition, a shortage of safe drinking water, poor health services and education systems.

2.3.2 The Western Ghats

The Western Ghats, older than the Himalayas, also known as the Sahyadri Mountain, is not a true mountain range but only the eroded precipitous edge of the Deccan Plateau. The range starts near the border of Gujarat and Maharashtra, south of the river Tapti, and runs approximately 1600 km through the states of Maharashtra, Goa, Karnataka, Tamil Nadu and Kerala ending at Kanyakumari (see the extent of the region in figure 2.2). These hills cover 1,60, 000 km^2 and form the catchment area for a complex of river systems that drain almost 40% of India. The average elevation is about 1,200 m and the area is one of the world's ten hottest biodiversity hotspots.

There are approximately 5,000 vascular plant species in the Western Ghats, of which more than 34% species are endemic. There are also 58 endemic plant genera, and while some are remarkably speciose (like Niligrianthus, which has 20 species) nearly three-quarters of the endemic genera have only a single species. The Agasthyamalai Hills in the extreme south are believed to harbour the highest levels of plant diversity and endemism at the species level. The hotspot is home to about 11,000 animals. Among flagship mammal species, the most prominent are the lion-tailed macaque and the endemic Niligiri tahr. One of the most threatened Indian mammals, the Malabar civet is known only from the Malabar plains, which are densely populated and the focus of many development activities. The highest level of vertebrate endemism in the Western Ghats is among reptiles and amphibians. However, due to habitat loss, over 85 species of the latter are considered threatened.

Climate in the Western Ghats varies with altitudinal gradation and distance from the equator. The climate is humid and tropical in the lower reaches, tempered by the proximity to the sea. Average annual temperature is about 15^{o}C. In some parts frost is common, and temperatures touch freezing points during winter months. During the monsoon season between June and September, the unbroken Western Ghats chain acts as a barrier to the moisture-laden clouds. The heavy, eastward-moving rain-bearing clouds are forced to rise and in the process, deposit most of their rain on the windward side. Rainfall in this region averages 3,000-4,000 mm while the eastern region of

Index Map of Western Ghats

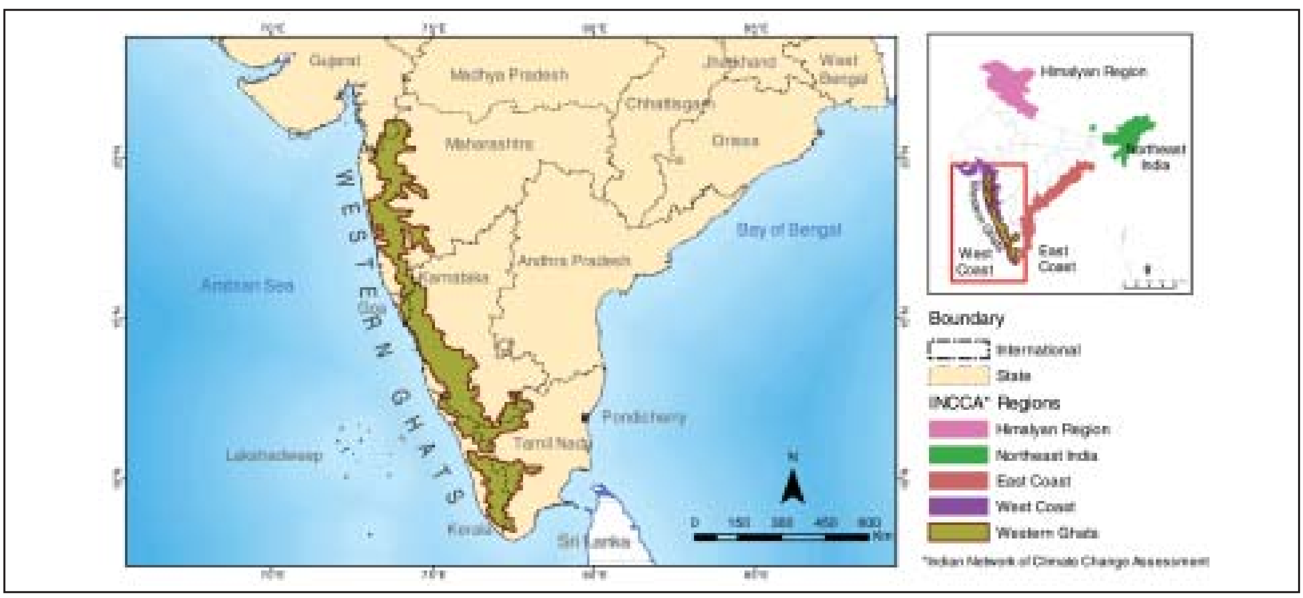


Figure 2.2: The Western Ghats

the Western Ghats receives far less rainfall (average of 1,000mm).

Principal crops include rice, *ragi, kodra, rabi jowar*, gram, groundnut, niger and sugarcane. The area under spices is about 353 ha. and that under fruits and vegetables is 2933 ha. The region has well-suited conditions for rain-fed crops and fruits such as mango, cashew, jackfruit, jamun and karwanda. About 25% area is under forest. The forests of the Western Ghats have been selectively logged and highly fragmented throughout their entire range. Forests have been converted to agricultural land, cleared for building reservoirs, roads and railways. Encroachment into protected areas further reduces the extent of forests. Grazing by cattle and goats within and near protected areas causes severe erosion on previously forested slopes. Much of the remaining forest cover consists of timber plantations or disturbed secondary growth. Today, approximately 20%of the original forest cover remains in more or less pristine state, with forest blocks larger than 200 km² found in the Agasthyamala Hills, Cardamom Hills, Silent Valley-New Amarambalam Forests, and southern parts of the South Kannada district in Karnataka state. Remaining forest patches are subject to intense hunting pressure and the extraction of fuel wood and non-timber forest products. Uncontrolled tourism and forest fires are additional concerns. The growth of populations around protected areas and other forests has led to increasing human-wildlife conflict.

2.3.3 North-Eastern Region

The North-Eastern region refers to the easternmost part of India, consisting of the contiguous 'Seven Sister' states namely Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland and Tripura along with Sikkim (see map in Figure 2.3). Ethnically, North-East India is linguistically and culturally very distinct from the other states of India. This region is officially recognized as a special category of states and covers an area of 2,62,179 sq. km (ref. Table1) constituting 7.9% of the country's total geographical area. It is a true frontier region as it has over 2000 km of border with Bhutan, China, Myanmar and Bangladesh. It has a total population of 39 million; about 3.8% of the total population of the country (2001 census), but the distribution of this number is very uneven with over 68% living in the state of Assam alone.

From times immemorial, the region has been the meeting point of many communities, faiths and cultures. It is the home for more than 166 separate tribes, 160 scheduled tribes and over 400 other tribal and sub-tribal communities and groups, speaking a wide range of languages. Some groups have migrated over the centuries from places as far as South East Asia. They retain their cultural traditions and values but are beginning to adapt to contemporary lifestyles.

Index Map of North East India

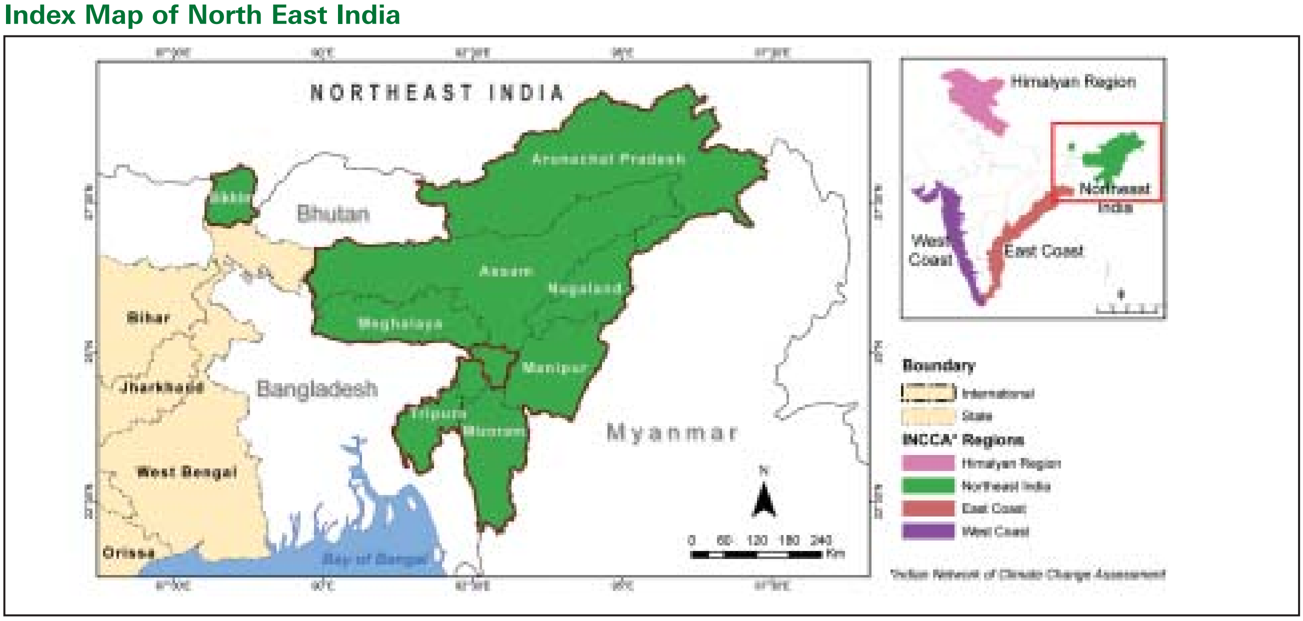


Fig.2.3: The North Eastern Region and its constituent states

For various reasons, the region has remained one of the most backward regions of the country. As a result of the partition, the access with the rest of the country trickled down to a mere 27 km wide Siliguri corridor leading to its isolation as a result of the constrained movements of people and goods. Poor infrastructure and governance combined with low productivity and market access has lead to the overwhelming dependence on the natural resources of this region. According to the 2001 census, the literacy rate is 68.4%; there are however, concerns over the quality of education, as the relatively high literacy level has not translated into high rate of employment or productivity.

The North-Eastern region is recognized as one of the world's biodiversity hotspots due to its rich natural endowments. The forest cover is about 52% of the total geographical area and petroleum and natural gas reserves of this region constitute about one-fifth of the country's total potential. Agriculture is the mainstay of most of the states.

The North-Eastern region has distinct climate variations. The rapid changes in topography result in climate changes within short distances. Generally, the daily temperature in the plains of Brahmaputra and the Barak Valley as well as in Tripura and in the western portion of Mizo Hills is about 15°C in January, whereas in other parts of the region, the temperature is between 10°C to 15°C. From April, it rises and in July except the south-eastern portion of Mizo Hills and Shillong, the mean temperature ranges from 25°C to 27.5°C. During October, daily mean temperature in the hilly areas ranges between 20°C and 25°C, whereas in Brahmaputra and Barak Valley, Tripura and the western portion of the Mizo Hills, it is above 25°C. Further, the lowest temperature is experienced below freezing point in the upper Himalayas in Arunachal Pradesh. The salient feature of the North-Eastern states is shown in Table 2.1.

North-East India is vulnerable to water-induced disasters because of its location in the eastern Himalayan periphery, fragile geo-environmental setting and economic under-development. The powerful hydrological and monsoon regime of the region, especially the Brahmaputra and the Barak (Meghna) river systems are both a resource and a source of vulnerability. Moreover, the average state of economic development and growth in the North-

Table 2.1: North-Eastern region: Various Indicators

S.No	State	Forest coverage (%) 2003	Area (sq. km. 2001)	Population (lakh persons)	Literacy Rate % (2001)	overty ratio based on MRP consumption2004-05
1.	Arunachal Pradesh	61.55	83,743	10.98	54.3	13.4
2.	Assam	34.45	78,438	266.55	64.3	15.0
3.	Manipur	78.0142.34	22,327	22.94	70.5	13.2
4.	Meghalaya	75.71	22,429	23.19	62.6	14.1
5.	Mizoram	52.05	22,081	8.98	88.8	9.5
6.	Nagaland	82.29	16,579	19.90	66.6	16.5
7.	Sikkim	60.01	7,098	5.41	68.8	15.2
8.	Tripura	54.52	10,486	31.99	73.2	14.4
9.	NER	23.57	2,62,179	389.84	68.5	13.9#
10.	India	23.57	32,87,240	10,287.37	64.8	23.6

Sources:

1. North Eastern Vision 2020 (2008)
2. Statistical Abstract of India (2006)
3. NEDFi Data Quarterly (2005), Vol. 4, No. II, April
4. Chapter 8 on Human Development Report
5. www.mospi.nic.in used for Col. 6.
6. http://www.planningcommission.nic.in used for Col. 5.
7. Note: # Simple averages used for NER; + Refers to estimated per capita GSDP for 2003-04 and 2004-05; ++ refers to its Estimated value for 2004-05; * Per capita GDP at factor cost (RE) from RBI, Handbook of Statistics on the Indian Economy, 2005-06.

East Indian region is lower than other parts of the country. The average per-capita income of the region is approximately 30 percent lower than the national average. Assam and Manipur have the lowest per-capita income in the region. The region has higher incidences of poverty, even when compared with states having similar average per-capita income. Increasing population and decreasing land productivity, relatively higher dependence on natural resources (e.g. forests) are also constraints for the region's environmental sustainability.

2.3.4 The Coastal Region

The coastline of India extends to 75,500 km as per the notification CRZ, 2010. Figure 2.4 shows the extent of coastal region. The coastal plains of India lie to both the eastern and western side of the peninsula. The western coastal plain of the peninsular plateau extends from Gujarat in the north to Kerala in the south. It lies between the Arabian Sea and the Western Ghats, and is a narrow strip of plain area ranging from 50 to 100 km in width, except in Gujarat. The Indian coastline can be divided into the Gujarat region, the west coast, the east coastal plains and the Indian islands.

The east of the Gujarat region comprises the Khambat or Cambay region. The delta on the Gulf of Cambay has an area of over 1,000 km^2 and a population of over 1.5 million. Some areas have a high population density of over 300 people / km^2. Most urban areas lie along the railways near the coast. Surat is the leading industrial district in this region, with about 16% of the industrial establishments of the State. Cambay region is also an important area for hydrocarbon production.

The west coast can be divided into 3 parts namely, Konkan, the Karnataka coast and the Malabar coast in Kerala. Vegetation is mostly deciduous, but the Malabar coast moist forests constitute a unique eco-region. Sand dunes and saline water lakes are found along the Malabar coast. The western coast is highly deserted, hence many national parks have been developed here. Numerous rivers and backwaters inundate the region. Originating in the Western Ghats, the rivers are fast flowing and mostly perennial, leading to the formation of estuaries. Major rivers flowing into the sea are the Tapti, Narmada, Mandovi and Zuari.

The coastal zone comprises of a narrow lowland plain, interspersed by hills, occasionally up to 300m. The shoreline comprises sand beaches, coastal sand dunes, mud flats and alluvial tracts at river mouths. The undulating lowlands of the Konkan are about 530 km long and 30 to 50 km wide. The landscape of the northern Konkan is characterized by sandy spits intruding into muddy shallows close to the sea and low coastal ranges alternating with longitudinal valleys farther inland. In contrast, the southern Konkan is rocky and rugged, with high hills and elevated plateaus, interspersed by creeks and navigable streams. The coast around Goa is characterized by estuaries, rias (rocky indented coast), and straight beaches between headlands.

Index Map of Coastal region

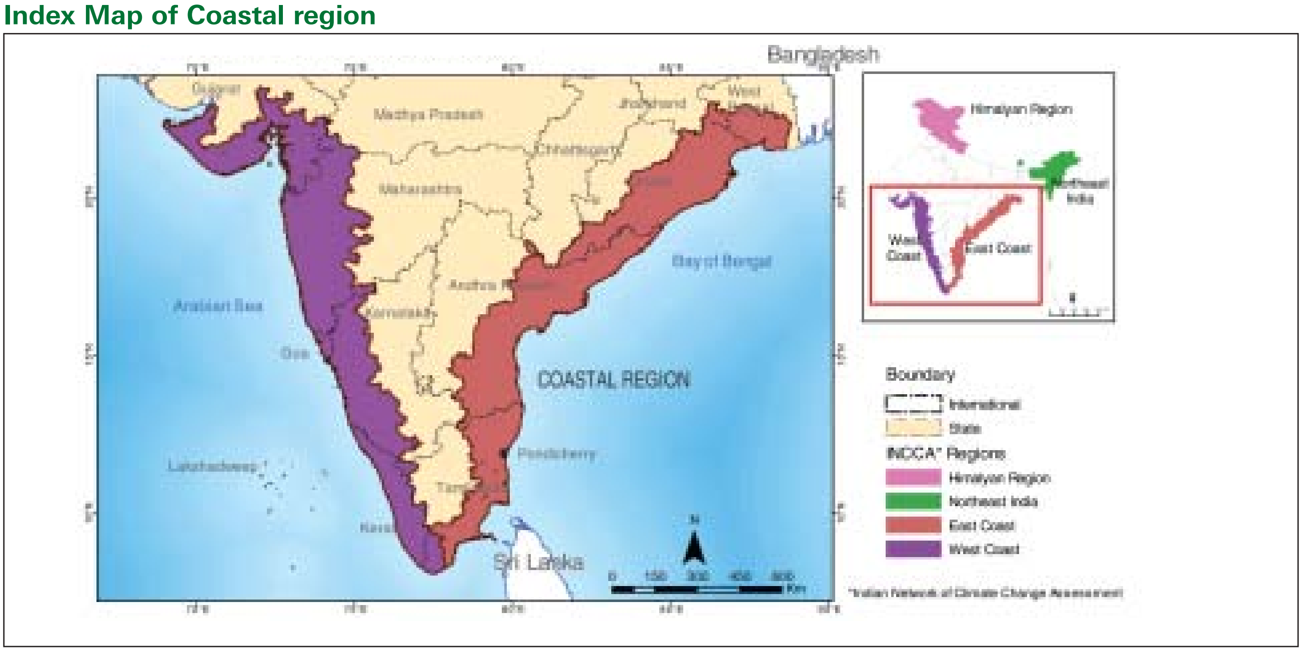


Figure 2.4: The Coastal region of India

The Malabar coastal zone is 550 km long and 20 to 100 km wide. Sand dunes, locally know as teris, are found along most of the Kerala coast, except south of the Kovalam. These Pleistocene and recent dunes have helped to form a large number of shallow lagoons and backwaters. The backwaters constitute an important physical feature of the Malabar coast.

The region has a total population of over 29 million. The main population centers are in the alluvial lowlands where rice cultivation occurs and around urban centers such as Mangalore, Ernakulam, Trivandrum and most importantly, Mumbai. Within this region, the Malabar coast has the highest population density with about 700 people / km^2 and the Karnataka coast has the least with 200 people / km^2.

The eastern coastal plain lies between the Eastern Ghats and the Bay of Bengal. It extends from West Bengal in the north to Tamil Nadu in the south. It covers about 1,03,000 km^2 with a population of about 83 million. The four major units of the eastern coastal plains are the Tamil Nadu coast, the Andhra coast, the Utkal coast and the West Bengal coast. The eastern coastal plains are more even, fertile and broad as compared to the western coastal plains. Almost all the major rivers form deltas on this coast. Numerous lakes are found along the coast; Chilka and Palicut are famous lakes among them.

This area is a wide coastal plain comprising four deltas: the Mahanadi, the Godavari, the Krishna and the Cauvery, besides the intervening tracts of older tertiary marine sediments. In addition, a part of the Ganges-Brahmaputra delta falls on Indian territory near Kolkata. The total area of the East coast exceeds 20,000 km^2 with a population of 19.9 million. The coastal plain is widest in the deltaic regions, having well-defined morphological units parallel to the shoreline. Sandbars often form in front of the river mouths, for example, the Godavari and the Mahanadi rivers.

Sand dunes occur along the coast, sometimes extending up to 10 km inland. The dunes support a thin vegetation of Palmyra Palms and thorny scrubs. Some of these dunes are still active under wind actions and migrate slowly towards east and southeast.

Adjoining the line of sand dunes along the coast, are lagoons formed by coastal uplift; the Chilka Lake and the Palicut Lake areas are the largest and most important of these. The Chilka Lake is located on the southwest edge of the Mahanadi delta. It is the largest brackish water body in India, its area varying between 800 to 1150 km^2 from the winter to monsoon months. The salinity also varies seasonally. Farther south, on the border of Andhra and Tamil Nadu is the Palicut Lake, a brackish backwater lake. It occupies an area of approximately 800 km^2 and is connected to the sea.

Agriculture has been the dominant occupation in the coastal plains since ancient times. However, the three sub-regions differ appreciably in their agricultural characteristics. While rice cultivation is always predominant, jute in Utkal, tobacco and oil-seeds in Andhra Pradesh and the groundnut and cotton in Tamil Nadu create a regional distinctiveness in agriculture. Large-scale industry is not significant due to a lack of raw materials. Tamil Nadu is the most industrialized state.

The temperature in the coastal regions exceeds 30°C coupled with high levels of humidity. The region receives both the northeast and southwest monsoon rains. The southwest monsoon splits into two branches - the Bay of Bengal branch and the Arabian Sea branch. The Bay of Bengal branch moves northwards crossing northeast India in early June, while the Arabian Sea branch moves northwards and discharges much of its rain on the windward side of the Western Ghats. Annual rainfall in this region averages between 1,000 mm (40 in) and 3,000 mm (120 in).

About 20% of the population of India lives in the coastal areas, a larger percentage of this being in coastal cities, such as Mumbai, Chennai and Kolkata. One of the major factors responsible for the degradation of coastal ecosystems is the growth in human population that requires space for settlement and other resources, like soil and water.

2.4 The four sectors

2.4.1 Agriculture

The assessment provided in this publication reviews the studies that project the changes of impact of climate change on various types of crops in the Indian region that confirm decline in agricultural productivity with climate change. However, agricultural impacts in special ecosystems that are ecologically and economically very important, such as the Western Ghats, Coastal areas, North-Eastern region and Himalayan ranges, have not received adequate attention. Agriculture in these areas is multi-dimensional, ranging from rice-based agriculture, horticultural crops, plantations, fisheries and dairy. The projected changes in climate such as increase in temperature, change in frost events and glacier melt are likely to influence the hill agriculture. Sea-level rise is another climate change related threat, which has potential influence on the coastal agriculture and fisheries.

Keeping these potential threats in view, this chapter analyses the impacts of climate change on agriculture in the eco-sensitive regions of North-East, Western Ghats and the Coastal regions for the 2030's on

- Four cereals, namely, wheat, rice, maize and sorghum;
- Coconut plantations
- Coastal fisheries and
- Dairy

The impacts have been assessed using a simulation model called InfoCrop. InfoCrop is a generic crop growth model, developed by the Indian Agriculture Research Institute, that can simulate the effects of weather, soil, agronomic managements and major pests on crop growth and yield. The analysis has been done for every 1° x 1° grid in the entire zones of the ecosystem, Soil data rescaled to grid values from NBSSLUP (National Bureau of Soil Science and Land Use Planning) and ISRIC soil data base (World Soil Information), data on crop management practices as followed by the farmer, genetic co-efficients of varieties best suitable for different regions and climate change scenarios of PRECIS A1b for 2030 periods.

The Himalayan region has a distinctive entity as the variations in topographical features occuring along its three-dimensional framework (i.e., latitudinal: East-West; longitudinal: South-North; altitudinal: Low-High) cause diversity in climate and habitat conditions within the region. This leads to overwhelming richness of biodiversity elements and to their uniqueness. The major crops grown here are apple, potato, temperature horticultural crops, wheat and mustard. This assessment gives an analysis of how the crop of apple has been affected by the changing climate in the Himalayan region. The productivity projections of apple have not been carried out as the climate projections data simulated for this region are based on a very sparse set of observed climate data.

2.4.2 Forests

Analysis of 29,000 observational data series, from 75 studies (IPCC, 2007) carried out since 1900, show significant impact on many physical and biological systems on all continents and in most oceans, with a concentration of available data in Europe and North America. Most of these changes are in the direction expected with warming temperature. These changes in natural systems since at least 1970 are occurring in regions of observed temperature increases, and the temperature increases at continental scales cannot be explained by natural climate variations alone.

Long-term observations are not available from India that can comprehensively detect a clear change in biodiversity due to observed changes in climate in India. However, a study on impacts of climate change on forests in 2050's and 2080's is available, which indicates 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. Enhanced levels of CO2 are projected to result in an increase in the net primary productivity (NPP) of forest ecosystems over more than 75 percent of the forest area. It is projected that in 2050's most of the forest biomes in India will be highly vulnerable to the projected change in climate and 70 percent of the vegetation in India is likely to find itself less than optimally adapted to its existing location, making it more vulnerable to the adverse climatic conditions as well as to the increased biotic stresses.

Considering that the likely impacts on biodiversity in the 2030's are a matter of concern, as a sizeable population in India lives off the forest products, this report in this context provides an assessment of the impact of climate change on the forests in 2030's, with a focus on the very eco-sensitive regions in India for the four regions, namely, Western Ghats, the Himalayas, the Coastal regions, the North-Eastern part of India. Currently, much of these regions are covered with moderate to dense forests, except the coastal region. Such an assessment helps to assist in developing and implementation of adaptation strategies to ensure sustained flow of ecosystem services, including conservation of biodiversity from the forests.

2.4.3 Human health

Public health depends on people having enough food and safe water, a decent home protection against disasters, a reasonable income and good social and community relations. Climate change is projected to have mostly negative and large health impacts on many population groups, especially the poorest, in large areas in the four regions. These could include direct health impacts such as heatstroke, and indirect impacts such as increased diarrhoea risk from water contamination via flooding, or higher risk of mortality from the impact of large-scale loss of livelihoods.

Research on health impacts of climate change in India is rather limited. This assessment principally focuses on impacts of climate change on malaria. The projections of the climate change impacts related to windows of opportunity of proliferation of the malarial vector have been estimated for 2030's using the PRECIS climate change regional model run on A1B scenario. Further, this assessment provides a qualitative description of the impacts of climate change on health issues in India such as nutrition availability, communicable diseases, heat stress, vector-borne diseases *vis a vis* heat waves, extreme weather events, increase in mean annual temperature, air quality, aeroallergens, droughts, and increase in UV radiation.

2.4.4 Water

In India's initial national communication, river run off for 20 river basins of India were simulated for the current climate, and future projections were made for the 2050's and 2080's. These were done using the SWAT model driven by the climate inputs from HadRM2 regional model run on the Is92a IPCC socio-economic scenario. Since then, the progression in the climate model development has been made along with generation of new socio-economic scenarios. The present assessment, other than reviewing the water resources in India, assesses the impact of climate change on water yields in 2030's with respect to 1970's in river basins that are a part of the 4 regions under focus. Climate outputs from PRECIS – a version of the latest version of the Hadley Centre Regional Model HAdRM3 run on A1B IPCC SRES socio-economic scenario -- form the inputs to the hydrologic model SWAT (Soil and Water Assessment Tool - see chapter 8 for details of the tool) to assess not only the potential impacts of climate change on water yield but also other hydrologic budget components such as evapo transpiration and sedimentation yields. Further, the outputs from the hydrological model have been used to assess the impact of the climate change on the river basins for the same regions in terms of occurrence of droughts and floods. Further, the possible future floods have been generated using the daily outflow discharge taken for each sub-basin from the SWAT output for 2030's.

3

Observed Climate and Climate Change Projections

3.1 Introduction

Human activities since the beginning of the industrial revolution have led to unprecedented changes in the chemical composition of the earth's atmosphere. The global atmospheric concentration of carbon dioxide, a greenhouse gas (GHG) largely responsible for global warming, has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005. Similarly, the global atmospheric concentration of methane and nitrous oxides, other important GHGs, has also increased considerably.

As per the IPCC 4th assessment report (IPCC, 2007a), most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. The AR4 concludes that discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns.

Although meteorological data compiled over the past century suggest that the earth is warming, there are significant differences at regional levels. Climate variations and change, caused by external forcings, may be partly predictable, particularly on the larger (e.g. continental, global) spatial scales. Because human activities, such as the emission of greenhouse gases or land-use change, do result in external forcing, it is believed that the large-scale aspects of human-induced climate change are also partly predictable. However, the ability to actually do so is limited because we cannot accurately predict population change, economic policy, technological development, and other relevant characteristics of future human activity. In practice, therefore, one has to rely on carefully constructed scenarios of human behaviour and determine climate projections on the basis of such scenarios.

The effects of climate change are expected to be greatest in the developing world, especially in countries reliant on primary production as a major source of income. One of the high priorities for narrowing gaps between current knowledge and policy-making needs is the quantitative assessment of the sensitivity, adaptive capacity and vulnerability to climate change, particularly in terms of the major agro-economic indicators in the developing countries. To systematically pursue such assessments, the most fundamental requirement is the availability of reliable estimates of future climatic patterns on the regional scale, which can be readily used by different impact assessment groups. This needs a systematic validation of the climate model simulations and development of suitable regional climate change scenarios and estimations of the associated uncertainties.

This assessment examines the trends in observed seasonal temperature and precipitation over India using a century long data. This is done in the context of the changes in climate that are being observed globally. Since one of the drivers of climate is the greenhouse gases; the concentration of which are likely to increase in the future, the chapter reviews the current knowledge about the changes in global and local climate that may occur in the very near future i.e. 2030's. In doing so, the nature of the models available for projecting global and regional climate are discussed.

With the availability of a hierarchy of coupled atmosphere-ocean-sea-ice-land-surface global climate models (AOGCMs), having a resolution of 250-300 km, it has been possible to project the climate change scenarios for different regions in the world. The present assessment first describes the changes in climate in 2030's with respect to 1970's for the South Asian region. The projected climate change over this region for 2030's is an average of projections for the period 2021 to 2050 and is made using selected models from Coupled Model Inter-comparison Project 3 (CMIP3).

India has a unique climate system dominated by the monsoon, and the major physio-graphic features that drive this monsoon are its location in the globe, the Himalayas, the central plateau, the western and eastern ghats and the oceans surrounding the region. The global models, however, fail to simulate the finer regional features, and the changes in the climate arising over sub-seasonal and smaller spatial scales. Keeping these limitations in view, the assessment describes the simulations and projections of climate for 2030's at a sub-regional scale, using PRECIS (a regional climate model developed by the Hadley centre, UK) that has a resolution of 50 km by 50 km. The GHG forcing for the future on the climate models is derived from the IPCC A1B socio-economic scenario (see chapter 4 for description of the scenario) that assumes significant innovations in energy technologies including renewables, which improve energy efficiency and reduce the cost of energy supply.

3.1.1 Observed Trends of Global Climate

The analysis of instrumental records of more than one and a half century reveals that the earth has warmed by 0.74 [0.56 to 0.92]°C during the last 100 years, with 12 of the last 13 years being the warmest on record. Long-term drying trends during the period 1900-2005 have been observed in precipitation over many large regions such as Sahel, the Mediterranean, southern Africa and parts of southern Asia. Temperatures of the most extreme hot nights, cold nights and cold days has increased with increased risk of heat waves. Global average sea level has risen at an average rate of 1.8 mm per year over 1961 to 2003. The rate was faster over 1993 to 2003, about 3.1 mm per year. More intense and longer droughts have been observed over wider areas since the 1970's, in the tropics and sub-tropics. Significantly increased rainfall has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Mountain glaciers and snow cover have declined on average in both hemispheres The maximum area covered by seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15%. The intense tropical cyclone activity is observed to have increased substantially over North Atlantic since about 1970.

3.1.2 Projected Changes in Global Climate

Knowledge of the climate system, together with model simulations, confirm that past changes in greenhouse gas concentrations will lead to a committed warming and future climate change because of the long response time of the climate system, particularly the oceans. Committed climate change due to atmospheric composition in the year 2000 corresponds to a warming trend of about 0.1°C per decade over the next two decades i.e up to 2020's, in the absence of large changes in volcanic or solar forcing. About twice as much warming is expected, that is around 0.2°C per decade. if emissions were to fall within the range of the SRES marker scenarios. Sea level is expected to continue to rise over the next several decades. During 2000 to 2020 under the SRES A1B scenario in the ensemble of AOGCMs, the rate of thermal expansion is projected to be 1.3 ± 0.7 mm yr^{-1}, and is not significantly different under the A2 or B1 scenarios. These projected rates are within the uncertainty of the observed contribution of thermal expansion for 1993 to 2003 of 1.6 ± 0.6 mm yr^{-1}.

Table 3.1: Projected global average surface warming and sea level rise at the end of the 21st century

	Temperature Change		Sea Level Rise
	(°C at 2090-2099 relative to 1980-1999)		(m at 2090-2099 relative to 1980-1999)
Case	**Best estimate**	**Likely range**	**Model-based range excluding future rapid dynamical changes in ice flow**
Constant Year 2000 concentrations	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Source: IPCC, AR4, 2007

The ratio of committed thermal expansion, caused by constant atmospheric composition at year 2000 values, to total thermal expansion (that is the ratio of expansion occurring after year 2000 to that occurring before and after) is larger than the corresponding ratio for global average surface temperature.

Projected global average surface warming for the end of the 21st century (2090–2099) is scenario-dependent and the actual warming will be significantly affected by the actual emissions that occur. According to IPCC AR4, the rise in temperature by the end of the century with respect to 1980-1999 levels would range from 0.6°C to 4.0°C and the sea level may rise by 0.18 m to 0.59 m during the same period. Warming compared to 1980 - 1999 for six SRES scenarios and for constant year 2000 concentrations, given as best estimates and corresponding likely ranges are shown in Table 3.1.

3.2 Assessing Climate Change

The tools for assessing climate change generally used are the global climate models also known as the generation circulation models which generally have a spatial resolution of 250-300 km. However, they are unable to capture the climate at smaller scales as they do not capture the typical driving factors such as the topography of these smaller regions and the land use pattern. The sections below give a brief description of the two types of models being used globally for climate change projections in the future.

3.2.1 Global Climate Models

The General Circulation Models (GCMs) are the most advanced tools currently available for simulating the global climate system that includes complex physical processes in the atmosphere, ocean, cryosphere and land surface. These models synthesize the current understanding of oceanic and atmospheric circulation, assimilated through "continuous interplay among theory, observations and, more recently, model simulations" (IPCC, 2007). The models are thus constituted of mathematical equations derived from physical laws describing the dynamics of atmosphere and ocean. GCMs depict the climate using a three-dimensional grid over the globe, typically having a horizontal resolution of 250 - 300 km, with about 20 vertical layers in the atmosphere and about 30 layers in the oceans. Such coarse resolution, does not allow representation of physical processes, such as those related to clouds. These processes are averaged over the larger scale and represented through parameterisation schemes, which is a major source of uncertainty in GCM-based simulations of climate. Various feedback mechanisms in models like, water vapour and warming, clouds and radiation, ocean circulation and ice and snow albedo are also not understood adequately, resulting in further uncertainties and the wide variations in model projections.

The need for understanding and constantly improving the representation of different feedback mechanisms and processes requires the use of 'hierarchy of models'. This provides a linkage between theoretical understanding and the complexity of realistic models (Held, 2005). Simpler model formulations either restrict the number of physical processes considered or the spatial domain – single column or one- or two-dimensional latitudinal. Use of hierarchy of model also means complementing global circulation models with regional models of higher resolution over a particular area. Studies on longer time scales, such as glacial to interglacial cycles, have used Earth Models of Intermediate Complexity. Understanding the present climate and making reliable future projections at global and regional scales, therefore requires the use of a variety of modelling tools.

The climate modelling community is now considering expanding AOGCMs to encompass chemical and biological aspects of the Earth System. Sub-models, of atmospheric chemistry, the carbon cycle, aerosols, and dynamic vegetation are already being implemented (WCRP, 2007). Groups are also working on dynamic ice sheet models for inclusion in the next generation of climate models – the Earth System Models (ESMs).

3.2.2 High Resolution Climate Models for Regional Assessments

Developing high- resolution models on a global scale is not only computationally prohibitively expensive for climate change simulations, but also suffers from errors due to inadequate representation of high-resolution climate processes globally. It is in this context that Regional Climate Models (RCMs) provide an opportunity to dynamically downscale global model simulations to superimpose the regional detail of specified regions. As highlighted by Noguer et al., (2002), developing high-resolution climate change scenarios helps in:

- A realistic simulation of the current climate by taking into account fine-scale features of the terrain etc.;

- More detailed predictions of future climate changes, taking into account local features and responses;
- Representation of the smaller islands and their unique features;
- Better simulation and prediction of extreme climatic events; and
- Generation of detailed regional data to drive other region-specific models analysing local-scale impacts.

Keeping in view the recent large magnitude of global warming and the possible impacts of climate change on every aspect of life, which is of vital importance especially for densely populated agrarian regions like South Asia; in this report we discuss the observed trends in temperature and precipitation over India by using long instrumental records. Also, projected changes in seasonal rainfall and temperature patterns under transient climate change scenarios in the mid 21st century have been discussed by analysing coupled climate model outputs. The features which are not captured by the coarse resolution coupled models are examined by using high-resolution regional model PRECIS (Providing Regional Climates for Impact Studies).

3.3 Observed Climate trends Over India

3.3.1 Description of data used in this assessment

High-resolution (1°x1° lat/long) daily gridded rainfall data available from 1803 well distributed stations over India, prepared by the India Meteorological Department and set for the Indian region for 1951-2007 have been used in this assessment. The century long gridded rainfall data for the period 1901-2004 has also been used in this analysis to examine the long-term trends over the region. This data has been collected from 1384 observation stations of IMD in India (Rajeevan et al, 2005, 2006). The data is available for 1 January to 31 December for each year. However, analysis in this study is restricted to the Indian Summer Monsoon season, June to September, since nearly 80% of the annual rainfall over major parts of India occurs during this period. The study has demarcated the regions for assessment as follows:

- Western Himalayas constituting of Jammu and Kashmir, Uttarakhand and Himachal Pradesh
- West Coast (starting from Gujarat in the north to Kerala in the south)
- East Coast (starting from West Bengal in the north to Tamil Nadu in the south) and
- North-East (comprising of the states of Sikkim, Arunachal Pradesh, Meghalaya, Manipur, Assam, Tripura and Mizoram).

The monthly maximum and minimum temperature data from 121 stations well distributed over the country during the period 1901-2007 have also been used in the present study. The data for the period 1901-1990 are taken from monthly weather reports of the India Meteorological Department (IMD) Pune, and the monthly data for the period 1991-2007 have been estimated from the daily data reported in the Indian Daily Weather Reports (IDWRs) of IMD.

Temperature data from 121 stations have been converted to monthly anomaly time series for the period 1901-2007, with reference to the respective station normal values, and then they are objectively interpolated onto a 5°x5° grid (Kothawale and Rupa Kumar, 2005). Annual and seasonal temperature series for the period 1901-2007 have also been constructed for all India.

Further, the global monthly air temperature 5°x5° gridded data from Climatic Research Unit (CRU), University of East Anglia for the period 1961-1990 have been used for evaluating the model skills in baseline simulations of the mean surface air temperature.

3.3.2 Annual Mean temperature trends

Indian annual mean temperature showed significant warming trend of 0.51°C per 100 year, during the period 1901–2007 (Kothawale *et al*., 2010). Accelerated warming has been observed in the recent period 1971–2007, mainly due to intense warming in the recent decade 1998–2007. This warming is mainly contributed by the winter and post-monsoon seasons, which have increased by 0.80°C and 0.82°C in the last hundred years respectively. The pre-monsoon and monsoon temperatures also indicate a warming trend.

Mean temperature increased by about 0.2°C per decade (i.e. 10 years) for the period 1971–2007, with a much steeper increase in minimum temperature than maximum temperature (see figure 3.1). In the most recent decade, maximum temperature was significantly higher compared to the long-term (1901–2007) mean, with a stagnated trend during this period, whereas minimum temperature showed an increasing trend, almost equal to that observed during 1971–2007. On a seasonal scale, pronounced warming trends in mean temperature were observed in winter and monsoon seasons, and a significant influence of El Niño Southern Oscillation events on temperature anomalies during certain seasons across India was observed. The spatial distribution of changes in temperatures between 1901 and 2007 is shown in figure 3.2 – upper panel. Most parts of India show a warming trend, except in the north-western parts of the country where a cooling trend is observed.

3.3.3 Annual trends in Maximum temperature

The all-India maximum temperatures show an increase in temperature by 0.71°C per 100 year (figure 3.1a, middle panel) and the spatial patterns indicate a warming trend for all the regions under consideration in this document (see Figure 3.1b – middle panel).

The trends of daily maximum temperatures in India are observed to be increasing from January, attaining a peak in the month of May. Beyond, May, the temperature starts decreasing up to December. During the pre-monsoon (March+April+May) season, the Indian region is marked by clear skies, which, coupled with intense as well as increased solar radiation, results in high temperatures. The occurrence of heat wave conditions is more frequent in May than in June, while very few heat waves occur in the months of March and April (Kothawale 2005).

During the pre-monsoon season, a large part of the country between 75°E to 85°E and 14°N to 25°N has uniform maximum temperatures between 34°C to 40°C. Steep temperature gradient is found over the west and east coasts of India. Monsoon season follows the pre-monsoon and the seasonal temperature variation is considerably modified by the southwest monsoon. The temperatures are nearly uniform over the Indian region except over Northwest India, where the temperature is more than 34°C. Maximum temperatures are almost uniform over the entire country in the post-monsoon season, and decrease from west to east (72°E to 96°E), ranging between 28°C and 30°C. The highest annual mean maximum temperatures are observed in the north-western and central parts of India.

3.3.4 Annual trends in minimum temperature

All-India mean annual minimum temperature has significantly increased by 0.27°C per 100 years during the period 1901-2007 (see Figure 3.1c). The spatial changes in minimum temperatures is observed to be decreasing in most parts of western ghats, increasing in most parts of the Himalayan region and certain parts of the North-Eastern region (see figure 3.2 lower panel). The warming is mainly contributed by winter and post-monsoon temperatures. However, the results presented here are somewhat different from those reported in Kothawale and Rupa Kumar (2005), where it was summarised that the all-India annual minimum temperature showed a very small increasing trend that was not statistically significant. However, their analysis is based on the data during the period 1901-2003. The warming during the recent period (2004 to 2007) may have played a vital role in making the trend statistically significant in our analysis.

There are some conspicuous changes noted in different sub-periods in the minimum temperature. During the period 1901-55, the all-India mean annual minimum temperature shows a warming tendency but after 1955, it decreases sharply up to 1970 and later it gradually increases. In the recent three and half decades, the all-India mean annual minimum temperature shows a significant warming trend of 0.20°C/10 years. Unlike maximum temperature, the trend in the minimum temperature during the latest decade is maintained at the rate noted for the recent three and half decades. On the seasonal scale, all the seasons show significant warming trends except post-monsoon, where the trend is positive but not significant.

3.3.5 Annual trends of extreme temperature events

For India as a whole, frequency of hot days shows a gradual increasing trend and frequency of cold days shows a significant decreasing trend during the pre-monsoon season over the period 1970–2005 (see table 3.3). On the regional scale, the trends in the frequency of occurrence of temperature extremes are slightly different. The homogeneous regions of East Coast, West Coast and Indian Peninsula show a significant

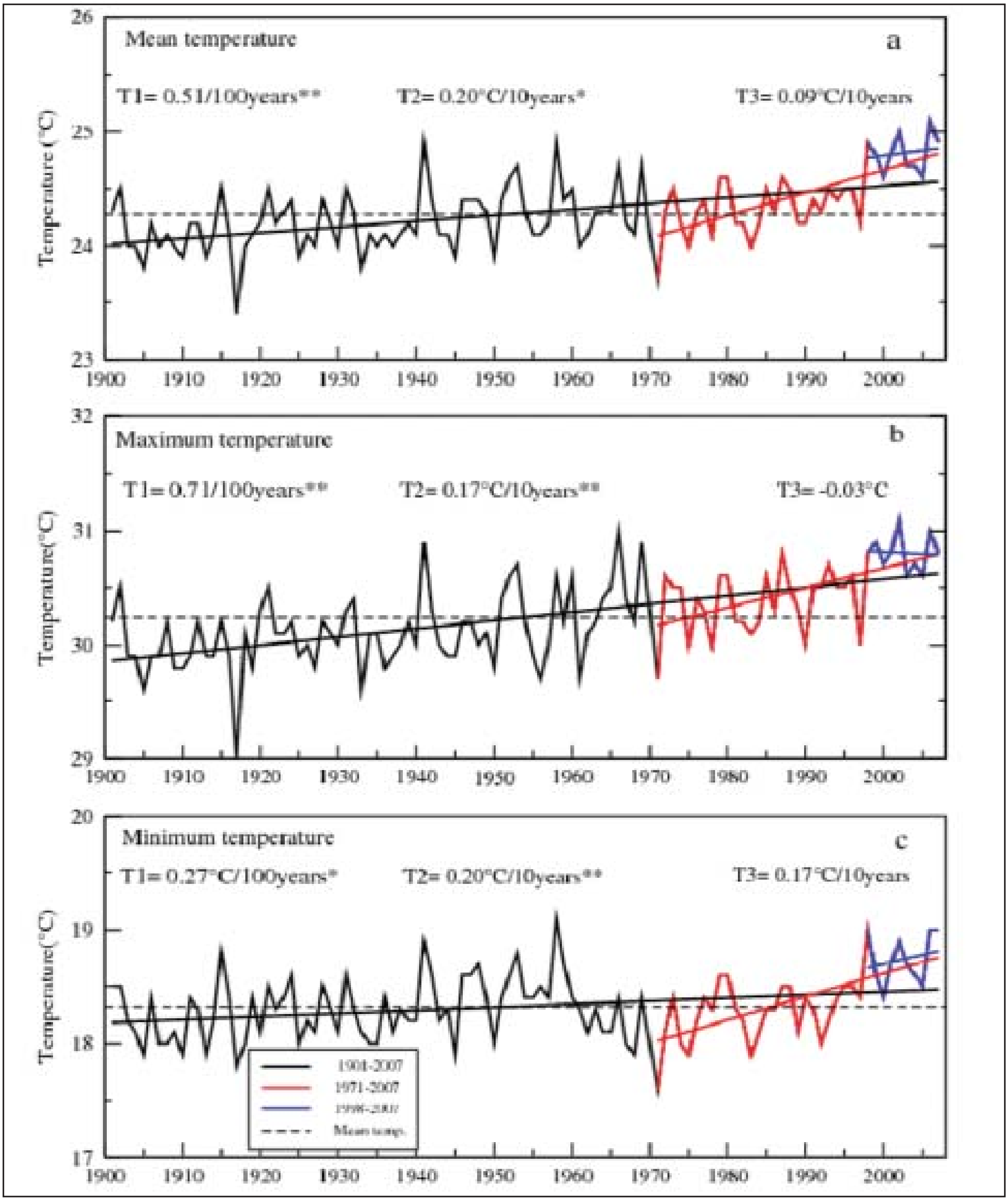
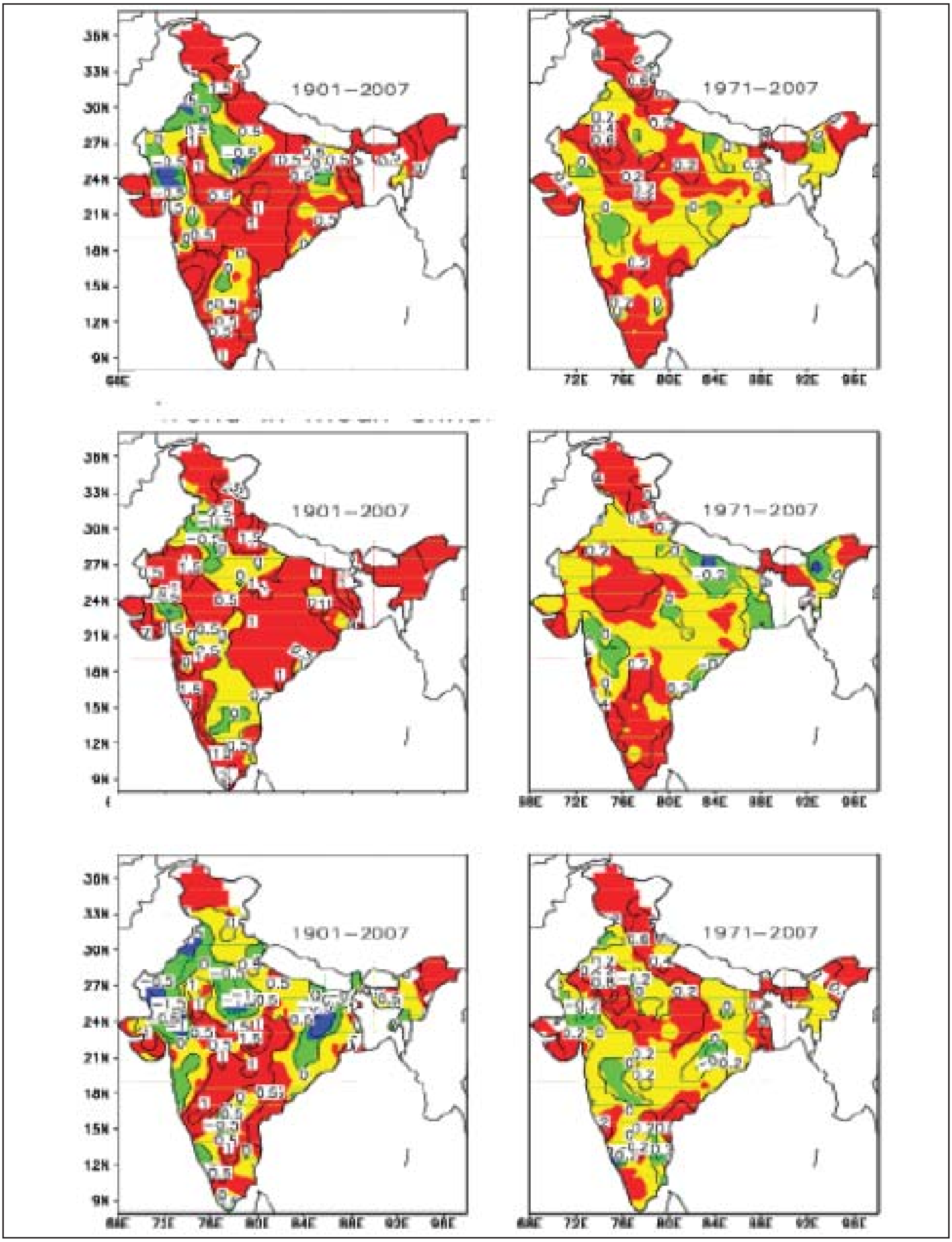


Figure 3.1: All-India annual mean, maximum and minimum temperature variations during 1901-2007



Key: Red- warming trend at 5%; Blue- Cooling trend at 5%; Green- cooling trend; yellow- warming

Figure 3.2: Spatial patterns of linear trends of annual mean, maximum and minimum temperature. Upper panel: Mean annual temperatures; **Middle panel:** Trends in maximum temperatures; **Lower panel:** Trends in minimum temperatures

increasing trend in frequency of hot days. The regions in the northern part of India (north of 22°N) do not show significant increasing or decreasing trend in the extreme temperature events. Nearly 70% of the stations falling in these regions showed decreasing trend and remaining 30% showed increasing trend, while few stations in North-Eastern India showed a significant decreasing trend (see figure 3.2a below).

All homogeneous regions show a decreasing trend in frequency of cold days. Out of seven homogeneous regions, only two regions namely Western Himalayas and Western Coastal region show significant decreasing trend of 2.1 and 2.7 days per decade respectively. Kothawale and Rupa Kumar (2005) reported earlier that over these two regions (WH and WC), pre-monsoon maximum temperatures have increased significantly. The significant decreasing trend in cold days over these two regions may be a manifestation of the increasing trend in seasonal maximum temperatures. Further, Kripalani et al (2003) have reported that the spring snow cover of Western Himalaya has been declining and that the snow was melting faster from winter to spring after 1993, which is consistent with the trends observed in the present study. For India as a whole, the frequency of cold nights decreased at the rate of 0.9 days per decade. Out of the seven homogeneous regions, the statistically significant decreasing trend in frequency of cold nights was found over WH and NE.

An analysis of changes in diurnal temperatures indicates that the hot nights have increased and cold nights have decreased almost over the entire country. The frequency of hot days has been increasing over almost all the regions, significantly over the eastern coast, western coast, and Interior Plateau and decreasing over North-East.. On the other hand, the number of cold days has been decreasing over all the regions with significant trends over WH and WC regions of India. In more detail, over the entire country, a majority of stations showed decreasing trends while only 4to 5 observing stations showed significant increasing trends. For India as a whole, the significant decreasing trend in the frequency of cold days and increasing trend (close to 5% significant level) in frequency of hot days have been found.

3.3.6 Variability of Indian summer monsoon rain fall

All-India monsoon rainfall series based on 1871-2009 indicates that the mean rainfall is 848 mm with standard deviation of 83 mm. Inter-annual variability of Indian monsoon rainfall between this period is shown in figure 3.3. The Indian monsoon shows well defined epochal variability with each epoch of approximately 3 decades. Though it does not show any significant trend, however, when averaged over this period, a slight negative trend i. e. -0.4mm/year is seen.

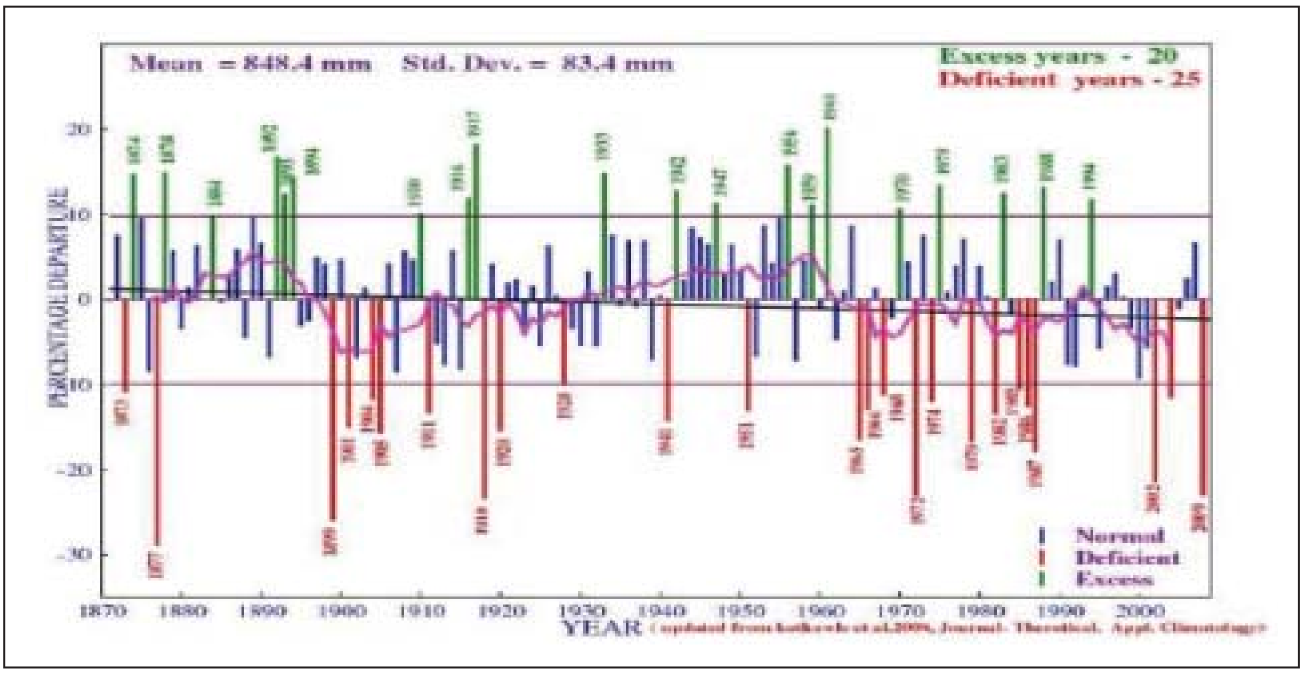


Figure 3.3: Inter-annual variability of Indian monsoon rainfall 1871-2009. Bars denote percentage departure from normal (blue) with excess (green) and deficient (red) years. The long term trend is denoted by the black line. The pink curve denotes decadal variability of Indian monsoon rainfall.

The rainfall is deficit or in excess if all-India monsoon rainfall for that year is less than or greater than mean standard deviation. With this definition, the deficient years are marked red , excess are marked green and the normal as blue. It is seen that in this 139-years period, there are total 23 deficient, 20 excess and remaining are normal monsoon years. The Indian monsoon shows well-defined epochal variability with each epoch of approximately 3 decades. It is observed that the excess and deficit years are more frequent in above and below normal epochs respectively. For all-India as one unit, excess and deficient monsoon rainfall years have been identified per decade during the period 1871-2009. During the period 1871-1920, the occurrence of deficient monsoon rainfall years are more than the excess years, whereas during the period 1921-1960 excess years are more than deficient years. After 1961 to 2009, deficient monsoon rainfall years are 13 and excess are only 6 .

3.3.7 Spatial trends of monsoon rain fall

The all-India, northwest, west coast and peninsular India monsoon rainfall shows a slightly higher negative trend, though not significant, than for the total period. However, pockets of increasing / decreasing trends in 36 meteorological sub-divisions over India are seen (see Fig 3.4a and Fig 3.4 b). North west India, west coast and peninsular India shows increasing trends though not statistically significant. Coastal Andhra, West Bengal and Punjab show significant increasing trends. Central India depicts a decreasing trend, which is significant over Chattisgarh and East Madhya Pradesh. In all, 14 (22) sub-divisions show decreasing (increasing) trends. However, in recent decades (top panel) 16 (20) sub-divisions show decreasing (increasing) long-term trends. East central India shows positive trends, which were decreasing based on the entire period 1871-2008. Only West Bengal showed a significant increasing trend in the recent period.

3.3.8 Extreme Precipitation trends

The highest rainfall pockets in India are generally those receiving orographically induced rainfall caused by forced moist air ascent over the slopes during the active monsoon situations. Western Ghats and North-East India receive such type of heavy rainfall. Along the monsoon trough region also, more than 50 cm rainfall has been recorded in 1-day duration. Central parts of peninsular India, i.e. lee side of Western Ghats have never experienced rainfall of the order of 30cm/ day. Trend analysis of 1-day extreme rainfall series based on the period 1951-2007, indicate that these extreme rainfall amounts are increasing at many places in India as seen from Fig 3.5. This observation is based on analysis of highest rainfall recorded from 1000 stations across India for the period 1951-2007 at a resolution of 1°x1°. These results are in good agreement to that of Sen Roy and Balling (2004), who reported overall increase in extreme rainfall events and their intensities during the period 1901-2000.

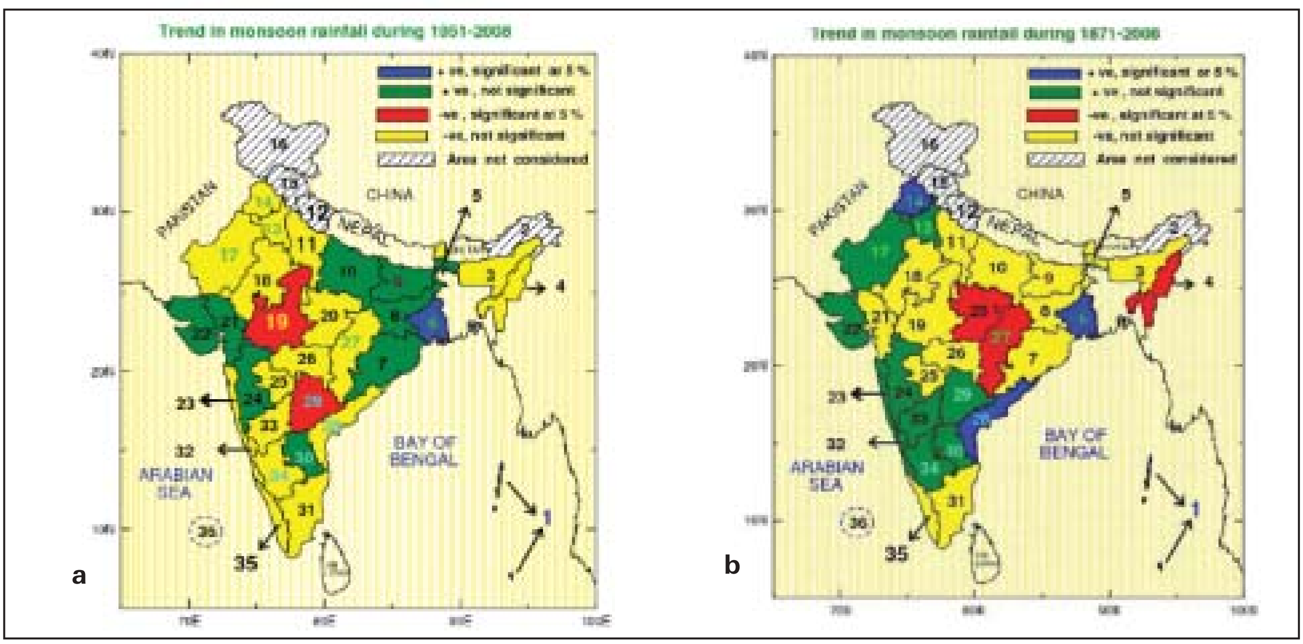


Figure 3.4 : Trends in summer monsoon rainfall for 1951-2008 (a) and 1871-2008 (b) for 36 meteorological subdivisions

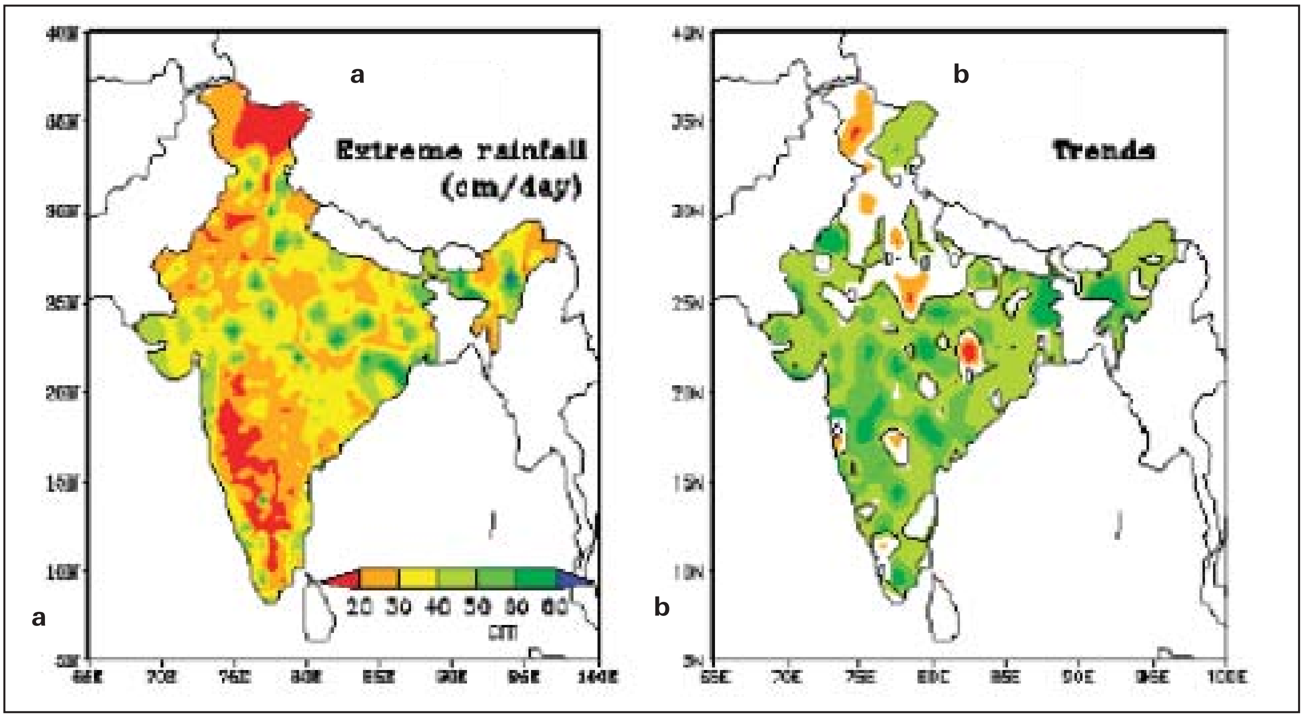


Figure 3.5 : Highest recorded rainfall (cm) during 1951-2004 (a) and trends in annual extreme rainfall (b). Dark green color indicates significant increasing trend

Khaladekar *et al*., 2009, report a study of extreme rainfall pattern in the Indian region with a data series spanning the period 1960-2003. Total 165 stations well spread across the region with the data availability of at least 50 years up to 1980 are considered (Source: Climatological Tables of Observatories in India: 1951-1980, IMD, 1999). Only the cases with the minimum rainfall of 10 cm/day are taken into account to give weightage to the high rainfall values. The rainfall data after 1980 are compiled from different IMD publications. The instances of extreme precipitation events at the stations are classified chronologically according to the decades. The high rainfall events that occurred at the stations after 1980 are compared

Table 3.2 : Comparison of magnitudes of Extreme Precipitation Rainfall Event (EPRE) in cms, before and after 1980 in selected regions

Station	Region	Max EPRE upto 1980	Max EPRE recorded between 1980 and 2010
Himalayas			
Ambala	Punjab	23 (Aug 10, 1896)	34 (Aug 03, 2004
Leh	Jammu and Kashmir	-	250 mm/hr (Aug 6, 2010)
Coastal Region			
Amini devi	Lakshwadeep	25 (Nov21, 1977)	170 (May 06, 2004)
Santacruz	Mumbai	38 (July 05, 1974)	94 (July 27, 2005)
Male gaon	Mumbai	16 (July 26, 1896)	29 (Oct 11, 2001)
Bhira	Konkan & Goa	43 (June 29, 1967)	71 (July 24, 1984)
Sand heads	Anadaman	37 (July 14, 1972)	51 (June 12, 1981)
Sagar	West bengal	38 (July 30, 1973)	48 (April 07, 2005)
North East			
Cherrapunji	Assam	19 (Sept 13, 1974)	156 (June 16, 1995)
Silchar	Assam	29 (My 30, 1893)	47 (July 7, 1991)
Jalpaiguri	North Bengal	39 (July 8, 1892)	47 (July 10, 1989)
Malda	North Bengal	24 (Oct 1, 1971)	57 (Sept 28, 1995)
North West			
Jaipur	Rajasthan	19 (August 16, 1959)	22 (July 19 (1981)

with those of the earlier period to assess whether the previous extreme precipitation events are exceeded in recent decades. Subsequently, the extreme rainfall events that occurred on different time scales are also discussed in the paper.

The rainfall of 10 cm/day may be an extreme for the North-West region, whereas it may not be a significant amount for the north-east region or along the west coast of India during summer monsoon. Even in summer monsoon season, the west coast of India gets heavy rainfall spells in the first fortnight of June while the northern part of the country is devoid of the rainfall. Therefore for this study, the magnitude of Extreme Point Rainfall Event (EPRE) has not been taken as a fixed threshold for all the stations but it is different for each station and varies according to the month. Considering the climatological data, the magnitude of the extreme precipitation event at the station is defined as its highest 24-hour rainfall reported in a particular month during the entire period of the data availability. Accordingly, it may increase for certain stations, if their previous EPRE are exceeded in the course of time. This definition is adopted in order to examine whether there was any change in the number and intensity of the EPRE in the recent decades and if so, which parts of the region are affected most.

The study shows that majority of the stations have reported their highest 24-hour rainfall during 1961-1980 with an alarming rise in their intensity in the subsequent period from 1980 onwards till 2009. Out of 165 stations analysed, the majority (77.6 %) have registered their EPRE during 1961-1980. Thereafter, several stations have reported the rainfall events surpassing the intensity of their previous highest rainfall. Some records were established on different time scales varying from hourly to the annual scales with most of them noticed from 1995. Table 3.2 shows 20 stations where the previous EPRE have been exceeded after 1980. Many stations have experienced an alarming rise (40-370%) in their intensity. These stations are located in north, north-east, north-west, central India and along the coastal zones.

3.4 Regional projections of Climate

Our current level of understanding of the components of the climate system and their interactions has reached an advanced stage, with the availability of a hierarchy of coupled ocean-atmosphere-sea-ice-land-surface models to provide indicators of global response as well as possible regional patterns of climate change. A variety of experiments has been performed by different modelling groups in the world, to simulate expected climate change patterns under different emission scenarios prepared under IPCC (Intergovernmental Panel on Climate Change), together which, describe divergent futures defining various future concentrations of greenhouse gases arising from different paths of development.

While global atmosphere-ocean coupled models provide good representations of the planetary scale features, their application to regional studies is often limited by their coarse spatial resolution (~300km). For example, these models do not represent realistic topographical features like the Western Ghats along the west coast of India and consequently fail to reproduce their predominant influence on the monsoon rainfall patterns over India. Rajendran and Kitoh (2008) have used the super high-resolution global model to study the impact of global warming on the Indian summer monsoon.

The analysis shows spatially varying rainfall projection, with widespread increase in rainfall over interior regions and significant reduction in orographic rainfall over the west coasts of Kerala and Karnataka, and eastern hilly regions around Assam. However, developing high-resolution models on a global scale is not only computationally expensive for climate change simulations, but also suffers from the errors due to inadequate representation of high-resolution climate processes on a global scale. It is in this context that the Regional Climate Models (RCMs) provide an opportunity to dynamically downscale global model simulations to superimpose the regional details of specific regions of interest.

3.4.1 Model and scenario used for the regional assessment

The projections of climate for the present work have been derived from PRECIS, an atmospheric and land surface model having a high-resolution, which is locatable over any part of the globe. PRECIS, which has been developed by the Hadley Centre, UK is run at IITM, Pune, at 50 km x 50 km horizontal resolution over the South Asian domain. PRECIS is forced at its lateral boundaries by a high-resolution GCM (150 km) called HadAM3H in so called 'time slice' experiments. The basic aspects explicitly handled by the model are briefly outlined in Noguer et al., (2002).

The model simulations are carried out for the period 1961-1990 (baseline simulation) and 2071-2100 (A2 and B2 scenarios) for various surface as well as upper air parameters, on daily and monthly scales. Some basic parameters like rainfall, surface air temperature, mean sea level pressure and winds are analysed to get the projection scenarios towards the end of present century (Rupa Kumar et. al, 2006).

High-resolution regional climate model (PRECIS) simulations using lateral boundary forcing from three QUMP (Quantifying Uncertainties in Model Projections) runs are made at IITM for A1B emission (see box 3.1) scenario for the period 1961-2098. These are part of the seventeen member Perturbed Physics Ensemble (PPE) produced using HadCM3 under the Quantifying Uncertainty in Model Predictions (QUMP) project of Hadley Centre Met Office.

The perturbed physics approach was developed in response to the call for better quantification of uncertainties in climate projections. The basic approach involves taking a single model structure and making perturbations to the values of parameters in the model, based on the discussions with scientists involved in the development of different parameterisation schemes. In some cases, different variants of physical schemes may also be switched in and out. Any number of experiments that are routinely performed with a single model can then be produced in 'ensemble mode' subject to constraints on computer time. A significant amount of perturbed physics experimentation has been done with HadCM3 and variants, starting with the work of Murphy et al., (2004) and Stainforth et al., (2005). Three PRECIS runs, Q0, Q1 and Q14 are carried out for the period 1961-2098 and are utilised to generate an ensemble of future climate change scenarios for the Indian region. These simulations are made at 50x50km horizontal resolution. The climate change scenarios are based on A1B socio-economic scenarios of the IPCC, that assumes significant innovations in energy technologies, which improve energy efficiency and reduce the cost of energy supply (for details see Box 3.1).

Box 3.1: A1B Scenario

The A1B scenario assumes significant innovations in energy technologies,which improve energy efficiency and reduce the cost of energy supply. Such improvements occur across the board and neither favor, nor penalize, particular groups of technologies. A1B assumes, in particular, drastic reductions in power-generations costs, through the use of solar, wind, and other modern renewable energies and significant progress in gas exploration, production and transport. This results in a balanced mix of technologies and supply sources with technology improvements and resource assumptions such that no single source of energy is overly dominant. The assumptions are in line with a low carbon world.

*(Source: IPCC, 2000)

3.4.2 Projections of precipitation

The projections of precipitation indicate a 3% to 7% overall increase in all-India summer monsoon rainfall in the 2030's with respect to the 1970's. However, on a seasonal scale, except for the Himalayan region, all other regions are likely to have lower rainfalls in the winter period as well as pre-summer period. Spatial patterns of monsoon rainfall indicate a significant decrease in the monsoon rainfall in future except in some parts of the southern peninsula. See figure 3.6 and Tables 3.3 a, b, c and d for spatial distribution of observed and projected rainfall.

Himalayan region: The PRECIS run for 2030's indicates that the annual rainfall in the Himalayan region may vary between 1268±225.2 mm to 1604±175.2 mm respectively. The projected precipitation show a net increase in 2030's with respect to the simulated rainfall of 1970's in the Himalayan region by 60 to 206 mm. The increase in annual rainfall in 2030's with respect to 1970's ranges from 5 to 13%. All seasons in the Himalayan region indicate an increase in rainfall, with the monsoon months of June, July, August and September showing the maximum increase in rainfall by 12 mm. The winter rain in the months of January and February are also projected to increase by 5mm in 2030's with respect to 1970's, with minimum increase in October, November and December.

Costal Region- West coast: The west coast projections indicate that in 2030's the annual rainfall will vary from 935± 185.33 mm to 1794±247.1 mm. The trend of rainfall in 2030's is showing an increase with respect to the 1970's in this region as well. The increase in rainfall is by 6 to 8 %, an increase that is ranging from 69 to 109 mm. Though June, July and August show an average increase of 8mm rainfall in 2030's with respect to 1970's, however, the winter rainfall is projected to decrease on an average by 19 mm during the period January and February in 2030's with reference to 1970's. The period March, April and May also show a decrease in rainfall with respect to 1970's.

Costal Region- East coast: In the eastern coast of India, the projected annual rainfall varies from a minimum of 858±10mm to a maximum of 1280±16mm. The increase in 2030's with respect to the 1970's is estimated to be 2 to 54 mm, an increase of 0.2% to 4.4 % respectively. The maximum increase in rainfall is projected to happen in March, April and May in 2030's, with rainfall set to increase by 14 mm on an average with respect to the same period in 1970's. The winter rainfall is projected to decrease by 6 mm with respect to 1970's.

North- Eastern Region: The projected mean annual rainfall is varying from a minimum of 940±149mm to 1330 ±174.5 mm. The increase with respect to 1970's is by 0.3% to 3%. The north-east also show a

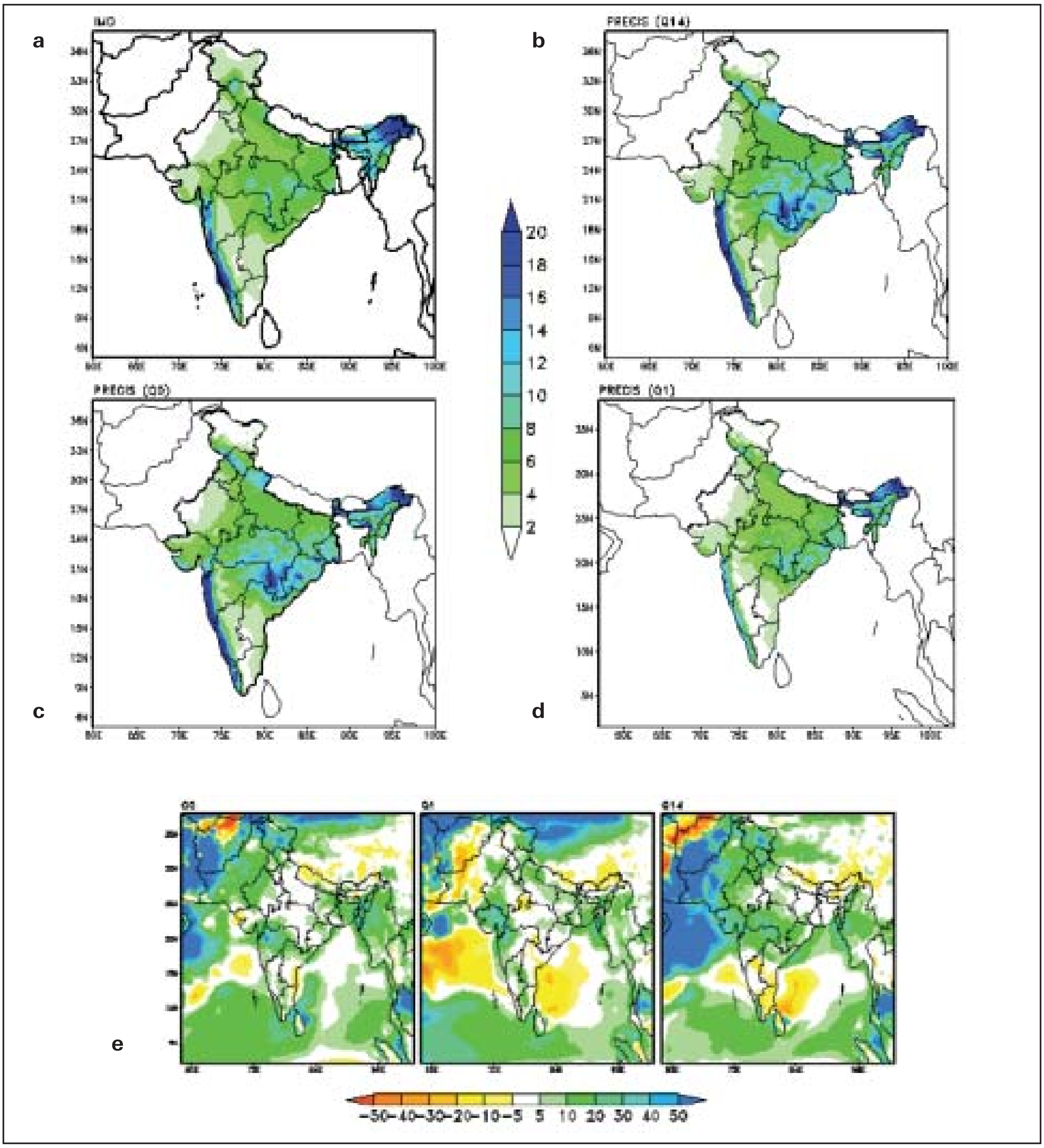


Figure 3.6: (a) The observed summer monsoon rainfall climatology; (b), (c) and (d) are Q0, Q1, Q14 simulation of observed monsoon rainfall; (e) projected changes in summer monsoon rainfall in 2030s with respect to 1970s.

substantial decrease in rainfall in the winter months of January and February in 2030's with respect to 1970's with no additional rain projected to be available during the period March to May and October to December. In fact, recent data indicates the same pattern. However, the monsoon rainfall during June, July and August is likely to increase by 5 mm in 2030's with reference to 1970's. A rise of 0.6%.

All regions are projected to have an enhanced rainfall in 2030's with respect to 1970's. The increase in rainfall in 2030's with respect to 1970's varies from 6%, 3% and 7% for Q0, Q14 and Q1 simulations respectively.

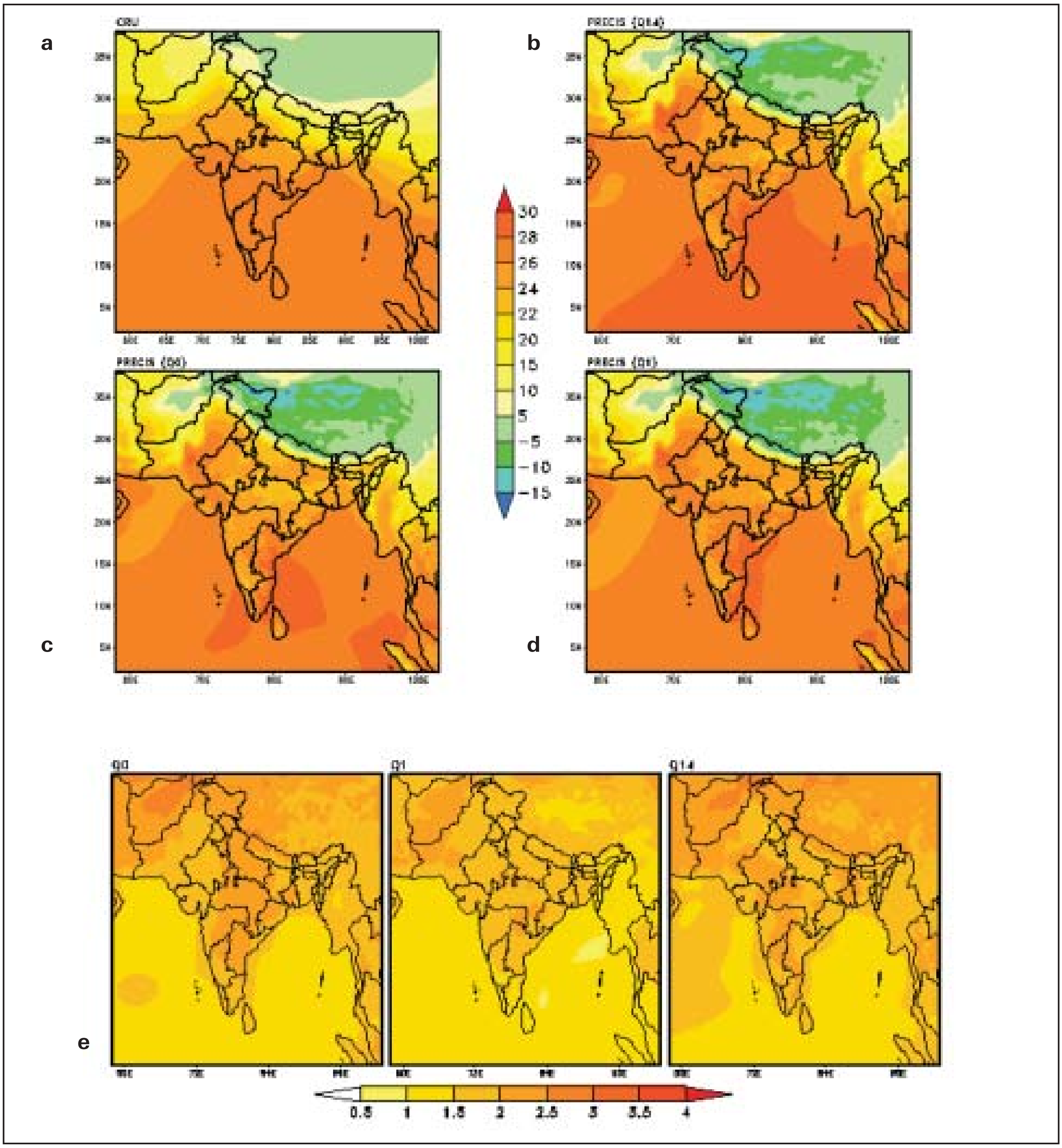


Figure 3.7: Top panel (a,b,c and d)- Mean annual surface air temperature climatology based on observations and simulated by three PRECIS runs compared with the observed climatology for baseline period (1961-1990);. (e) Bottom Panel: Projected changes in the annual surface air temperature in 2030's with respect to the 1970's.

3.4.3 Projections of mean annual surface Temperature

PRECIS simulations for 2030's indicate an all-round warming over the Indian subcontinent associated with increasing greenhouse gas concentrations. The annual mean surface air temperature rise by 2030's ranges from 1.7°C to 2°C as in the three simulations. The seasons may be warmer by around 2°C towards 2030's. The variability of seasonal mean temperature may be more in winter months. (See figure 3.7 and Tables 3.3 a, b, c, d and e).

Himalayan region: The annual temperature is projected to increase from 0.9±0.6 °C to 2.6±0.7°C in 2030's. The net increase in temperature is ranging from

Table 3.3a: Characteristics of simulated seasonal and annual rainfall and mean temperature for the Himalayan region (baseline and A1B scenario) as simulated by PRECIS.

Himalayan	Rainfall (mm)					Mean Temperature (oc)				
Q0	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	141	315	551	202	1208	-13.3	0.6	10.1	-7.0	-0.4
2030s	144	307	615	203	1268	-10.6	5.8	12.1	-4.4	1.3
Standard Deviations										
1970s	71.9	101.5	101.3	103.1	173.4	1.8	1.3	0.4	1.4	0.6
2030s	99.0	86.2	115.8	125.8	225.2	1.4	1.8	0.6	1.0	0.7

Himalayan	Rainfall (mm)					Mean Temperature (oc)				
Q1	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	176	346	412	221	1154	-11.8	-0.2	0.9	-6.8	-0.8
2030s	201	361	449	216	1227	-9.6	1.7	10.1	-5.2	0.9
Standard Deviations										
1970s	70.6	100.7	57	98.4	169.7	1.4	0.9	0.6	0.8	0.4
2030s	84.1	79.1	67.4	84.7	164.6	1.5	1.0	0.5	1.2	0.6

Himalayan	Rainfall (mm)					Mean Temperature (oc)				
Q14	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	232	355	527	284	1398	-12.0	0.9	10.9	-0.6	0.4
2030s	232	399	612	362	1604	-9.9	2.9	12.9	-3.2	2.6
Standard Deviations										
1970s	123	94.3	86.1	115.6	175.2	1.4	1.3	0.3	0.9	0.4
2030s	89.1	121.8	100.2	126.6	175.2	1.4	1.2	0.8	1.0	0.7

Table 3.3b: Characteristics of simulated seasonal and annual rainfall and mean temperature for the West Coast region (baseline and A1B scenario) as simulated by PRECIS.

West Coast	Rainfall (mm)					Mean Temperature (oc)				
Q0	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	16	126	1443	89	1674	23.3	28.5	24.4	23.5	25.1
2030s	12	99	1561	90	1762	25.4	30.7	26.0	25.6	26.8
Standard Deviations										
1970s	11.0	84.6	205.2	37.2	220.7	0.7	0.5	0.9	1.0	0.4
2030s	10.4	57.7	250.9	46.7	254.9	0.8	0.7	0.5	1.2	0.6

West Coast	Rainfall (mm)					Mean Temperature (oc)				
Q1	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	8	51	742	66	866	23.5	28.4	25.4	24.2	25.5
2030s	6	53	808	69	935	25.3	30.0	27.0	25.7	27.0
Standard Deviations										
1970s	6.8	17.2	219.1	24	217.7	0.6	0.6	0.5	0.9	0.5
2030s	1.7	17.7	173.8	22	185.3	0.5	0.5	0.6	0.9	0.5

West Coast	Rainfall (mm)					Mean Temperature (oc)				
Q14	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	18	114	1463	91	1685	23.9	28.8	25.0	24.6	25.7
2030s	16	110	1577	91	1794	26.0	30.7	26.5	26.7	27.5
Standard Deviations										
1970s	21.3	78.9	205.1	39.9	226.2	0.7	0.5	0.4	0.7	0.4
2030s	8.6	61.7	228.9	32	247.1	0.8	0.6	0.5	0.7	0.4

Table 3.3c: Characteristics of simulated seasonal and annual rainfall and mean temperature for the East Coast region (baseline and A1B scenario) as simulated by PRECIS.

East Coast	Rainfall (mm)					Mean Temperature (oc)				
Q0	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	35	172	798	220	1226	22.8	31.4	28.2	22.7	26.7
2030s	31	190	826	233	1280	25.1	34.7	29.9	24.7	28.7
Standard Deviations										
1970s	25.5	76.8	79.7	83.1	140.3	0.9	0.8	0.7	0.7	0.5
2030s	27.3	91	69.0	89	131.2	0.7	1.2	0.8	1.1	0.6

East Coast	Rainfall (mm)					Mean Temperature (oc)				
Q1	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	18	81	618	143	860	23.6	31.9	29.6	23.2	27.6
2030s	13	90	621	134	858	25.3	33.7	31.1	24.9	29.2
Standard Deviations										
1970s	23.1	33.8	109.7	55	138.2	0.7	0.7	0.9	0.9	0.7
2030s	8	45.1	100.0	58	137.6	0.8	0.9	1.2	1.1	0.9

East Coast	Rainfall (mm)					Mean Temperature (oc)				
Q1	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	52	157	790	210	1208	23.3	32.2	28.7	23.8	27.4
2030s	54	190	816	203	1262	25.4	34.1	30.2	25.8	29.3
Standard Deviations										
1970s	36.1	72.0	87.1	82.2	156.3	0.9	0.8	0.7	0.8	0.5
2030s	37.4	80.3	109	61.7	145.0	1.0	1.0	0.9	0.7	0.7

Table 3.3d: Characteristics of simulated seasonal and annual rainfall and mean temperature for the North East region (baseline and A1B scenario) as simulated by PRECIS.										
North East	**Rainfall (mm)**					**Mean Temperature (oc)**				
Q0	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	26	157	963	118	1265	16.6	30.9	26.5	17.6	23.7
2030s	28	155	1013	126	1321	19.2	35.0	28.2	20.1	25.8
Standard Deviations										
1970s	22.7	89.7	106.4	52.0	134.9	1.6	0.9	0.9	1.0	0.6
2030s	45.8	122.5	131.8	61.1	225.6	1.4	1.4	1.0	1.7	0.8

North East	**Rainfall (mm)**					**Mean Temperature (oc)**				
Q0	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	21	60	773	83	937	18.2	31.4	23.0	18.8	25.0
2030s	15	62	791	73	940	20.7	33.3	29.4	21.0	26.8
Standard Deviations										
1970s	22.1	32.2	90.5	45	136.2	1.3	0.9	0.9	1.3	0.7
2030s	13.2	34.7	127.9	32.6	149.0	1.4	1.0	1.3	1.8	0.9

North East	**Rainfall (mm)**					**Mean Temperature (oc)**				
Q0	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual
Means										
1970s	56	129	968	128	1281	17.0	31.6	27.3	19.0	24.6
2030s	44	110	1043	133	1330	19.0	33.8	28.9	21.3	26.6
Standard Deviations										
1970s	39.5	87.7	92.4	65.8	141.6	1.5	1.1	0.8	1.1	0.5
2030s	28.2	74.3	154.8	60.3	174.5	1.9	1.4	1.0	1.4	0.8

1.7°C to 2.2°C with respect to the 1970's. Seasonal air temperatures also show rise in all seasons. However, winter temperatures during October, November and December in the Q1 simulations show a decrease by 2.6°C in 2030's with respect to 1970's.

West coast: The annual temperatures are set to increase from a minimum of 26.8°C to a maximum of 27.5°C in the 2030's. The rise in temperature with respect to the 1970's correspondingly ranges between 1.7 to 1.8°C. Temperatures are also projected to rise for all seasons for all the three simulations from 1.5 to 2.2°C , with the rainfall period of June, July, August and September showing the minimum rise amongst all seasons.

East coast: In the east coast, the surface annual air temperature is set to rise from 28.7°C to 29.3°C. The standard deviation in temperatures varies from 0.6 to 0.7 respectively. The rise in temperature with respect to 1970's is of the order of 1.6 to 2.1 °C . The maximum increase in temperature is for March, April and May in all simulations and is ranging from 1°C to 3.3 °C.

North-East: Surface air temperature is projected to rise by 25.8 to 26.8 °C in 2030's with a standard deviation ranging from 0.8 to 0.9. The rise in temperature with respect to 1970's is ranging from 1.8 to 2.1 °C.

3.4.4 Projections of extreme precipitation

Any particular day, receiving rainfall greater than 2.5 mm, is considered as a rainy day. In simulations, the frequency of rainy days is more in east and north-east India and less over western India. Q0, Q1 and Q14 simulation for 2030's however, indicate that the

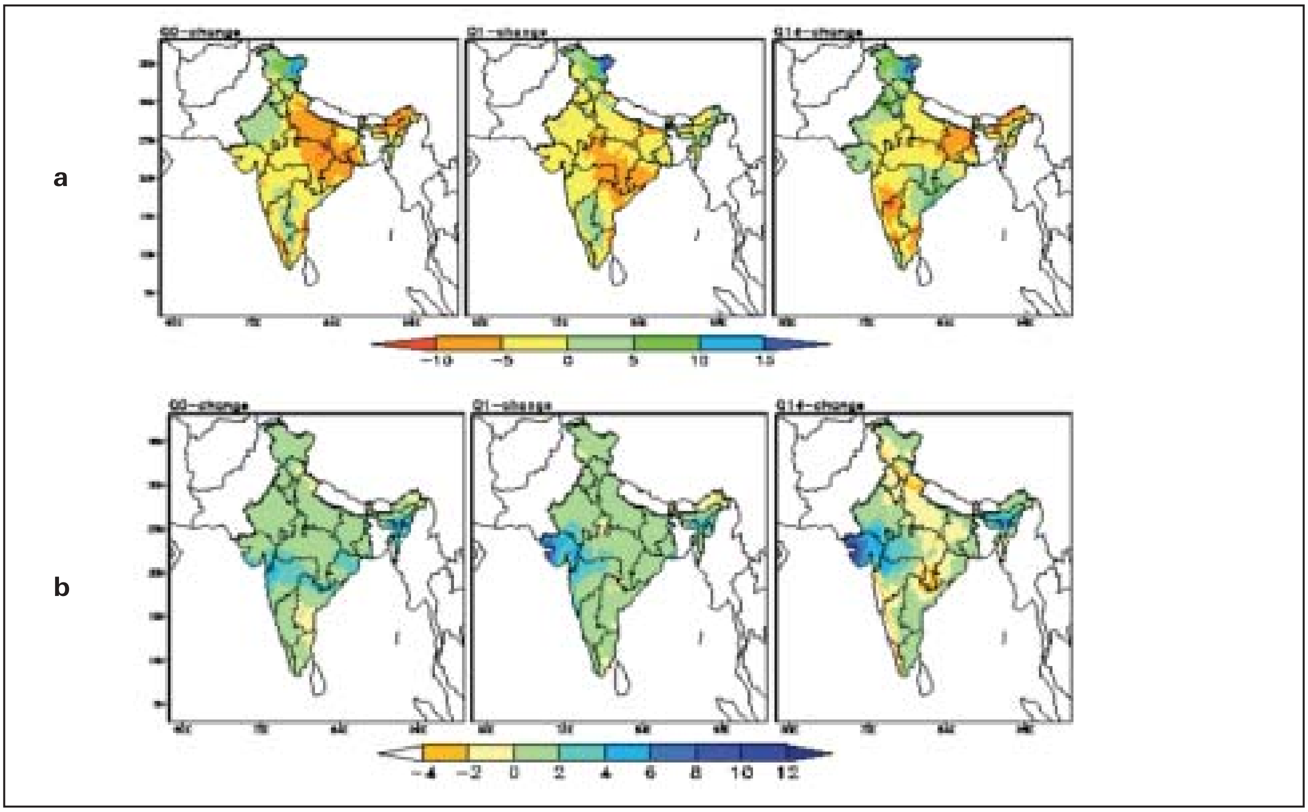


figure 3.8: (a) Change in frequency of rainy days, (b) Change in intensity of raindays. Both changes are observed in 2030s with respect to 1970s

frequency of the rainy days is set to decrease in most parts of the country, except in the Himalayas, the North-western region and the Southern plateau. Q14 simulations also indicate that there will be minimal changes along the upper eastern coast of India. [Figure 3. 8 (a)].

Presently, intensity of a rainy day is more in Western Ghats and North-East India. The intensity of the rainy days increases in a more warming scenario in Q14 with respect to simulations Q0 and Q1. However Q14 simulation suggests decrease in the intensity of rainy days over Western Ghats and Northern India and increase in intensity by 2-12% in the Himalayan region, North-Eastern region, Western and North-Western regions and the Southern Eastern coastal regions. [Figure 3.8 (b)].

3.4.5 Projected changes in temperature extremes

The analysis of the three model simulations indicates that both the daily extremes in surface air temperature may intensify in the 2030's. The spatial pattern of the change in the lowest daily minimum and highest maximum temperature suggests a warming of 1 to 4°C towards 2030's. (see figure 3.9, changes in the lowest and maximum temperatures in 2030's with respect to base year is given.) The warming in night temperatures is more over south peninsula, central and northern India, whereas day time warming is more in central and northern India. Over the entire Indian landmass, this value exceeds 40°C, except over the mountainous regions and the west coast. This threshold enhances further by 1-1.5°C in 2030's. PRECIS simulations for 2030's indicate an all-round warming over the Indian subcontinent associated with increasing greenhouse gas concentrations. The annual mean surface air temperature rise by 2030's ranges from 1.7°C to 2°C as in the three simulations.

3.4.6 Projected changes in storms

As per studies carried out by Mandke and Bhide, 2003, the frequency of storms forming over Indian seas has decreased significantly. Studies of the long period data from 1901-1998 have revealed that the storm frequency has decreased on a decadal scale since 1980's in spite of increasing sea surface temperatures that are conducive to the formation of storm surges (see figure 3.10). Mean of storm frequency before 1980's is found to be significantly different than in the period after 1980. Decadal variation of anomalies of Sea Surface Temperature (SST), relative vorticity at

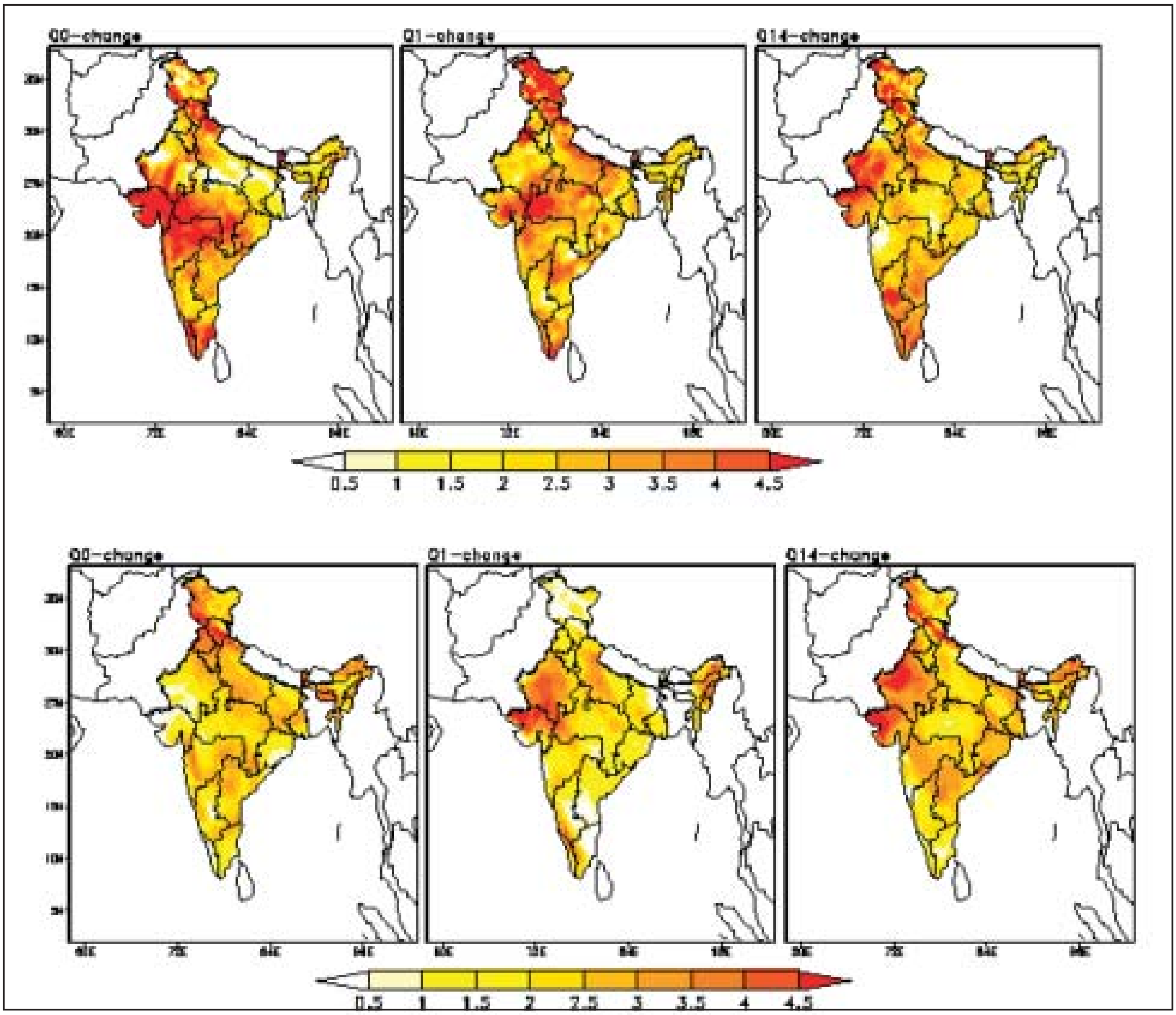


Figure 3.9: Changes in the minimum (upper panel) and maximum temperatures (lower panel) in 2030s with respect to base year

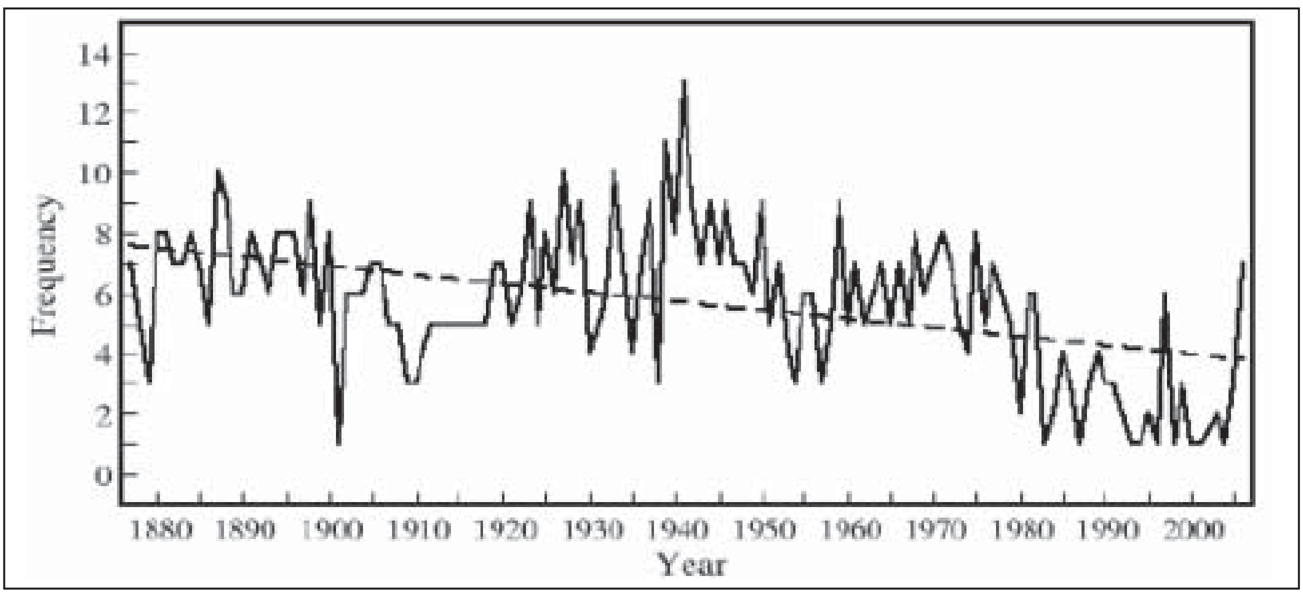


Figure 3.10: Frequency of Cyclonic disturbances forming over Bay of Bengal region. Dottedline shows the significant linear trend

Table 3.3: Frequency of monthly cyclonic disturbances in monsoon season simulated by PRECIS (Max. intensity in brackets (m/s))					
Q0	**Jun**	**Jul**	**Aug**	**Sep**	**JJAS**
1970s	30 (34.4)	42 (32.5)	31 (31.2)	37 (30.9)	140 (32.4)
2030s	6 (40.2)	37 (33.2)	31 (33.0)	50 (32.2)	124 (34.6)
Q1					
1970s	17 (33.1)	35 (32.9)	50 (30.4)	42 (29.3)	144 (31.4)
2030s	17 (37.9)	31 (32.4)	48 (31.3)	38 (33.6)	134 (33.8)
Q14					
1970s	18 (35.7)	27 (32.8)	23 (30.4)	27 (29.6)	95 (32.1)
2030s	17 (35.7)	32 (33.1)	22 (31.0)	31 (31.5)	102 (32.8)

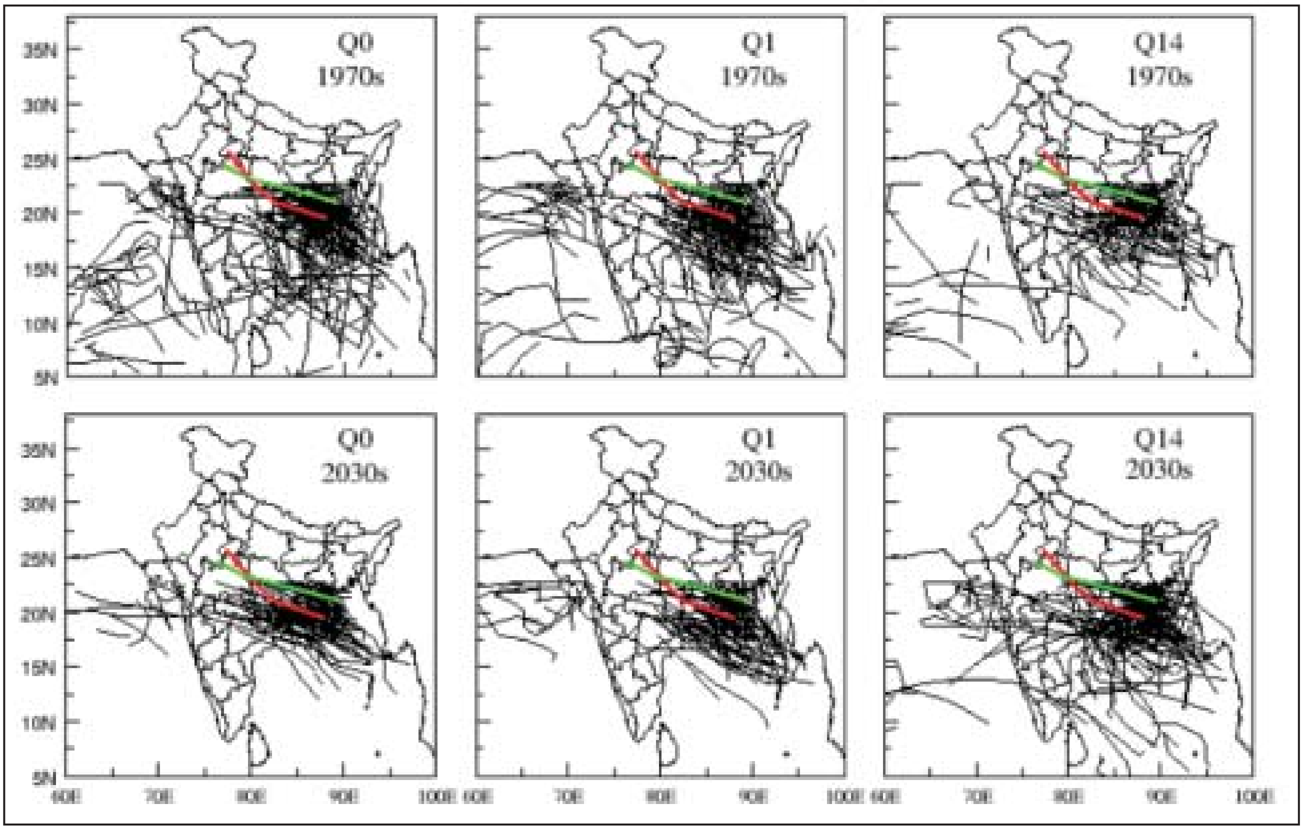


Figure 3.11: The storms simulated by PRECIS QUMP ensembles for 1970s (upper panels) and 2030s (lower panels). The normal tracks for Jun and Sept (red) and Jul and Aug (green) are shown

850hPa, horizontal and vertical shear of zonal wind averaged over Bay of Bengal during monsoon season, using monthly mean NCEP/NCAR re-analysis data for the period 1958-1998 indicates that the anomalies of these parameters are of opposite sign for periods prior to and after 1980. Results suggest that the changes in all the atmospheric parameters from before and after 1980's are related to decreasing storm frequency in spite of favourable SSTs.

The cyclone tracks have been simulated by PRECIS (see figure 3.11). Model simulated tracks are more towards southern latitudes as compared to the observed normal tracks. The regional model simulations also indicate the decrease in the frequencies of cyclonic disturbances. In two of the three simulations viz. Q0 and Q1, the storm frequency in 2030's is less as compared to the baseline frequencies. The number of cyclonic disturbances over Arabian Sea may be less in future as compared to the present simulations. However the analysis indicates that the systems might be more intense in the future as compared to the present under the global warming scenario (last column in Table 3.4)

4

Observed Sea level Rise, Extreme Events and Future projections

4.1 Introduction

The Indian coastline, including the coastlines of Andaman and Nicobar Islands in the Bay of Bengal and Lakshadweep Islands in the Arabian Sea, is 7517 km of which 81% (6100 km) is along the Indian mainland surrounded by Arabian Sea in the west, Bay of Bengal in the east and Indian Ocean in the south. More than 40 million people reside along this coastline. There are 13 coastal states and union territories susceptible to sea-level rise in the country, with about 84 coastal districts affected by tropical cyclones. Four states (Tamil Nadu, Andhra Pradesh, Orissa and West Bengal) and one UT (Puducherry) on the East Coast and one state (Gujarat) on the West Coast are the states that are the most affected by cyclonic activities. The mega cities of Mumbai, Chennai and Kolkata lie along this coastline. Additionally it is dotted with several major ports such as Kandla, Mumbai, Navasheva, Mangalore, Cochin, Chennai, Tuticorin, Visakhapatnam, and Paradip. A large portion of the population along the coastline is dependent on climate-dependent activities such as marine fisheries and agriculture. Sea level changes and occurrence of extreme events such as cyclones and storm surges are of considerable significance for India as these adversely impact human populations living in coastal regions and on islands as well as the sensitive ecosystems such as the mangroves (e.g. the Sundarbans).

With climate change, it is projected that the sea level may rise further than what it is today and with warming of the oceans, the intensity and frequency of cyclonic activities and storm surges may increase leading to large-scale inundation of the low-lying areas along the coastline. In this context, this chapter reviews the existing trends of these parameters based on observations. It also analyses the projections using modelling techniques. Both global and Indian context are reviewed, as sea-level rise as well as cyclones and storm surges do not occur in isolation but are a function of various parameters that are originating in different regions of the globe and occurring in the region

4.2 Observed sea-level rise and future projections

4.2.1 Observed sea-level-rise trends – Global and along the Indian coastline

Though the impacts of the sea-level rise are local in nature, the causes of sea-level rise are global and can be attributed to several non-linearly coupled components of the Earth system. At long-time scales, global mean sea level change results from mainly two processes, mostly related to recent climate change, that alter the volume of water in the global ocean: i) thermal expansion and ii) the exchange of water between oceans and other reservoirs - glaciers and ice caps, ice sheets, other land water reservoirs - including through anthropogenic change in land hydrology, and the atmosphere. Some oceanographic factors such as changes in ocean circulation or atmospheric pressure also cause changes in regional sea level, while contributing negligibly to changes in the global mean. All these processes cause geographically non-uniform sea level variations. Vertical land movements such as resulting from Glacial Isostatic Adjustment (GIA), tectonics, subsidence and sedimentation influence local sea level measurements. Measurements of present-day sea level change rely on two different techniques: tide gauges and satellite altimetry. Tide gauges provide sea level variations with respect to the land on which they lie. To extract the signal of sea level change due to global warming, land motions need to be removed from the tide gauge measurement.

According to the IPCC AR4 (Bindoff *et al*., 2007), the losses from the ice sheets of Greenland and Antarctica have very likely contributed to sea-level rise over 1993 to 2003 (see Table 4.1). Flow speed has increased for some Greenland and Antarctic outlet glaciers, which drain ice from the interior of the ice sheets. The corresponding increased ice sheet mass loss has often followed thinning, reduction or loss of ice shelves or loss of floating glacier tongues.

Table 4.1: Observed rate of global sea level rise and estimated contributions from different sources.		
	Rate of sea level rise (mm per year)	
Source of sea level rise	1961–2003	1993–2003
Thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35
Sum of individual climate contributions to sea level rise	1.1 ± 0.5	2.8 ± 0.7
Observed total sea level rise	1.8 ± 0.5[a]	3.1 ± 0.7a
Difference (Observed minus sum of estimated climate contributions)	0.7 ± 0.7	0.3 ± 1.0
Table note: [a] Data prior to 1993 are from tide gauges and after 1993 are from satellite altimetry.		
Source: Bindoff *et al*., 2007, IPCC, WGI		

Such dynamical ice loss is sufficient to explain most of the Antarctic net mass loss and approximately half of the Greenland net mass loss. The remainder of the ice loss from Greenland has occurred because losses due to melting have exceeded accumulation due to snowfall.

Global average sea level rose at an average rate of 1.8 mm per year over 1961 to 2003. The rate was faster over 1993 to 2003, at about 3.1 mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear. There is high confidence that the rate of observed sea-level rise increased from the 19th to the 20th century. The total 20th-century rise is estimated to be 0.17 m. Between 1993 and 2003, the sea level rose by 0.33 m with an uncertainty of ±1 mm/year.

Though global sea-level rise has been studied extensively during the last two decades based on tide-gauge data, the same is not true of trends in regional sea level. The variability seen in regional sea level is less well understood owing to two causes. First, the distribution of tide gauges is not uniform over the globe, and not many records from the tropics are long enough for a reliable estimate of sea-level trends. Second, vertical land movements make problematic the determination of changes at the coast, where the tide gauges are located. Global Positioning System (GPS) measurements to determine vertical land movements are often not available. Satellite altimetric data, available since 1993, not only overcome this shortcoming, but also have the advantage of spatial coverage: global patterns of sea-level rise using altimetric data, particularly TOPEX/Poseidon, have been widely documented (see Nerem and Mitchum, 2001; Cazenave and Nerem, 2004 for a review). The length of the satellite-based sea-level record is relatively small, however, for estimating long-term sea-level rise.

The sea-level data from the north Indian Ocean show considerable inter-annual and inter-decadal variability. These changes are forced primarily by large-scale winds (Clarke and Liu, 1994; Shankar and Shetye, 2001; Han and Webster, 2002) and large changes in salinity (Shankar and Shetye, 1999; Shankar and Shetye, 2001). That annual mean sea level, due to the large-scale winds tends to see-saw along the Indian coast, with its pivot at the southern tip of the Indian subcontinent, where a large gradient in salinity exists, leading to a differential response between the two coasts (Shankar and Shetye, 2001).

Studies on sea-level rise in the north Indian Ocean have been few, and are mostly based on tide-gauge data from India. Emery and Aubrey (1989) used monthly-mean sea-level data till 1982 at several tide-gauge stations along the Indian coast to estimate long-term trends in sea level. The trends showed considerable variability because even short records were included in the analysis. This inconsistency was also noted by Douglas (1991), leading him to conclude that the stations in the Indian subcontinent are not suitable for estimating global-mean sea-level rise. Using tide-gauge data all over the globe, Church et al. (2004) used reconstruction methods to determine the spatial pattern of sea-level variability during 1950–2000. These results were used to describe regional sea level changes and suggest values close to 2.0 mm yr^{-1} in the north Indian Ocean, except the north-eastern part of the Bay of Bengal, where values of more than 4 mm yr^{-1} are found.

Unnikrishnan and Shankar (2007) examined the tide gauge records along the north Indian Ocean coasts and checked their inter-consistency. All the records longer than 20 years were considered (see Figure 4.1 for the location of tide gauges). Those along the Arabian Sea coast were linearly correlated with the Mumbai record, which is the longest one in the region, while those records along the Bay of Bengal coast were correlated with the Visakhapatnam record. Finally, they chose the longest records in the region, which passed through the correlation tests and those having a statistical significance in the trend analysis. Those selected include Mumbai, Kochi, Visakhapatnam and Diamond Harbour. A correction factor for vertical land movements was applied to the records and the movements are associated mainly with two processes, local tectonic activity and Glacial Isostatic Adjustment (GIA). GIA is caused by post-glacial rebound of land. GIA corrections are accounted by using the ICE-5G model (Peltier, 2001; 2004).

The mean sea-level rise along the Indian coasts is estimated to be about 1.3 mm/year on an average (Table 4.2). These estimates are consistent with the values reported elsewhere (Church *et al*., 2001). However, these estimates are slightly lower than the global mean sea-level estimates of 1.8 mm/year for the period 1963-2003 (Bindoff *et al*., 2007). The study showed a large trend of 5.74 mm/year for the record at Diamond Harbour (Kolkata), which is attributed partly to the subsidence of the Ganges-Brahmaputra delta. The rate of subsidence in the region, as estimated from sedimentological studies, is about 4 mm/year (Goodbred and Kuehl, 2000).

4.2.2 Projections of sea level rise – Global and along the Indian coastline

Model-based projections of global average sea-level rise at the end of the 21st century (2090–2099) made for a number of climate scenarios indicate that the sea level may rise from a minimum of 0.18 m minimum to a maximum of 0.59 m (See Table 4.3).

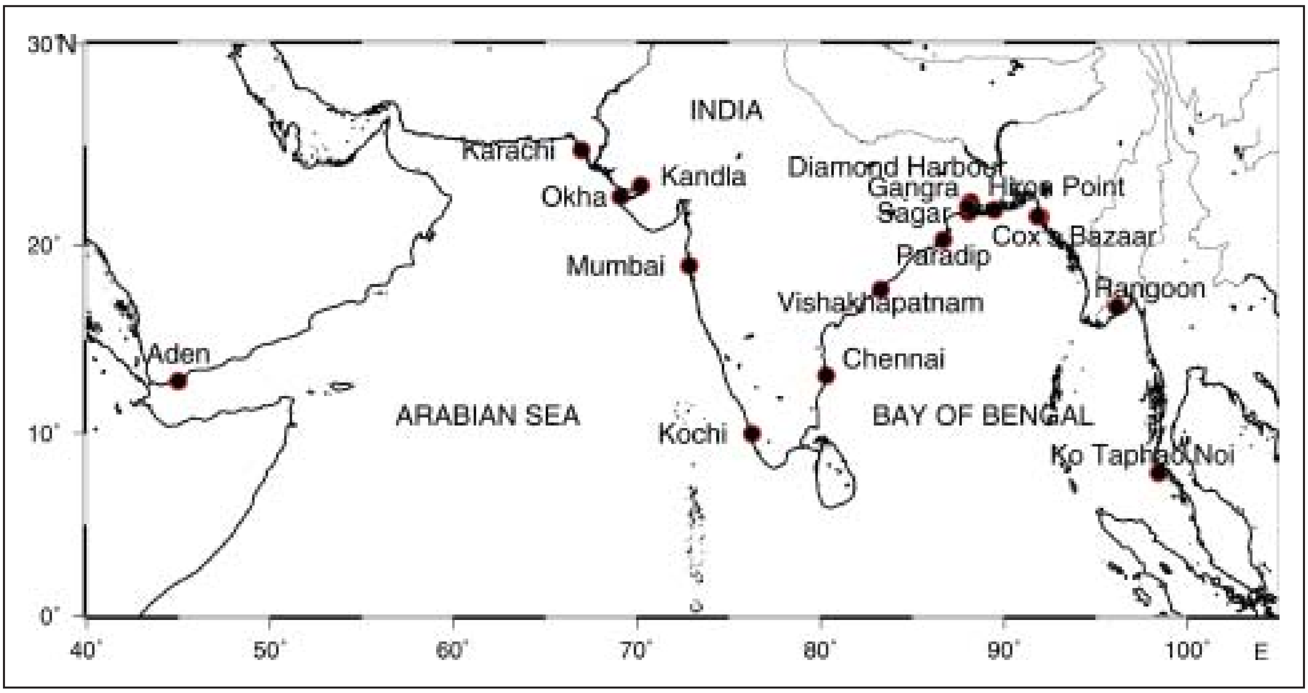


Fig. 4.1: Location of tide gauges having records longer than 20 years

Table 4.2: Mean-sea-level-rise trends along the Indian coast.

Tide gauge Station	Number of years of available data	Trends (mm/yr)	Glacial Isostatic Adjustment (GIA) Corrections(mm/yr)	Net sea level rise (mm/yr) trends
Mumbai	113	0.77	-0.43	1.20
Kochi	54	1.31	-0.44	1.75
Vishakhapatnam	53	0.70	-0.39	1.09
Diamond Harbour(Kolkata)	55	5.22	-0.52	5.74

Table 4.3: Global sea- level- rise projections	
	Sea Level Rise in m (5 % and 95 % range)
	in 2090-2099 with respect to 1980-1999)
Case	**Model-based range excluding future**
	rapid dynamical changes in ice flow
Constant Year 2000 concentrations	NA
B1 scenario	0.18 – 0.38
A1T scenario	0.20 – 0.45
B2 scenario	0.20 – 0.43
A1B scenario	0.21 – 0.48
A2 scenario	0.23 – 0.51
A1FI scenario	0.26 – 0.59
Table notes: A Year 2000 constant composition is derived from AOGCMs only.	
Source: Meehl *et al*., 2007, IPCC WGI	

Models used to date do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of changes in ice sheet flow, because a basis in published literature is lacking. The projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993 to 2003, but these flow rates could increase or decrease in the future. For example, if this contribution were to grow linearly with global average temperature change, the upper ranges of sea-level rise for SRES scenarios shown in 4.3 would increase by 0.1 to 0.2 m. Larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise.

However globally, sea level is expected to continue to rise over the next several decades. During 2000 to 2020 under the SRES A1B scenario in the ensemble of AOGCMs, the rate of thermal expansion is projected to be 1.3±0.7 mm yr^{-1}, and is not significantly different under the A2 or B1 scenarios (Meehl *et al*., 2007). These projected rates are within the uncertainty of the observed contribution of thermal expansion for 1993 to 2003 of 1.6±0.6 mm yr^{-1}. The sea-level rise at such short-term time lines are mainly due to committed thermal expansion, caused by constant atmospheric composition at year 2000 values.

Regional variations in sea level change occur also through changes in ocean density and circulation. For the north Indian Ocean region, this variation has been projected to be less than 0.05 m by 2100 (Meehl *et al* ., 2007) relative to the global mean for A1B scenario.

In the absence of availability of regional projections, global projections can be used as a first approximation of sea-level rise along the Indian coasts in the next few decades as well as towards the end of the 21st century.

4.3 Extreme Sea level along the east coast of India

4.3.1 Observed trends of cyclonic storms

North Indian Ocean basin has an average of 5.5 cyclones per year. Further, their frequency in the Indian Seas shows a bi-model character, with two maximum peaks, one from mid-April to mid-June and second one from October to December. The cyclonic disturbances are 5 to 6 times more frequent over the Bay of Bengal than over the Arabian Sea. One-third of the Bay disturbances and half of the Arabian Sea disturbances intensify into tropical storms. The ratio of tropical cyclones between the Bay of Bengal and the Arabian Sea is 4:1. This is probably due to the fact that SST over the Arabian Sea is cooler than that over the Bay of Bengal. Moreover, passage of westward moving remnants of the tropical cyclones forming in the west Pacific Ocean over the Bay of Bengal help in more cyclogenesis over the region. Presence of the Inter Tropical Convergence Zone (ITCZ) near the Equatorial region of the Bay of Bengal due to either advancement or retreat of monsoon (Southwest or Northeast) during these periods help to intensify low level cyclogenesis into cyclone. The Bay water maintains the critical ocean temperature of 26-27°C needed for cyclogenesis. The sensible heat maintains the vertical coupling between the lower and upper troposphere flow pattern in the cyclone. The absence of sensible heat leads to the degeneration of cyclone. Cumulus convection acts as the prime mechanism for vertical coupling.

A tropical cyclone unleashes its highest destructive potential when it makes landfall in the coastal belt. Violent winds, torrential rains and storm surge are the three major causes of destruction. The storm surge, which is not properly understood by common people is in fact, responsible for nearly 80% of the loss of lives. Though fewer tropical cyclones occur in the north Indian Ocean compared to the other oceanic basins, the shallow depth of the Bay of Bengal and the low flat coastal terrain produce much larger storm surges and take a very heavy toll of life. The amount of damage caused by a tropical cyclone is directly related to the intensity of the storm, the duration of the storm (related to its storm-center velocity, as discussed above), the angle at which it approaches the land, and the population density along the coastline. Satellite images and radar-based stations allow the tracking of the cyclones and if it poses a threat to land areas, then in situ observations using aircrafts flying through the cyclones record the wind speed, air pressure and moisture etc.

Analysis of Sea Surface Temperature data of the north Indian Ocean region for the past fifty years clearly shows a warming trend. It is expected that with the warming of the oceans, an increase in frequency and intensity may occur. However, cyclone frequency data for the last four decades (1961 onwards), since when significant monitoring tools are available, show a significant decreasing trend for all the months and seasons except in the post-monsoon period. However, the intensity of the cyclones is seen to be increasing during this period.

An important concern about the consequences of the global warming scenario is its impact on the frequency, the intensity and the duration of tropical cyclones. Theoretical and modelling studies (Emanuel, 1988; Holland, 1997; Knutson *et al*., 1998; Pielke *et al*., 2005, Elsner *et al*., 2008) indicate that tropical cyclone winds would increase with increasing ocean temperature. Though direct observational evidence of this relationship over the tropical oceans is lacking, it has been brought out in the recent study over the Atlantic Ocean (Elsner *et al*., 2008) that higher Sea Surface Temperatures (SSTs) over this region increase the intensity of Atlantic tropical cyclones.

Ramesh Kumar and Syam (2010) studied the effect of global warming on the frequency of storms and severe storms in the north Indian Ocean have been examined by analysing multiple datasets. Results obtained in the study suggest decreasing trend in the frequency of storms over the Bay of Bengal, contrary to the popular belief that there will be an increase. Their study further showed that the relationship between the SST and the maximum wind speed is quite complex and there is no preferred range for the formation of cyclonic or severe cyclonic storms over the north Indian Ocean. Results clearly indicate that warm SSTs alone are not sufficient for the initiation of convective systems over the Arabian Sea and the Bay of Bengal. However, other environmental parameters, such as the low-level vorticity, the mid tropospheric humidity and the vertical wind shear, also play an equally important role in their genesis and intensification.

Figure 4.2 shows the 11-year running mean of the seasonal Sea Surface Temperature Anomaly (SSTA) and the Storm Frequency Anomaly (SFA) for the seasons a) Pre-Monsoon, b) Monsoon and c) Post-Monsoon averaged over the Bay of Bengal (80N-280N; 800E-1000E) for the period 1951-2007. From the figure, it can be seen that the SFA is small and positive for all the three seasons during epoch I (1951-1978). During the same period (epoch I), the SSTA over the Bay of Bengal is small and negative.

During epoch II (1979-2007), the SSTA is small and positive over the Bay of Bengal, but the SFA is small and negative for the study area. It can be seen that the SFA is decreasing in spite of increased SSTAs. The SSTA and the SFA are out of phase. Thus, we feel that atmospheric parameters, such as the MTRH at 500 hpa, the VWS between the lower and the upper troposphere, and the low level vorticity, all play an equally important role in the cyclogenesis over the Bay of Bengal.

An analysis of the cyclone data for the last 118-year period (1891-2008) by Niyas et al (2009) shows that out of the total 618 cyclones, 485 (i.e. 78%) formed over the Bay of Bengal, while 133 (i.e. 22%) formed over the Arabian Sea. The maximum number (67) occurred in the decade 1921-30 and minimum (38) during 1981—90. The maximum number (18) of cyclonic storms and severe cyclonic storms occurred in the month of November during the decade 1921-30. Similarly in the pre-monsoon season, maximum number (14) of cyclonic storms and severe cyclonic storms occurred in the month of May during 1961-70. Fig.4.3 shows the trends during the last century.

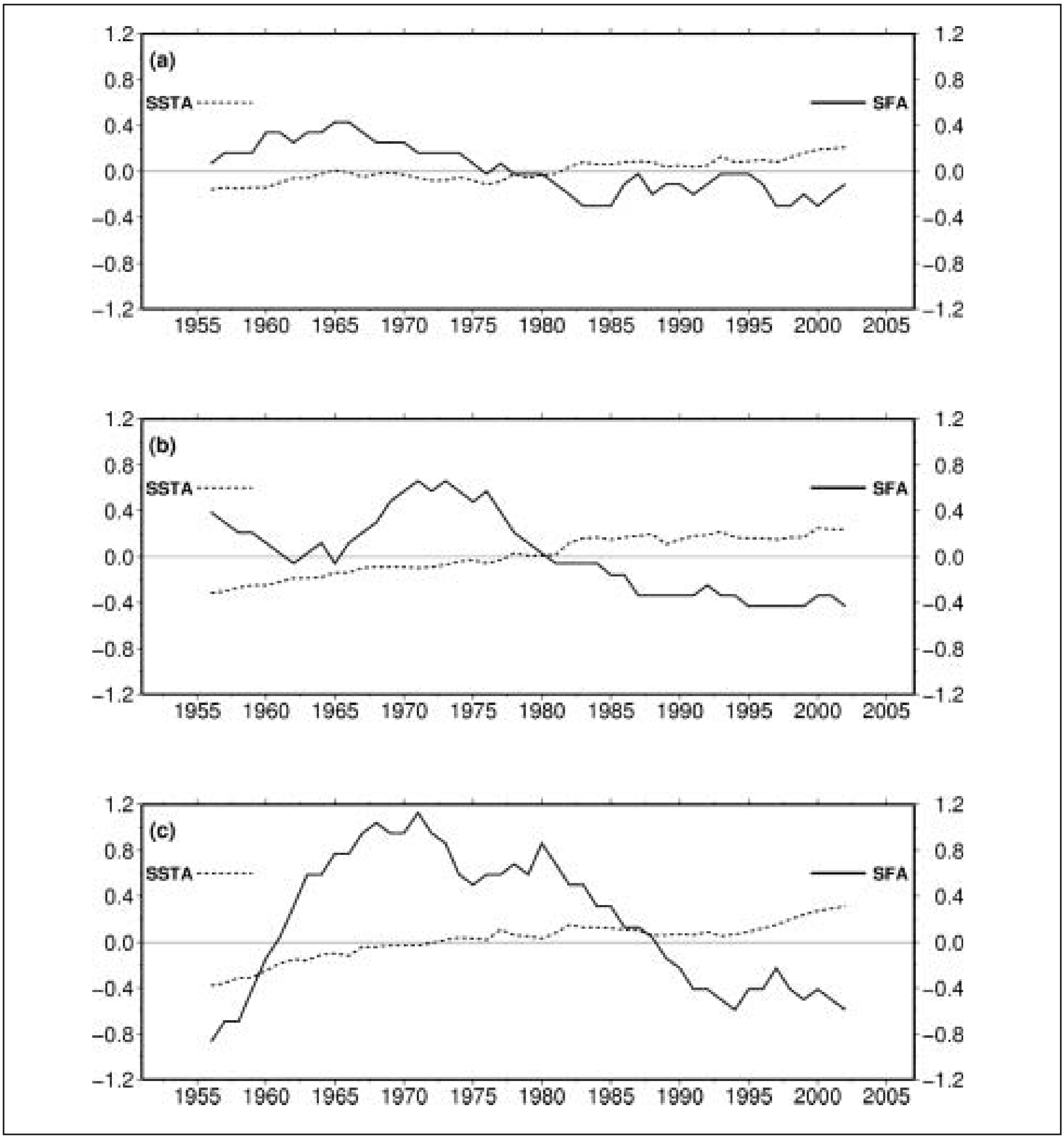
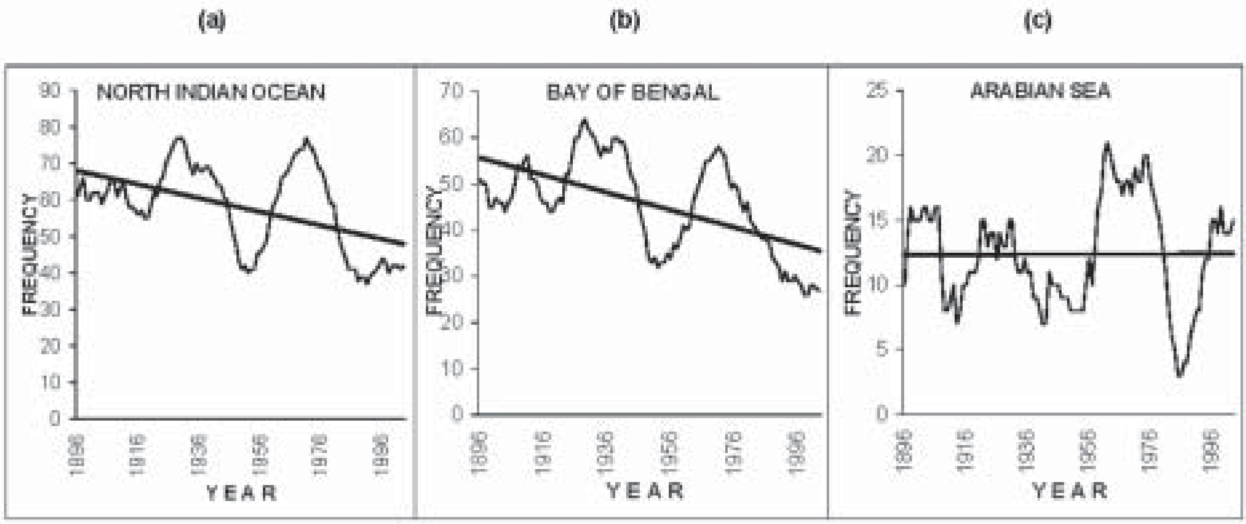


Figure 4.2 The SST anomaly (SSTA) and the Storm frequency anomaly (SFA) over the Bay of Bengal during a) the pre monsoon, b) the monsoon and c) the post monsoon seasons for the period 1951-2007. The anomalies are computed from the long-term mean for the period 1951-2007.

Storm surges in the eastern coastal region of India have been a matter of concern. They form when heavy winds produced by tropical cyclones generate the disturbances in the ocean. As these surges propagate into the shallow regions, they amplify and produce large variations of sea level at the coast. For a moving storm, greater winds occur on the right side of the storm (in the northern hemisphere). The height of the storm surge depends on wind speed, the shape of the coastline, and variations in the water depth along the coastline. Height also depends on phase of the tide. If a surge occurs during high tide, the storm surge will be higher than if it occurs during low tide. Category 5 tropical cyclones can produce storm surges in excess of 6m (20 feet). Because the storm surge occurs ahead of the eye of the storm, the surge will reach coastal areas long before the cyclone makes landfall. This is an important point



$Y = -0.1876x+68.179$ $R^2 = 0.246$

$Y = -0.1879x+55.816$ $R^2 = 0.3263$

$Y = 0.0003x+12.363$ $R^2 = 0.000005$

Figure 4.3 Trends of frequency of cyclonic storms during over (a) north Indian Ocean, (b) Bay of Bengal and (c) Arabian sea (Source Niyas *et al*., 2009)

to remember because flooding caused by the surge can destroy roads and bridges, making evacuation difficult before the storm lands.

4.3.2 Projections of changes in cyclonic activity

According to the IPCC AR4, 2007, results from embedded high-resolution models and global models, ranging in grid spacing from 100 km to 9 km, project a likely increase of peak wind intensities and notably, where analysed, increased near-storm precipitation in future tropical cyclones. Most recent published modelling studies investigating tropical storm frequency, simulate a decrease in the overall number of storms, though there is less confidence in these projections and in the projected decrease of relatively weak storms in most basins, with an increase in the numbers of the most intense tropical cyclones.

For the Indian coastline, simulations of the regional climate model, PRECIS (Rupa Kumar *et al*., 2006), are available for a baseline scenario, A2, B2 and A1B. In the present analysis, we compare the simulations between the A2 scenario (2071-2100) and a baseline scenario, BI (1961-1990). Even though the regional model domain covers the entire north Indian Ocean, the present analysis is carried out on the cyclones in the Bay of Bengal. For both the scenarios, two simulations are available, one, which included sulphur cycle and the other without the sulphur cycle. Since the two simulations do not show any significant differences (Rupa Kumar *et al*., 2006), we restrict our analysis to the simulations without sulphur cycle for the baseline as well as future scenarios. The parameters analysed are the near surface (10 m) wind fields and surface atmospheric pressure fields.

An analysis of atmospheric pressure fields at sea level obtained from PRECIS simulations is made to determine the frequency distribution of cyclones in the Bay of Bengal in different climate scenarios. The software, 'TRACK' (version 3.1.4) developed by Hodges (1994), is used to identify tracks of cyclones. Surface atmospheric pressure fields at daily time scale are used as the input and all the Low-Pressure Systems (LPS) are identified. This information is used for determining the frequency distribution of cyclones in BI and A2 scenarios.

The composite tracks of the cyclones (Figs. 4.4 and 4.5) for baseline (no sulphur cycle) and A2 (no sulphur cycle) scenarios respectively do not show any significant difference between them. However, the frequency of cyclones (Fig. 4.6) during the post-monsoon season in the future (2071-2100) scenario is found to be much higher than that during the baseline scenario (1961-1990).

4.3.3 Simulation of storm surges in present and future climate scenarios

A vertically integrated 2-D model developed in earlier studies (Unnikrishnan *et al*., 1999; Unnikrishnan *et*

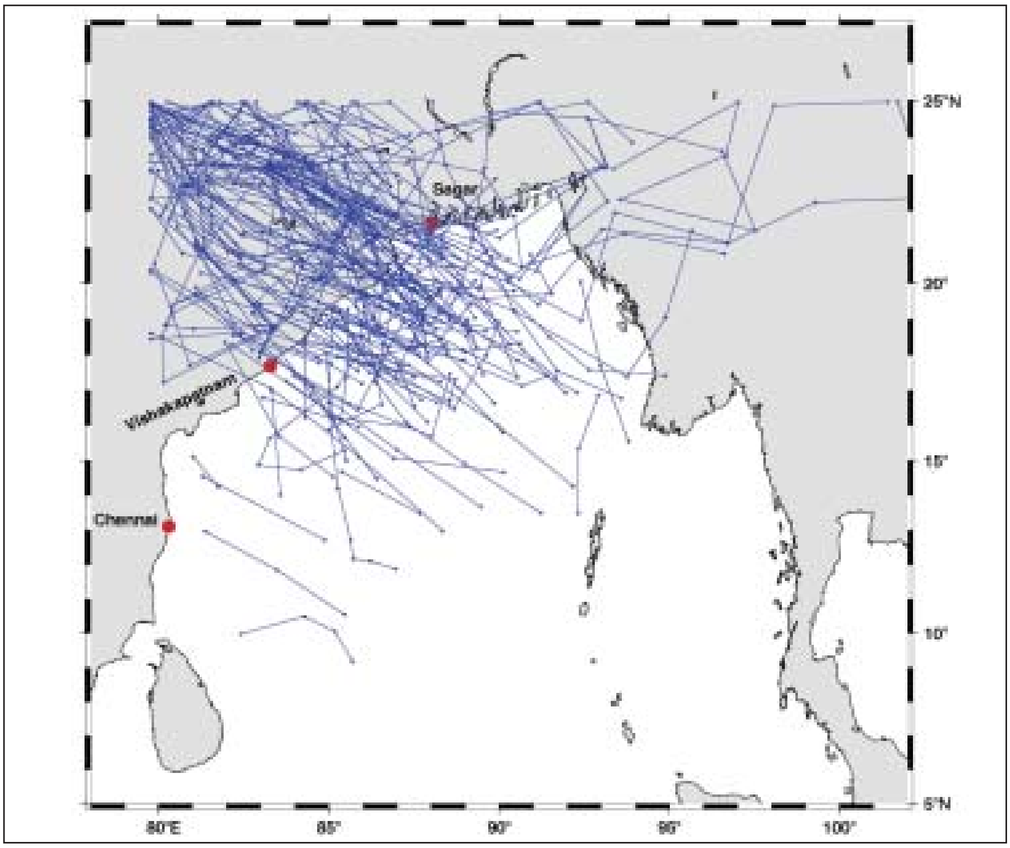


Fig.4.4: Composite track of cyclones during baselineBI (without sulphur cycle) scenario (1961-1990) from PRECIS simulations

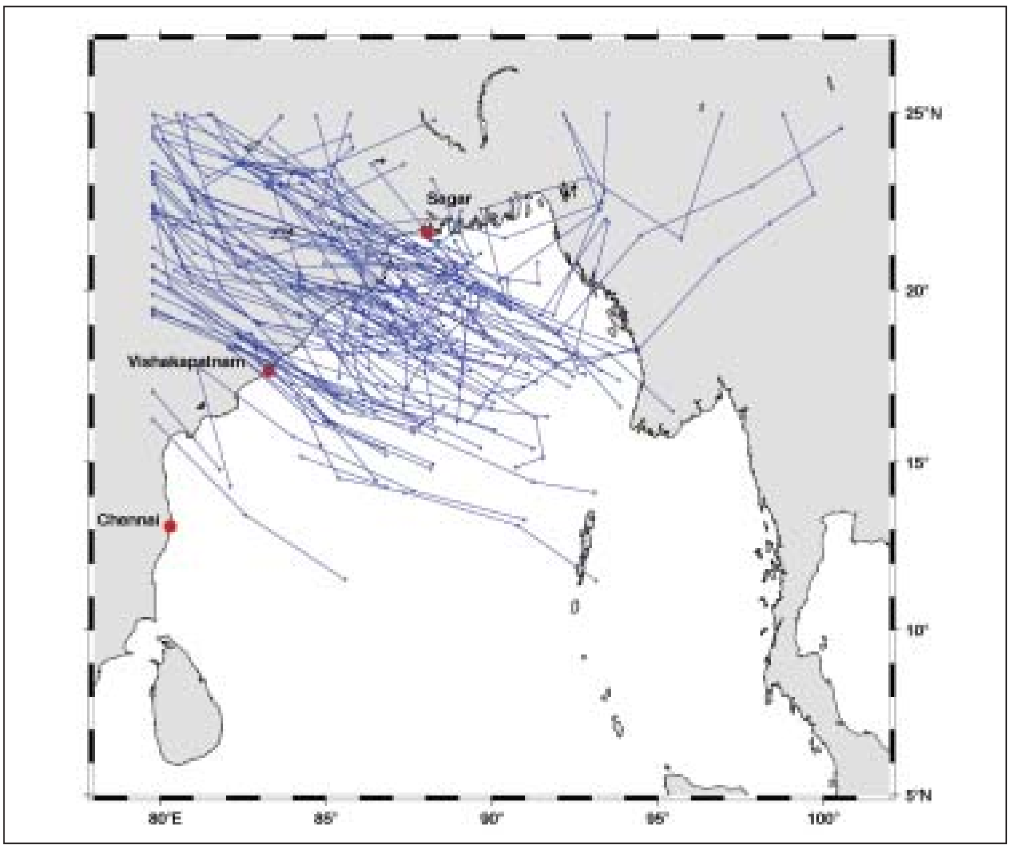


Fig.4.5: Composite track of cyclones during A2 (without sulphur cycle) scenario (2071-2100) from PRECIS simulations

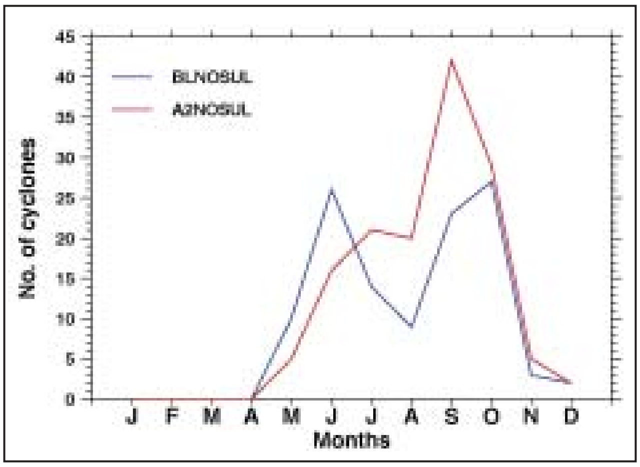


Fig 4.6: Frequency distribution of cyclones in the Bay of Bengal. Red colour indicates A22 scenario (2071-2100) and blue colour indicates bBlaseline scenario (1961-1990).

al., 2006) is used for developing a storm surge model for the Bay of Bengal. The southern open boundary (Fig. 4.7) is along 9.5^0 N. The eastern, northern and western boundaries are closed. The grid spacing is 18.33 km in x and y directions and the time step used is 24 sec.

The surface atmospheric pressure fields and wind velocity components at 10 m height obtained from PRECIS model simulations are used to force the storm surge model. Along the open boundary, tides are prescribed from the output of the global tidal model, FES2004 (Lyard *et al*., 2006) and a radiation boundary condition is defined. Two simulations have been made. In the first, the model was forced by winds and tides and in the second, forcing was done by tides alone. The difference between the two types of simulations provides surge fields, assuming that the interaction between tides and surges is linear. Surge fields are used to identify extreme events and the maximum sea level value for each event is identified. This is done by defining a window of 60 hours before and after the time of occurrence of the peak surge. The simulations were carried out for the Bl (1961-1990) and future scenario, A2 (2071-2100). For the simulations of A2 scenario, a sea-level rise of 4 mm/year, which is approximately the increase projected in A1B scenario, is added to the levels from 1990.

Extreme sea level values associated with storm surge events are fitted with a Gumbel extreme value distribution, and return levels at different locations are determined. The methodology is described in our earlier work (Unnikrishnan *et al*, 2004). Since most of the cyclones in the simulations cross the northern part of the coast, peak surges occur mainly in the northern and north-eastern regions. We present the estimated return period curves to selected stations (see Fig. 4.8), located north of Visakhapatnam. The 100-year return levels and standard errors associated with the Gumbel fit are shown in Table 4.4.

It is found that for all locations north of Visakhapatnam except at Sagar and Kolkata, the increase in 100-year return levels (Fig. 4.8) is about 15 to 20 % in the future scenario, when compared to those in baseline scenario. For the two stations considered in the head Bay, namely, Sagar and Kolkata, increase in 100-year return levels for the future scenario were found to be less than 5 %. Fig. 4.8 also indicates a reduction in 1000-year return periods at different stations. In the future scenario with increased sea level, 1000-year return period reduces to about 100-year period. However, in regions of very large tidal ranges, such as Sagar and Kolkata, the difference in return levels due to sea-level rise are relatively small.

4.4 Projected coastal inundation due to sea- level rise

Impacts at the coast depend on on-shore topography. Coastal regions having a gentle topography are more vulnerable than those having a steep topography. The east coast of India is more vulnerable than the west coast, because the former is low-lying and more prone to the occurrence of cyclones than the latter (Shetye *et al*., 1990). The central west coast of India is least vulnerable, by virtue of a steep on-shore topography and low occurrence of cyclones.

Three vulnerable regions were considered for impact studies. The area of inundation for a sea-level rise of 1m was estimated for regions surrounding Nagapattinam, Kochi and Paradip. Along the east

Table 4.4: 100-year return levels (m) at selected stations, estimated from the storm surge model simulations

Station	100-year return level (1961-1990) in m	100-year return level (2071-2100) in m
Vishakhapatnam	2.53±0.08	2.94±0.08
Paradip	3.63±0.09	4.36±0.11
Short Island	4.32±0.11	4.99±0.13
Sagar	7.98±0.26	7.96±0.20

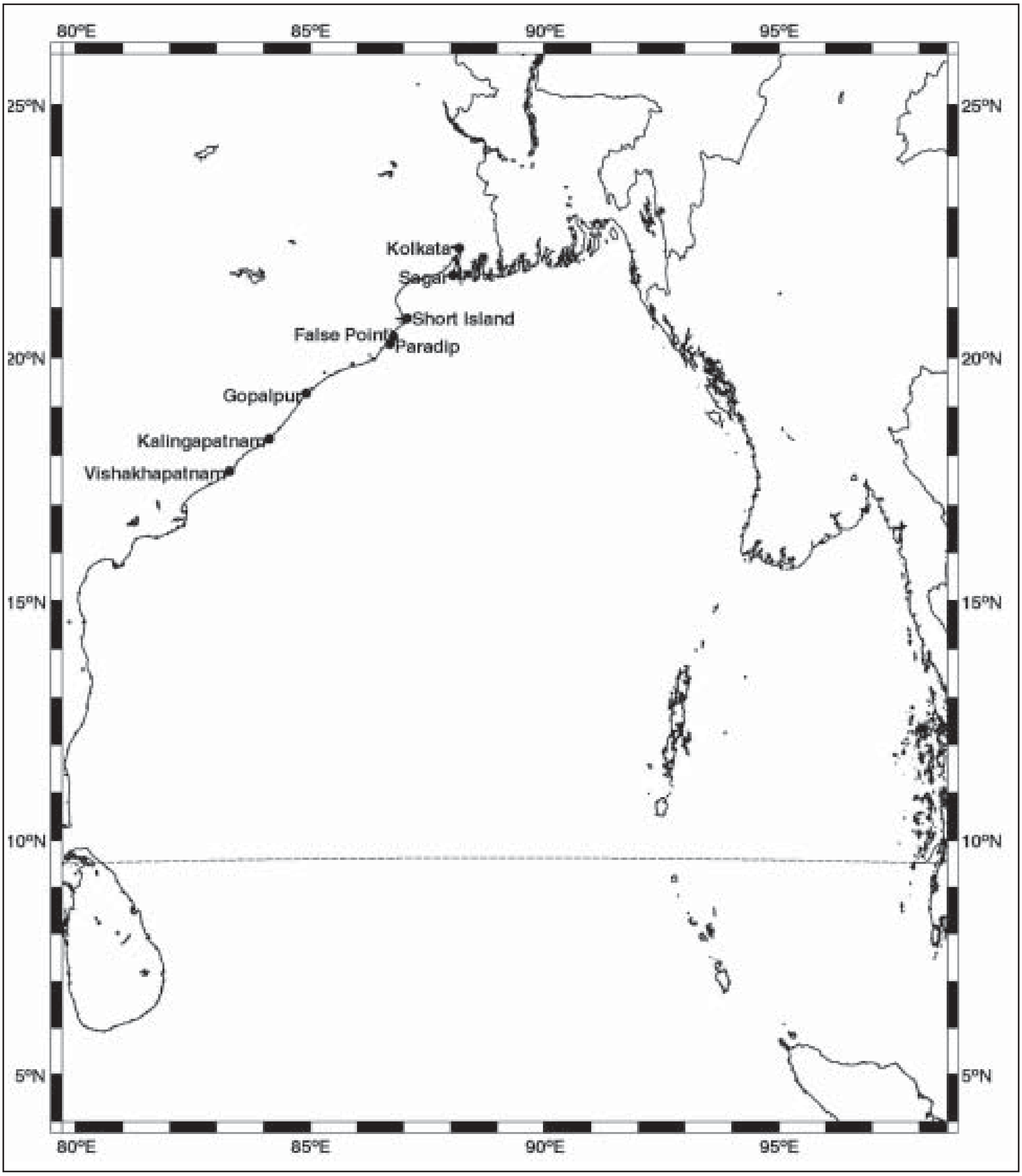


Fig. 4.7: Storm surge model domain for the Bay of Bengal with the dashed line indicating the southern open boundary. Return levels of extreme sea level were calculated for stations shown along the coast.

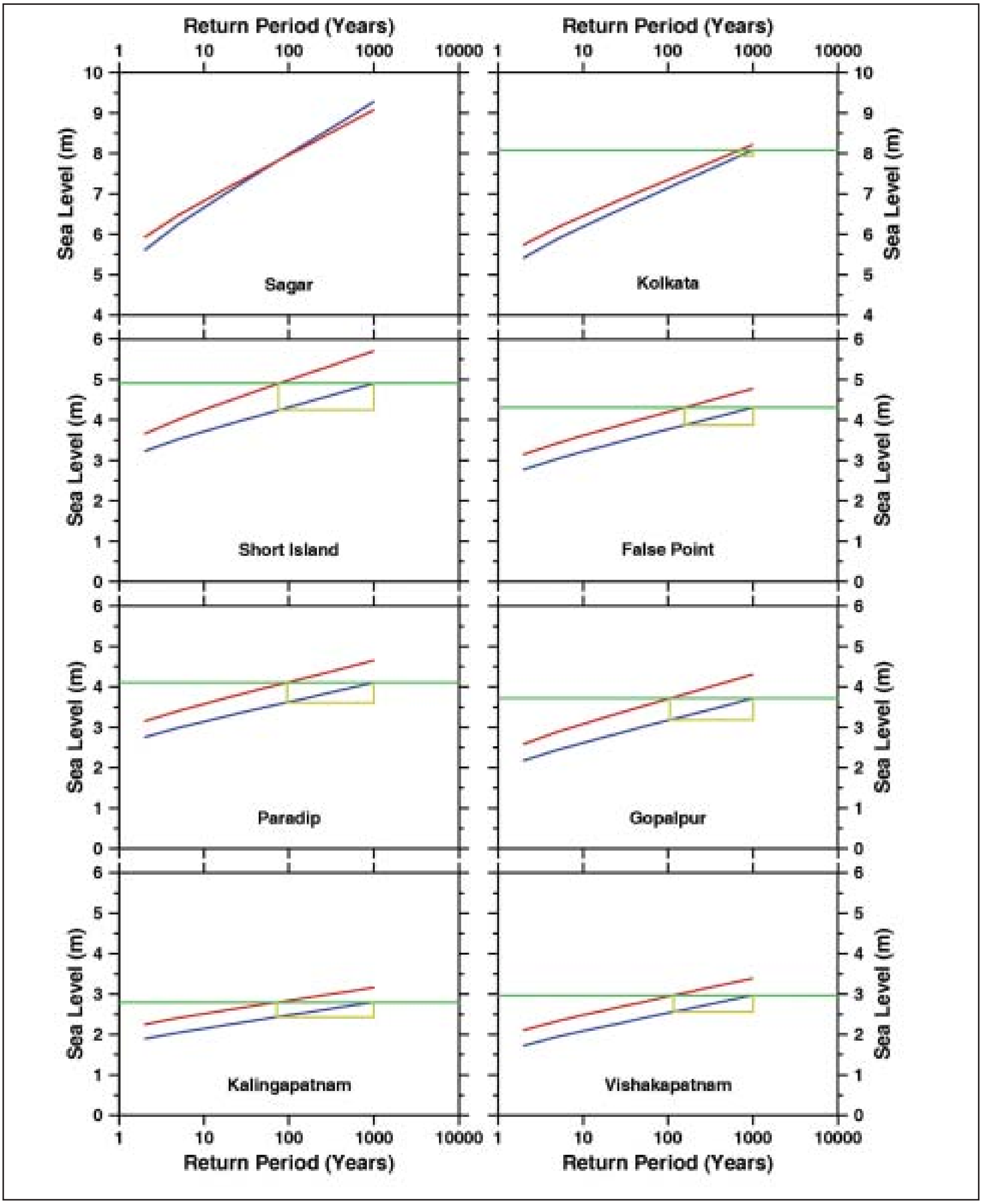


Fig. 4.8: Estimated return levels from 30-year storm surge model runs. Blue indicates the baseline scenario (1961-1990) and red indicates the A2 scenario (2071-2100). Mean-sea-level rise of 4 mm/ year is added from the 1990 levels for the model runs for A2 (2071-2100) scenario

coast, Nagapattinam had been a highly vulnerable region for the impact of storm surges and also for the tsunami of 2004. The region surrounding Kochi is low-lying and it is characterized by the presence of backwaters, while Paradip is known for the occurrence of storm surges resulting from the passage of cyclones.

Indian Remote Sensing satellite (IRS) P6 image with resolution of 23.5m and Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) with 90 m resolution, are used to estimate the inundated areas. Elevations from DEM are not available for less than 1 m accuracy. Therefore, maps are prepared for a 1.0 m sea-level rise scenario to estimate area of inundation.

Estimation of inundation of coastal areas due to sea-level rise was made for two locations (Nagapattinam and Paradip) along the east coast of India and for one location (Kochi) along the west coast of India. The study used the same methodology for all these regions. IRS P6 LISS III satellite image and SRTM (Shuttle Radar Topography Mission) digital elevation model data (90 m resolution) were used with the help of topographic sheets of the Survey of India for finding out the probable inundation areas for a 1 m sea-level projection. Digital image processing and Geographical Information system software were used for determining the area of inundation. The satellite imagery of the three study areas (Figs. 4.9, 4.12 & 4.15) and digital elevation maps (Figs. 4.10, 4.13 & 4.16) are presented. The estimated inundated areas are presented for a 1 m increase in sea level (Fig. 4.11, 4.14 & 4.17).

The estimates obtained from the present study can be improved by using higher resolution DEM. Validation with ground truth data is also an important component of the study, which will be taken up in future. The present study with the available data provides the following results. The estimate shows that the inundation area will be about 4.2 km^2 for a 1.0 m rise in sea level in the region surrounding Nagapattinam. But for the same sea-level rise projections, about 169 km^2 of the coastal region surrounding Kochi will be inundated. Since Kochi region covers the backwaters, a lot of inland areas far from the coast, but adjacent to the tidal creeks, backwaters and lakes will be inundated. This causes considerable increase in the total area of inundation.

In Paradip, the variations in topography are not smooth and low-lying areas are large, which are connected by tidal creeks and river inlets. This area seems to be the most vulnerable, as about 478 km^2 may be inundated in Paradip coastal region, for a 1.0 m sea-level rise. All the creeks, estuaries and low-lands adjacent to the shoreline increase the risk of inundation. The extent of probable inundation zone goes up to approximately 40 km landward. In a similar way, Kochi region is also vulnerable even in the interior land areas. The present study shows that all the three regions, considered for impact studies, are highly vulnerable to sea-level rise. The methodology used in the present study can be improved by using higher resolution DEM and more accurate area of inundation can be determined. Different land use classes, which get affected by the inundation can also be estimated, which will be helpful for planners and decision-makers to devise contingency plans for combating sea-level rise problems along the coast of India. Impact assessment provides useful information for different sectors such as ports and infrastructure development near the coast. It is useful for planners and policy-makers to develop long-term adaptation measures. Environmentalists and coastal zone managers need to work out the plans for managing the coastline and its environment affected by sea-level rise and natural disasters.

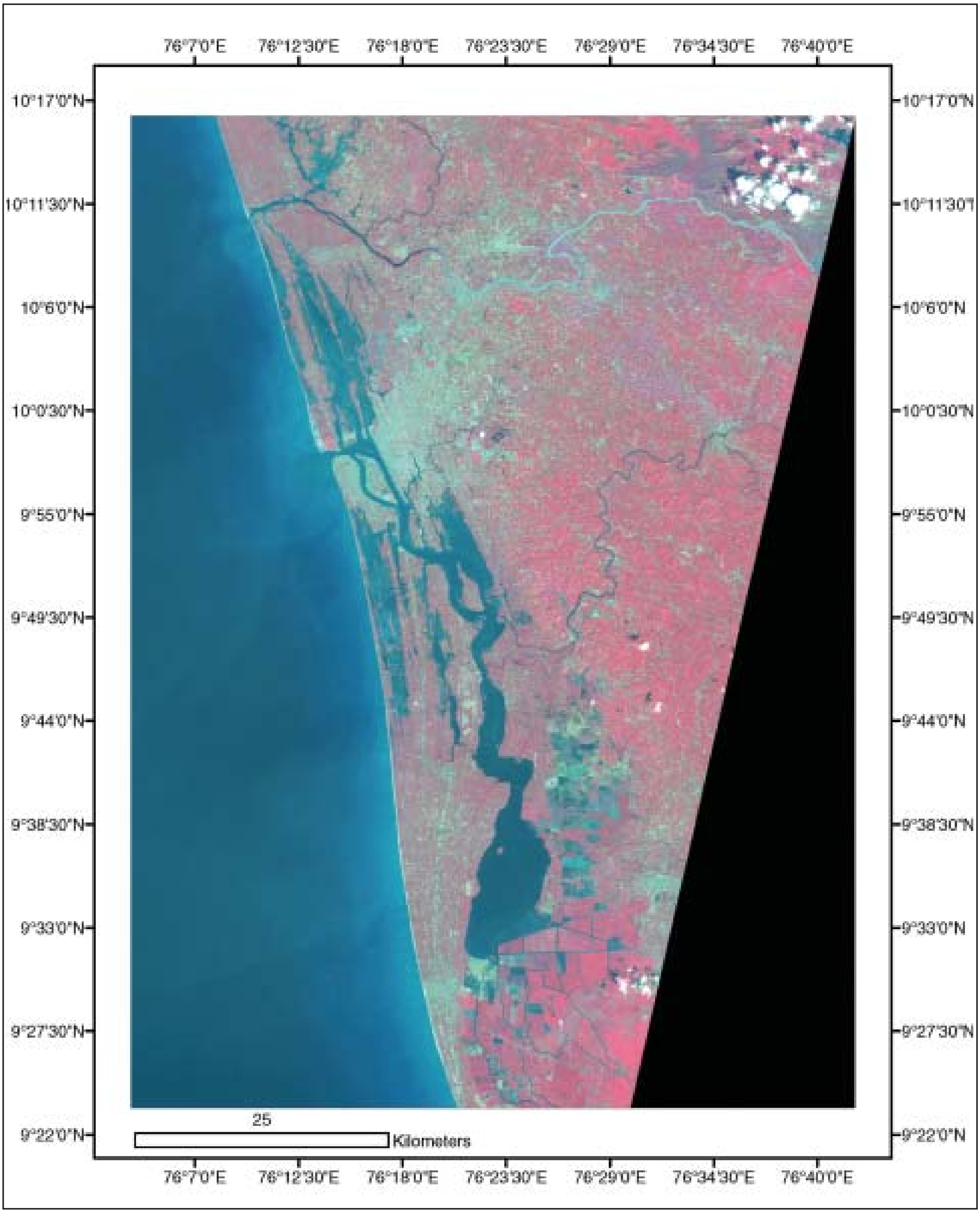


Fig. 4.9: IRS satellite image of Kochi region

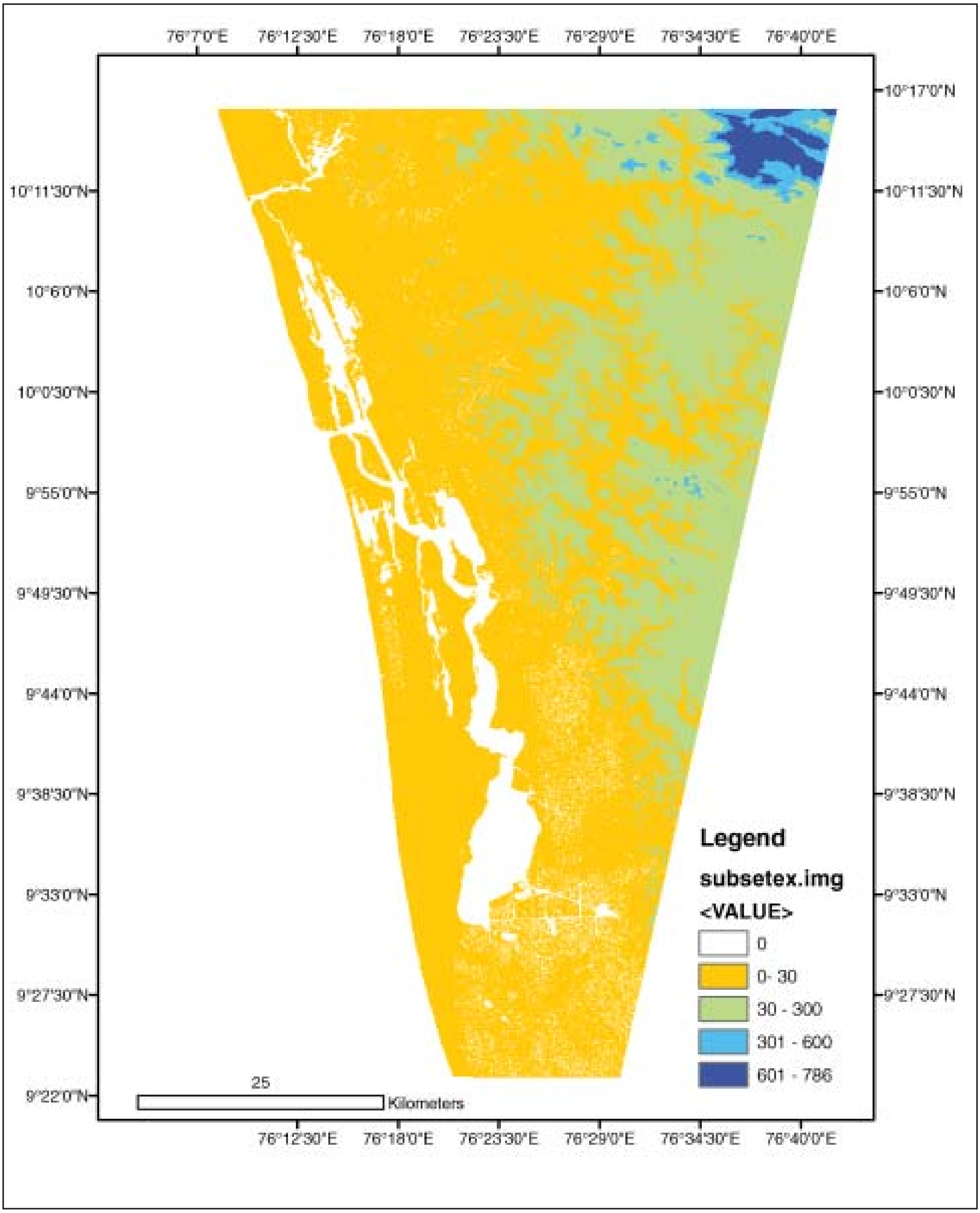


Fig. 4.10: Digital elevation map of Kochi region

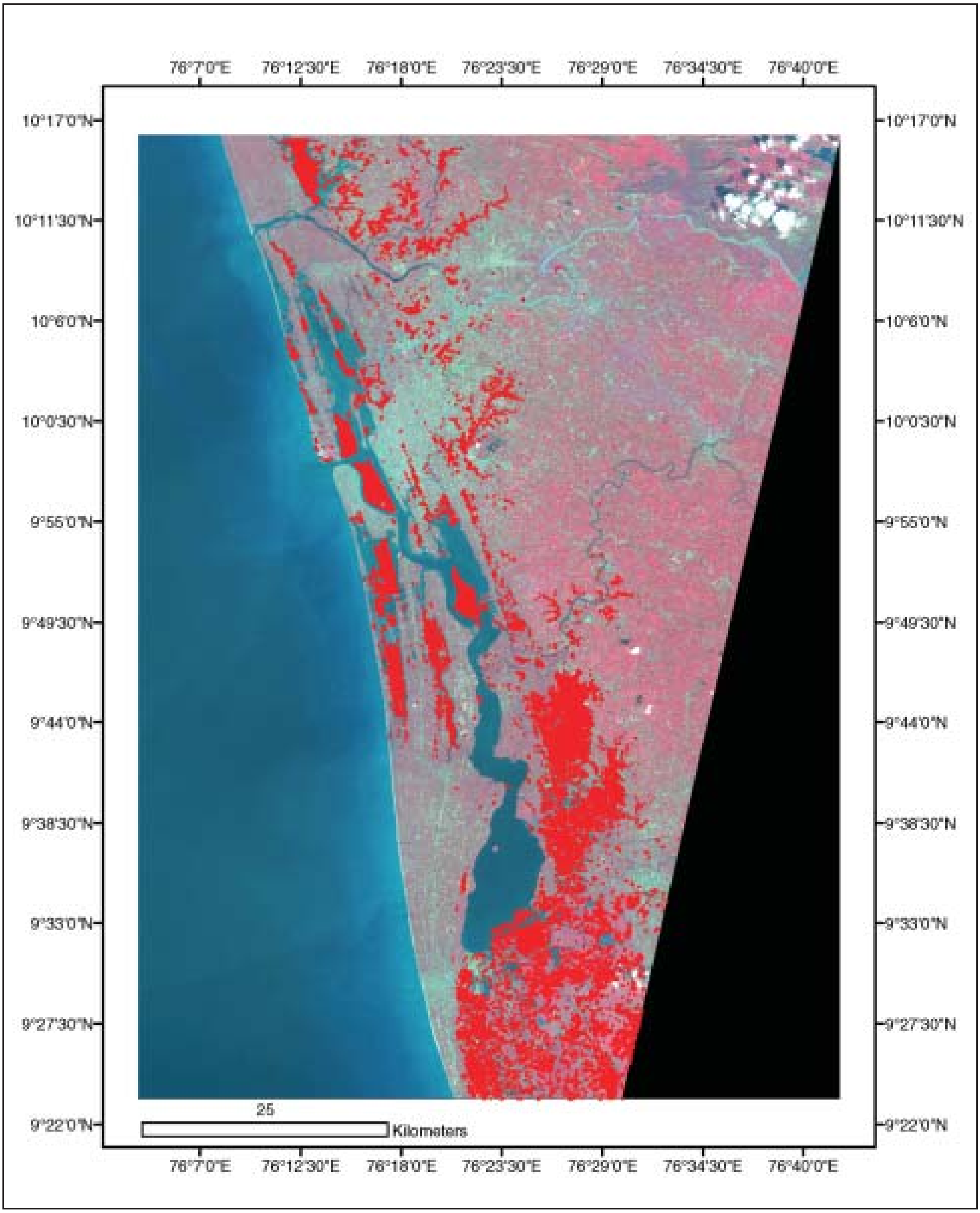


Fig. 4.11: Coastal inundation (red in colour) map of Kochi region for a 1.0 m sea-level rise

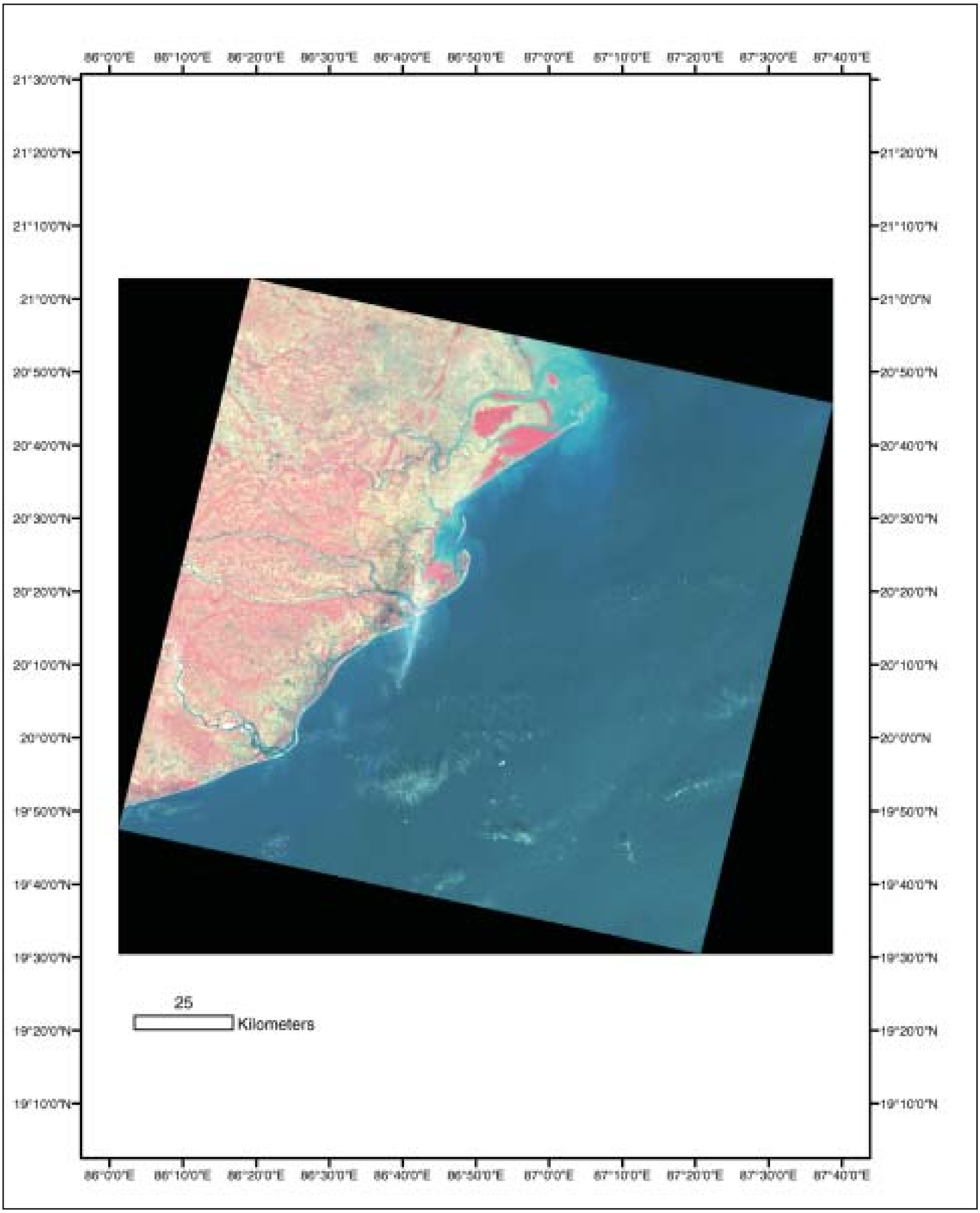


Fig. 4.12: IRS satellite image of Paradip region

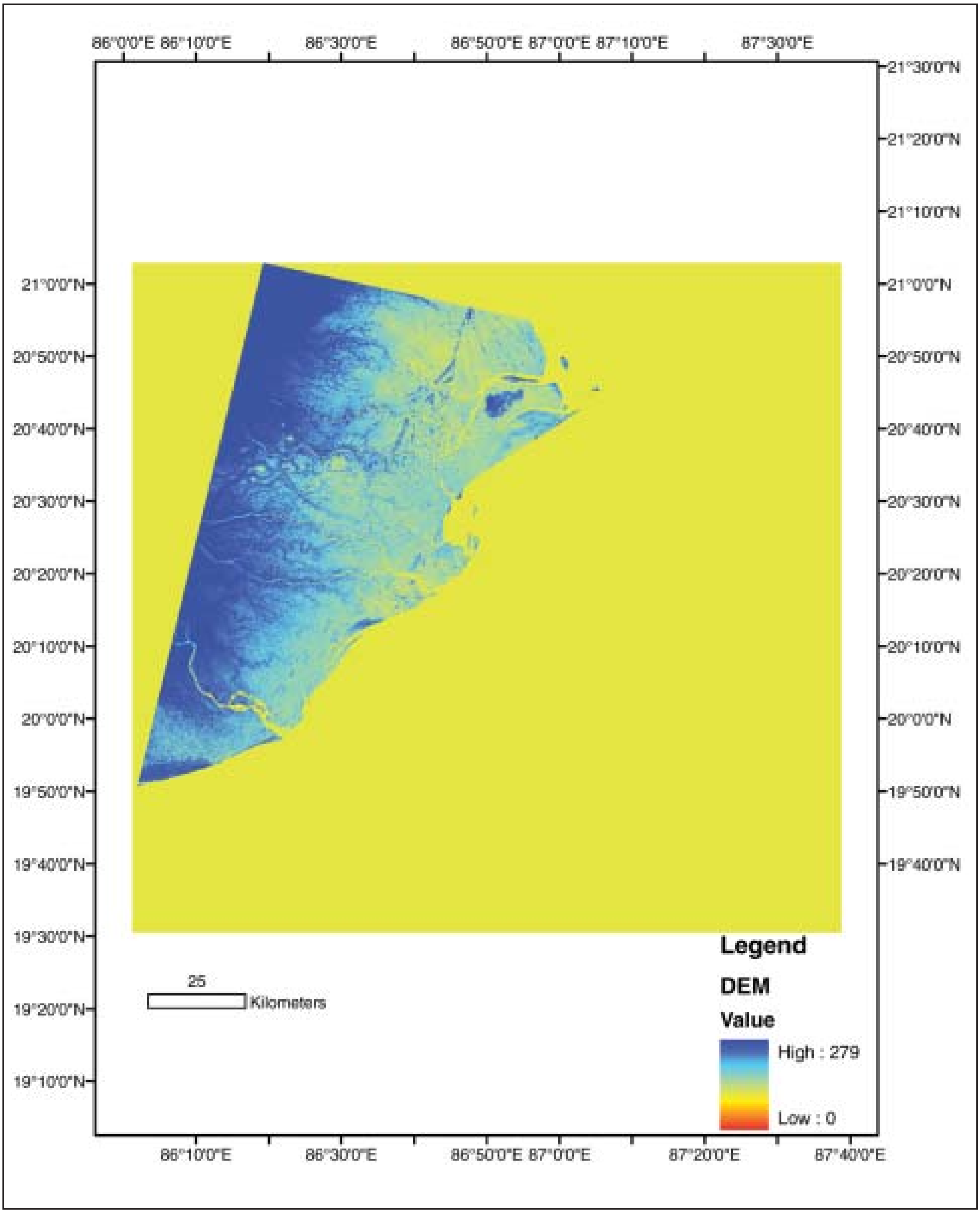


Fig. 4.13: Digital elevation map of the Paradip region

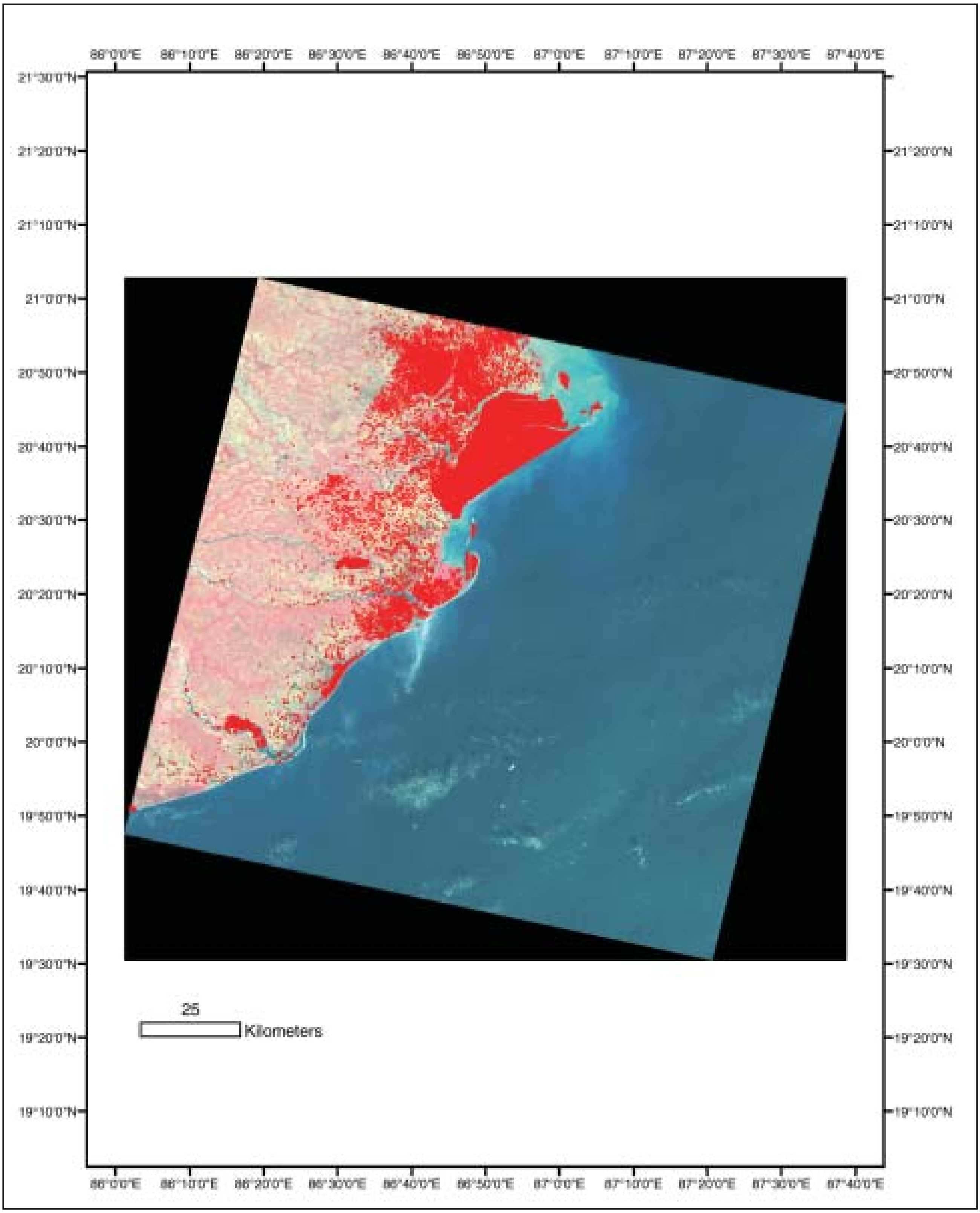


Fig. 4.14: Coastal inundation (shown in red) map of Paradip region for a 1.0 m sea-level rise

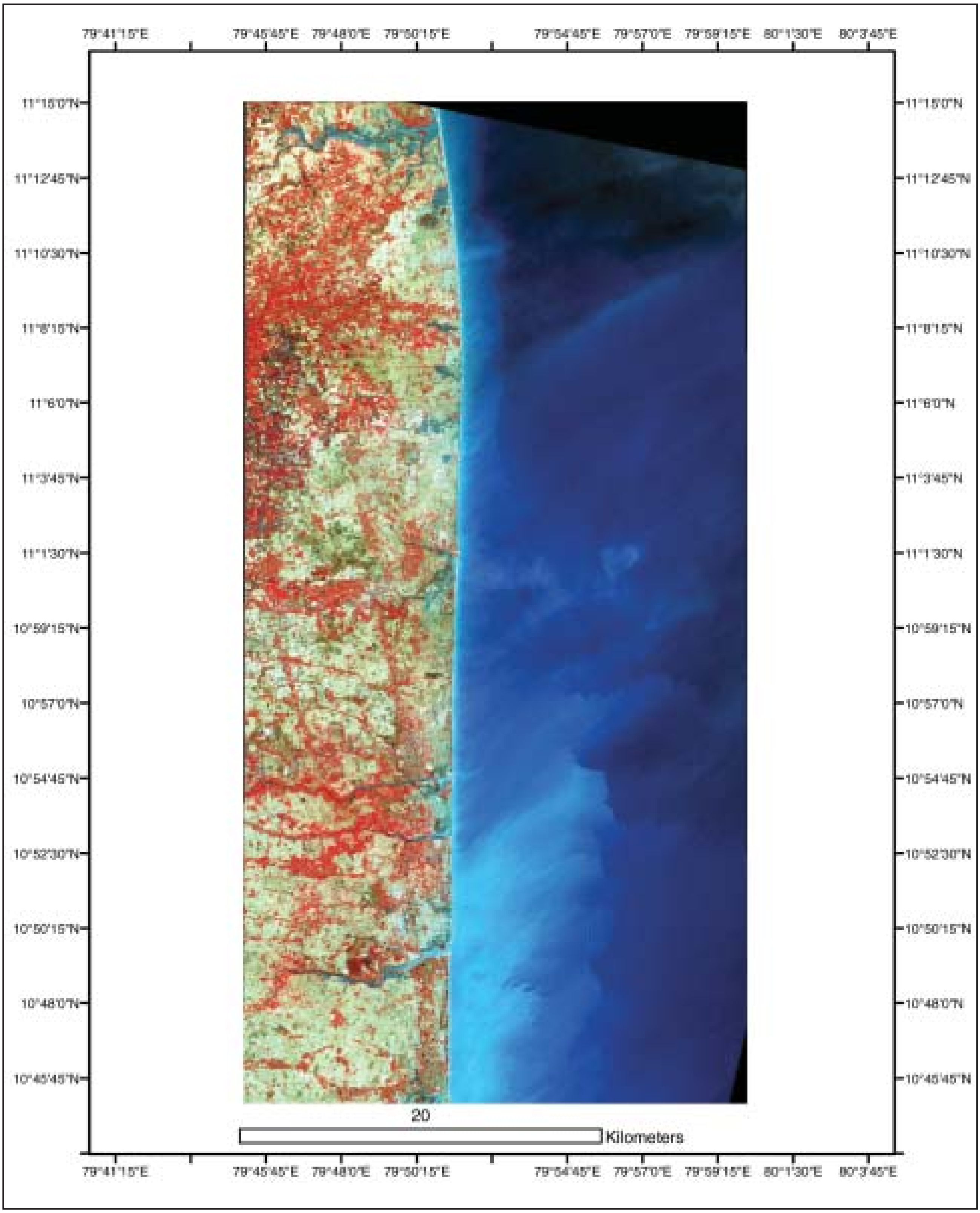


Fig. 4.15: IRS satellite map of the Nagapattinam region

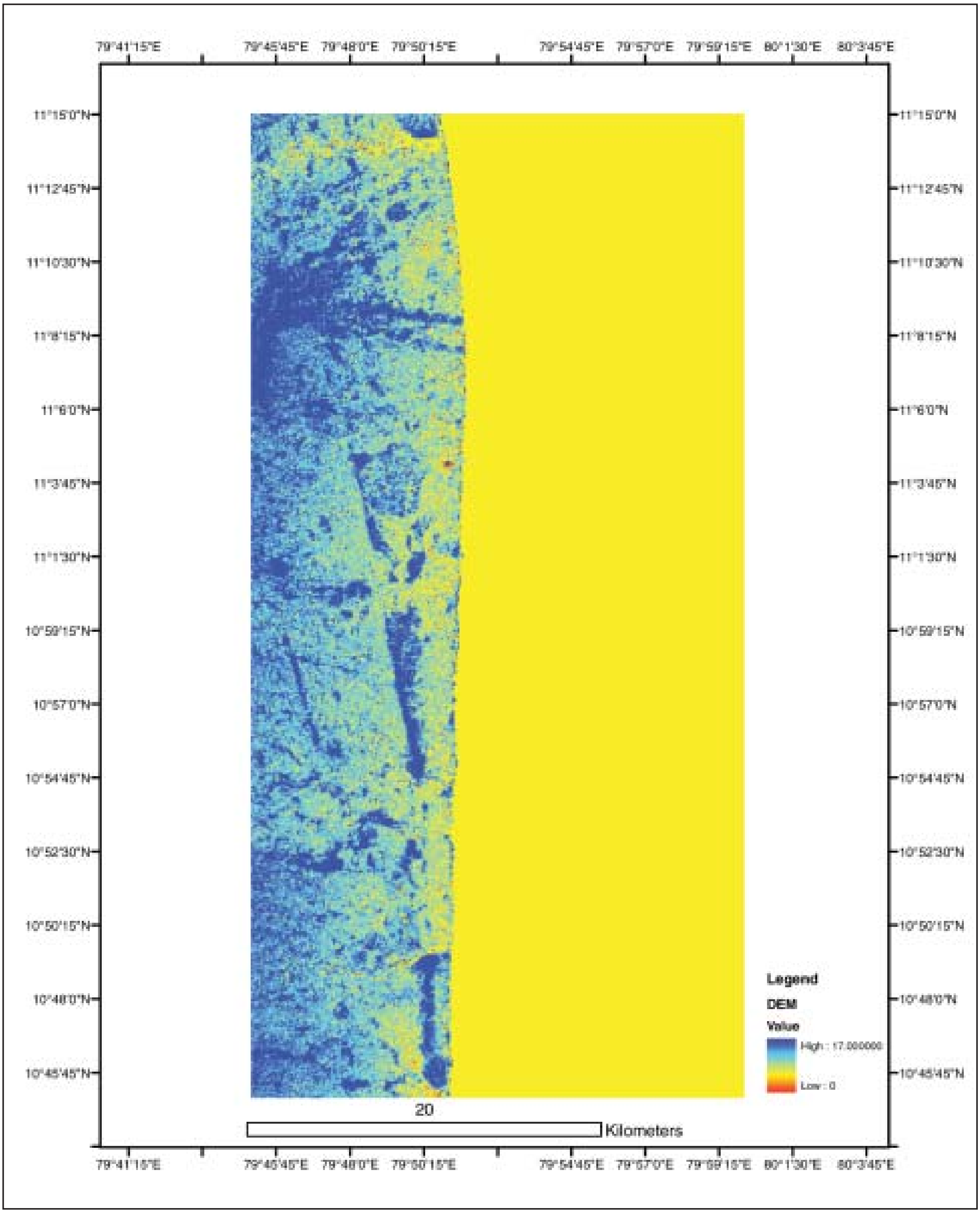


Fig. 4.16: Digital Elevation map of Nagapattinam region

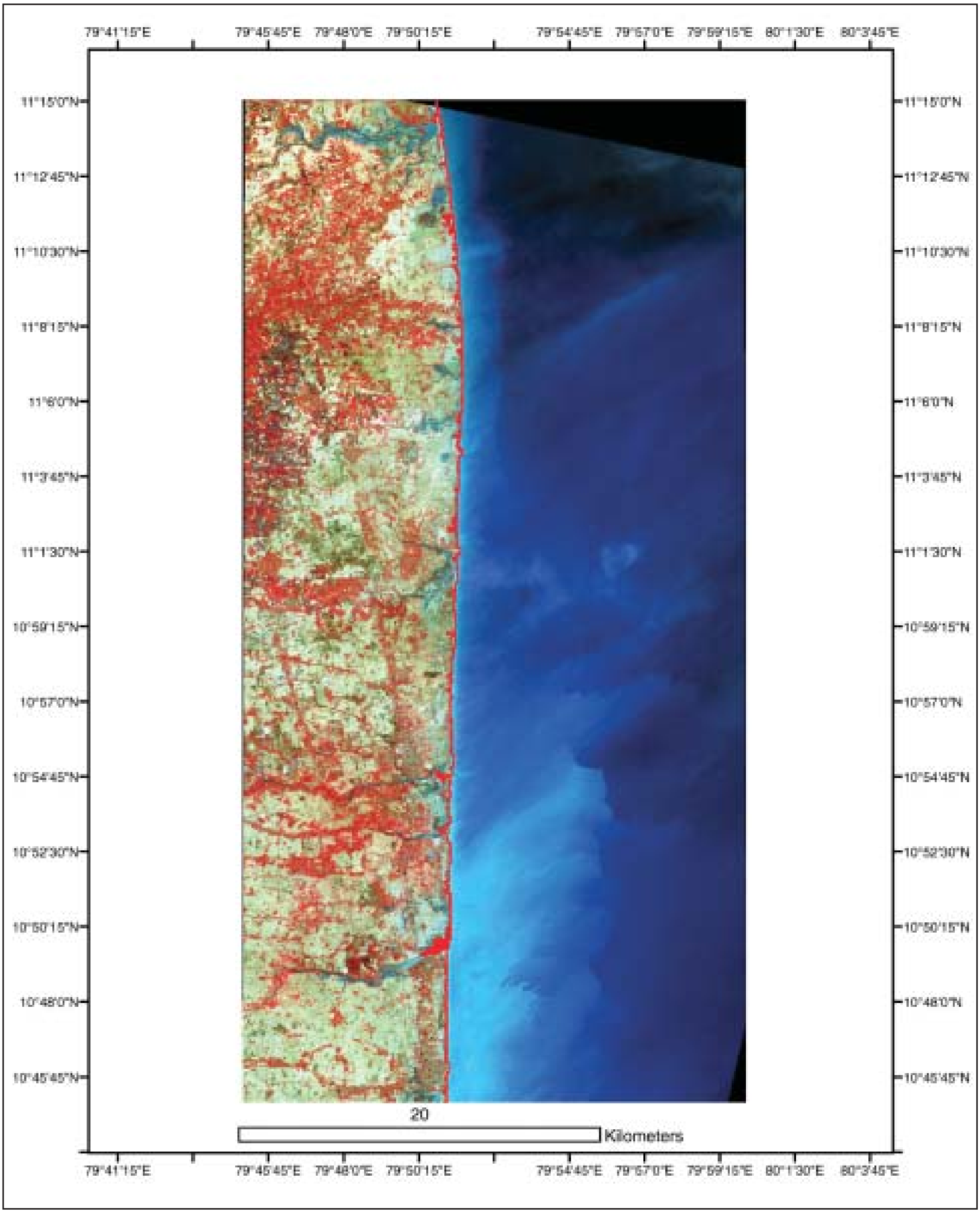


Fig. 4.17: Coastal inundation (red in colour) map of Nagapattinam region for a 1.0 m sea-level rise

5

Agriculture

5.1 Introduction

Agriculture contributes nearly 17.1 percent of Gross Domestic Product (GDP) of India. During 2008-09, the production of food grains was estimated to be around 233.88 million tonnes, including 99.15 and 80.58 million tonnes of rice and wheat, respectively. It is estimated that by 2020, food grains requirement will be almost 30-50% more than the demand during 2000 AD (Paroda and Kumar, 2000). Indian agriculture is facing challenges from several factors such as increased competition for land, water and labour from non-agricultural sectors and increasing climatic variability. The latter, associated with global warming, will result in considerable seasonal / annual fluctuations in food production. All agricultural commodities even today are sensitive to such variability. Droughts, floods, tropical cyclones, heavy precipitation events, hot extremes and heat waves are known to negatively impact agricultural production and farmers' livelihood. It has been projected by the recent report of the IPCC and a few other global studies that unless we adapt, there is a probability of 10-40% loss in crop production in India by 2080-2100 due to global warming (Rosenzweig *et al*., 1994; Fischer *et al*. 2002; Parry *et al*. 2004; IPCC 2007b) despite beneficial aspects of increased CO_2. A recent meta-analysis of CO_2 enrichment experiments in fields has shown that in field environment, 550 ppm CO_2 leads to a benefit of 8-10% in yield in wheat and rice, up to 15% in soybean, and almost negligible in maize and sorghum (Long *et al*., 2005).

There are a few Indian studies on this theme and they generally confirm a similar trend of agricultural decline with climate change (Aggarwal and Sinha 1993, Rao and Sinha 1994, Lal *et al*. 1998, Saseendran *et al*. 2000, Mall and Aggarwal 2002, Aggarwal 2003). Projections indicate the possibility of loss of 4-5 million tonnes in wheat production with every rise of 1°C temperature throughout the growing period with current land use (Aggarwal, 2008). In March 2004, temperatures were higher in the Indo-Gangetic plains by 3-6°C, which is equivalent to almost 1°C per day over the whole crop season. As a result, wheat crop matured earlier by 10-20 days and wheat production dropped by more than 4 million tonnes in the country (Samra and Singh 2004). Losses were also very significant in other crops, such as mustard, peas, tomatoes, onion, garlic, and other vegetable and fruit crops (Samra and Singh 2004). Similarly, drought of 2002 led to reduced area coverage of more than 15 million hectares of the rainy-season crops and resulted in a loss of more than 10% in food production (Samra and Singh 2002). The projected increase in these events could result in greater instability in food production and threaten livelihood security of farmers. Recent simulation analysis indicated that maize yields in monsoon are projected to be adversely affected due to rise in atmospheric temperature; but increased rainfall can partly offset those loses and the spatio-temporal variations in projected changes in temperature and rainfall are likely to lead to differential impacts in the different regions (Byjesh *et al*., 2010). Analysis on sorghum also indicated that the yield loss due to rise in temperature is likely to be offset by projected increase in rainfall. However, complete amelioration of yield loss beyond 2°C rise may not be attained even after doubling of rainfall (Srivastava *et al*., 2010).

While the above review indicates gross effects of climate change on crops in India, there are several special ecosystems that are ecologically and economically very important but agricultural impacts in these regions have not received adequate attention. These regions include Western Ghats, Coastal areas, North-Eastern region and Himalayan ranges. Agriculture in these areas is multi-dimensional ranging from rice-based agriculture, horticultural crops, plantations, fisheries and dairy. The projected changes in climate such as increase in temperature, change in frost events and glacier melt are likely to influence the hill agriculture. Sea-level rise is another climate change related threat, which has potential influence on the coastal agriculture. Keeping these potential threats in mind, efforts are initiated under INCCA to have an assessment on impacts of climate change on ecologically sensitive areas in India. The information provided here is largely based on simulation modelling of impacts but also supported by literature survey.

5.2 Methodology for estimating climate change impacts

The impact of climate change was assessed for four cereals (wheat, rice, maize and sorghum), two oil seeds (soybean and mustard), potato and coconut plantations. This was assessed using a simulation model called InfoCrop. The analyses were done for every 1° x1° grid in the entire zone of the ecosystems. The following inputs were used in the model:

1. Weather data: from India Meteorological Department at 1°x1° scale for baseline period (1969-1990).
2. Soil data rescaled to grid values from National Bureau of Soil Sciences for Land Use change and Planning and ISRIC soil data base.
3. Crop Management: normal crop practices as followed by the farmers.
4. Genetic coefficients of varieties best suitable for different regions.
5. Climate change scenarios of PRECIS A1B for 2030 periods.

InfoCrop is a generic crop growth model that can simulate the effects of weather, soil, agronomic managements (including planting, nitrogen, residue and irrigation) and major pests on crop growth and yield (Aggarwal *et al*., 2006). The model considers different crop development and growth processes influencing the simulation of yield. The total crop growth period in the model is divided into three phases, *viz*. sowing to seedling emergence, seedling emergence to anthesis and storage organ filling phases. The model requires various varietal coefficients *viz.* thermal time for phenological stages, potential grain weight, specific leaf area, maximum relative growth rate, maximum radiation use efficiency. It requires crop management inputs – time of planting, application schedule and amount of fertilizer and irrigation. Soil input data includes soil pH, soil texture, thickness, bulk density, saturated hydraulic conductivity, soil organic carbon, slope, soil water holding capacity and permanent wilting point. Location-wise daily weather data such as the solar radiation, maximum and minimum temperatures, rainfall, wind speed, vapour pressure are also required to simulate crop performance.

The InfoCrop model is well calibrated and validated for wheat (Aggarwal *et al*., 2004) and rice (Aggarwal *et al*., 2004), maize (Byjesh *et al*., 2010), sorghum (Srivastava, 2010), coconut (Naresh Kumar *et al*., 2008); potato (Singh *et al*., 2008), and mustard (Bhoomiraj *et al*., 2010) crops for the Indian region. These calibrated and validated models were used for simulating the yields during baseline period (1969-1990) and also for assessment of impacts.

In InfoCrop, change in temperature, CO_2 and rainfall are simulated in the following ways:-

1. The total development of a crop is calculated by integrating the temperature-driven development rates of the phases from sowing to seedling emergence, seedling emergence to anthesis and storage organ filling phases.
2. Dry matter production is a function of Radiation Use Efficiency (RUE), photosynthetically active radiation, total Leaf Area Index (LAI), and a crop/cultivar specific light interception coefficient. RUE is further governed by a crop-specific response of photosynthesis to temperature, water, nitrogen availability and other biotic factors. Carbon dioxide concentration has no direct influence on photosynthesis as maize is a C4 crop. But under water-stressed conditions, increase in CO_2 does indirectly increase photosynthesis and yield by reducing water use and delaying drought stress via reduction in stomatal conductance and transpiration rate (Ghannoum *et al*., 2000).
3. The net dry matter available each day for crop growth is partitioned as a crop-specific function of development stage, which as mentioned earlier, is affected by temperature.
4. In the initial stages of crop growth, leaf area formation is controlled by temperature. Senescence of leaves is also dependent on temperature.
5. Temperature influences potential evapotranspiration. Water stress is determined as the ratio of actual water uptake and potential transpiration. It accelerates phenological development, decreases gross photosynthesis, alters the allocation pattern of assimilates to different organs and accelerates rate of senescence.
6. Adverse temperatures during meiosis stage could significantly increase sterility. In crops, a part of the storage organ becomes sterile if either maximum or minimum temperatures of the day deviate from their respective threshold values during a short period between anthesis and a few days afterwards. This reduces the number of storage organs available subsequently for accumulating weight. The storage organs start filling up shortly after anthesis with a rate depending upon temperature, potential filling

rate and the level of dry matter available for their growth.

7. Influence of rainfall is operated in the model through soil water balance.

The data for the estimations are processed as follows:

1. ***Weather***: The IMD daily gridded data 1°x1° on rainfall, minimum and maximum temperatures were processed using the MS-Excel macro and was arranged grid-wise. These data were converted to InfoCrop weather file format using a custom-made software. Thus, files for 22 years each (1969-1990) for all corresponding grids were made. In simulations, solar radiation was calculated by the model based on Hargreaves method, which is reported to be best suited for Indian conditions (Bandopadhyay *et al*., 2008). The potential evapotranspiration was calculated by the model as per Priestly and Taylor method.

2. ***Soil data***: The data on soil parameters such as texture, water-holding characteristics, bulk density, soil pH, and depths of three soil layers were obtained from NBSSLUP, Nagpur and also from the database of ISRIC. The data was input grid-wise into the model.

3. ***Varietal coefficients***: The simulations were carried out assuming that the farmers have successfully optimised their resources in terms of variety and sowing time. Respective coefficients for all crops were taken for the dominant Indian varieties from the previous published studies. These were calibrated for each grid by simulating the performance of short, medium and long duration varieties grown timely, late and very late sown periods, respectively. The best combination was taken for the baseline and impact assessment.

4. ***Management***: In order to mimic the situation in farmers' field conditions, crop was provided with respective recommended doses of fertilizers for irrigated and rain-fed crops. Irrigation was provided at the desired stages in irrigated crops. It was assumed that there are no pests and disease infestation in the field.

5. ***Estimating baseline production***: Simulation was done with InfoCrop for each crop using the respective crop coefficients and management for each of the 22 years. The mean of 22 years yield was taken as the baseline yield. District yields were interpolated from the grid yields using GIS. This was multiplied by the area under each district to get the production figures. The production figures were calibrated to mean production values of 2000-2005 period for each district.

6. ***Crop simulation***: Impact of climate change on grain yield of crops was studied using A1B 2030 scenarios derived from the PRECIS RCM. The PRECIS is a Regional Climate Model with HadCM3 as its GCM. The climate model's outputs on temperature (minimum and maximum) and rainfall for A1B-2030 scenarios were coupled to the baseline weather data. The projected carbon dioxide levels as per Bern CC model for respective scenarios were also included in the model for simulations. All other simulation conditions were maintained as explained earlier. Based on the simulated yields in changed scenarios, production was calculated as in case of baseline production assuming that the area under wheat in each district would remain same in future as well. To express the impacts on production, the net change in production in climate change scenarios was calculated and expressed as the percentage change from baseline mean production.

5.3 The Western Ghats

5.3.1 Farming practices in Western ghats

The Western Ghats, one of the 24 global hot spots of biodiversity, comprise 63 districts in Kerala, Tamil Nadu, Karnataka, Maharashtra and Gujarat in peninsular India. Agriculture in this relatively high elevation area (average elevation is 1200 m) is characterized, in general, by four typologies:

1) Large tea, coffee and rubber estates.
2) Other plantations and spices, which are generally grown as inter crops.
3) Annual crops-based farming consisting of mainly paddy, vegetables, pulses, tuber crops and millets
4) Homestead farming. The homestead farming is one of the key features of this area, wherein a large number of species of trees (jackfruit, mango, papaya, guava, *kokum* etc), spices (pepper, nutmeg etc), medicinal plants, plantation crops (coconut, areca nut etc.), biennials and annuals including banana, pineapple, paddy, vegetables and tuber crops are included. Homestead gardens

Table 5.1: Major Crops in the Western Ghats Area			
CROP	**Area ('000 ha)**	**Production ('000 t)**	**Productivity (Kg/ha)**
Rice	2685	6530	2387
Jowar	2944	1751	863
Bajra	1066	675	871
Ragi	860	1215	1236
Maize	784	1778	2046
Groundnut	910	1008	1207
Coconut	1409	8369	5353 (nuts)
Sugarcane	843	72452	89562
Cotton (lint)	489	600	1420
Apart from these crops, many high value commercial and spice crops such as tea, coffee, cashew, rubber, areca nut, cocoa, pepper, cardamom, etc. are the major contributors to the agricultural sector in this region.			

are characterized by a mixture of above types of species grown in three to five layer vertical structure of trees, shrubs and ground cover plants apart from dairy and poultry. This system is efficient in nutrient recycling and soil and water conservation.

In this assessment, we have simulated the impacts on coconut plantations and for annual crops only. These farms are largely rain fed, as this area receives over 3000mm of rainfall. Many farmers nevertheless irrigate their crops as and when needed. Irrigation is provided by tapping the streams flowing through the farm or those flowing nearby. Water harvesting is done by constructing bamboo or wooden barriers across the small stream, or by digging tunnels across the slope (*surangams*) as found in northern Malabar of Kerala and in south Kannada district of Karnataka. Apart from these, pits are dug across the slope for storing the rainwater. Farmers do have open wells and tube wells for irrigation and drinking water purposes. Generally, farmers do not apply too many inorganic fertilizers and follow some of the soil and water conservation measures. However, these measures are inadequate to stop soil erosion in the region.

As far as the crop inputs are concerned, the majority of farmers cultivate local varieties of paddy, other annual crops and vegetables and also follow traditional agricultural practices, which are the major reason for low productivity. These approaches helped in maintaining the dwindling resources of the region.

5.3.2 Observed changes

Even though there are not many recorded observations on the impact of climatic extremes in the past on crops grown in the area, some of the striking effects have been the adverse impact of the drought of 1983 on many plantation crops. Some of the recorded impacts of climate-related events on agriculture are provided below.

The analysis of past weather data from different locations representing the major coconut growing Western Ghat areas and yield data from the respective districts, indicated warming trends in most of the areas (Naresh Kumar *et al*., 2009). The increase in average maximum temperature varied from 0.01 to 0.04^{o}C / year (Table 5.2). On the other hand, average minimum temperatures are decreasing in many places. The range in change varied from –0.03 to +0.03/ year. Dry spells are in increasing trends in these districts of Karnataka and Kerala, whereas reducing trends in coastal Maharastra. Change in dry spells varied from –1.98 to 0.27 days/year. Change in coconut yields across the country ranged from –114 to 270 nuts/ha/ year.

5.3.3 Projected impacts on agriculture productivity in the 2030s

Simulation analysis on possible impacts of climate change on some of the prominent crops in coastal districts was carried out for A1B 2030 scenario. At the outset, it is to be noted that the climatic variability changes in future are not considered in this analysis. The climatic variability of baseline period is assumed to exist even in future climate scenario.

Table 5.2: Past trends in weather and productivity of coconut in Western Ghat areas in India												
Centre	**Temperature**		**Change in T**	**Days >33 °C**	**Days with < 15°C**	**RH**	**Rainfall**			**Overall change**	**Dry spell**	**Coconut Productivity**
	Max.	Min.					Annual	intensity	Days<2.5 mm			
Ratnagiri (MS)	↑	↓	↑	↑	Nil	↓ (RH Max)	↑	↓	↑	Cool Night Warm DayDry	↓	↑
Mulde (MS)	↑	↑	↑	↑	↓	↑	↓	↓	↓	Warming	↓	↑
Kidu (Karnataka)	↑	↑	↓	↑	↓	NA	↓	↑	↑	Warming	↑	↓
Kasaragod (Kerala)	↑	↓	↑	↑	↑	↑	↓	↓	↑	Cool Night Warm Day	↑	↑
Trissur (Kerala)	↓	↔	↓	↓	Nil	↔	↓	↑	↓	RF Distribution changing	↓	↑
Trivendrum (Kerala)	↑	↑	↑	↑	Nil	NA		↓	↓	Warming	↑	↑
↑Indicates increase; ↓indicates decrease; ↔ indicates no significant change												

Coconut: Coconut yields are projected to increase by up to 30% in majority of the region due to climate change in this region (Fig 5.1a). Increase in coconut yield may be mainly attributed to projected increase in rainfall (~10%) and relatively less increase in temperatures, apart from CO_2 fertilization benefits. However, some areas like south-west Karnataka, parts of Tamil Nadu and parts of Maharashtra, may lose yield up to 24%.

Rice: The simulation analysis indicates that the productivity of irrigated rice in Western Ghats region is likely to change +5 to –11% in PRECIS A1B 2030 scenario depending upon the location. Majority of the region is projected to lose the yield by about 4% [Figure 5.1(b)]. However, irrigated rice in parts of southern Karnataka and northern-most districts of Kerala is likely to gain. In these areas, current seasonal minimum and maximum temperatures are relatively lower (20-22°C T_{min}; 27-28°C T_{max}). The projected increase in temperature is also relatively less in these areas (0.5°C-1.5°C).

In the case of rain-fed rice, the projected change in yield is in the range of –35 to +35% with a large portion of the region likely to lose rice yields up to 10%. The results thus indicate that, irrigated rice is able to benefit due to CO_2 fertilization effect as compared to rain-fed rice, which is supplied with less amount of fertilizers. Farmers in Western Ghat regions falling in north-west parts of Tamil Nadu, northern parts of Kerala and in some parts of Karnataka can reduce the impacts of climate change and can reap higher harvests by adopting crop management strategies and by growing varieties tolerant to climate change.

Maize and sorghum: Climate change is likely to reduce yields of maize and sorghum by up to 50% depending upon the region [Figure 5.1(c)]. These crops have C4 photosynthetic systems and hence do not have relative advantages at higher CO_2 concentrations.

5.4 Coastal region

5.4.1 Agriculture productivity in the coastal region

India has a long coast of about 9,000 km. Climate change is projected to cause sea-level rise, with significant consequences to the coastal agro-ecology and livelihoods of farmers and fishermen. Agriculture in coastal districts has rich agro-biodiversity as many of the coastal districts are fed by river streams, river deltas and backwater streams. These areas are not only suitable for crop production but also for fisheries and aquaculture. Rice is the major staple crop in the coastal region. Among the other crops, groundnut, and among plantations, coconut and cashew are some of the crops that are predominant in coastal agriculture. The major crops grown in the coastal region are shown in Table 5.3:a.

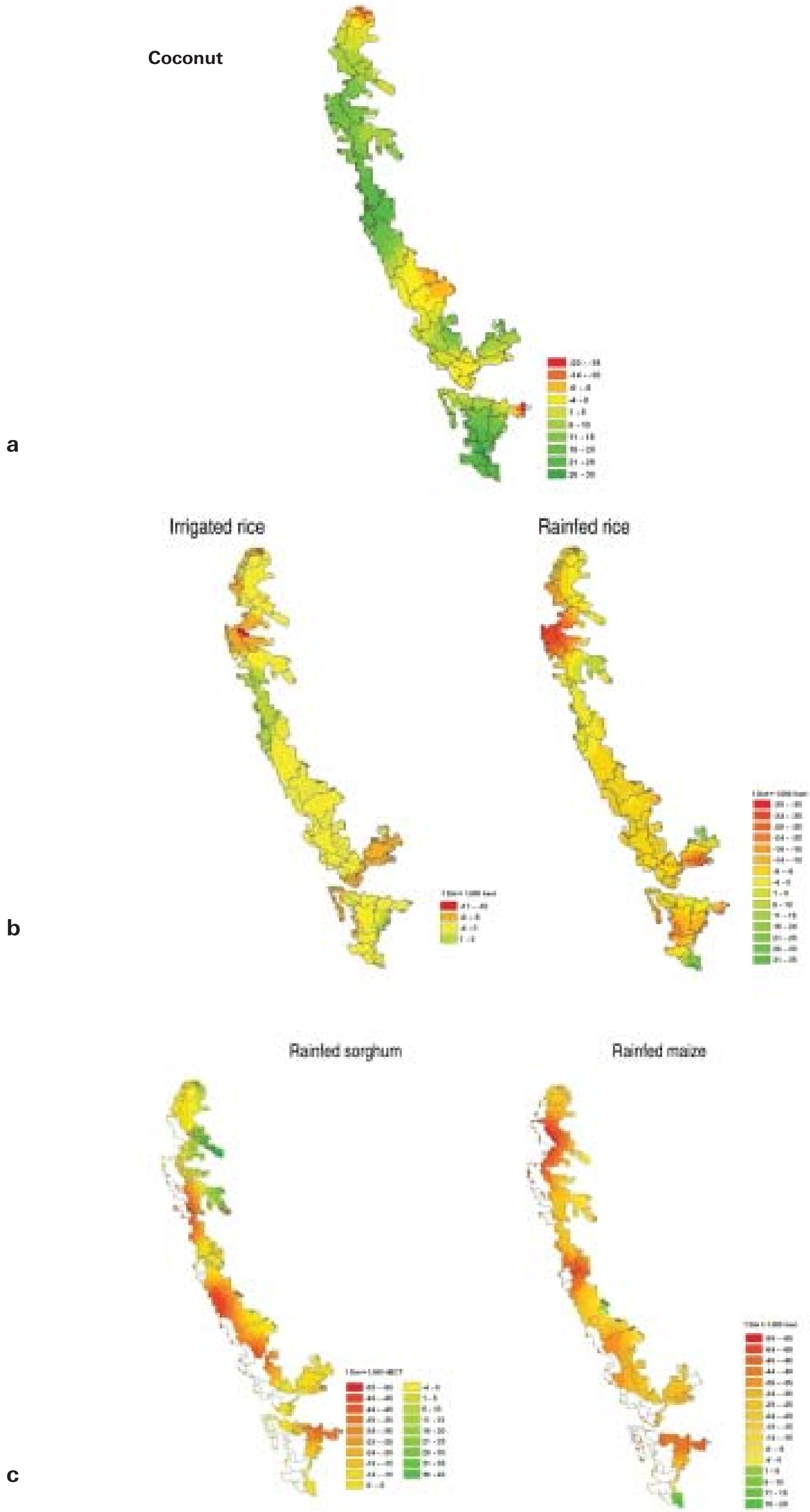


Figure 5.1: Projected impacts of climate change in the 2030's on a) Coconut (b) Rice and (c) Sorghum and Maize.

Table 5.3a : Major Cereal crops and Millets grown in the coastal districts of India			
Crop	Area ('000 ha)	Production ('000 t)	Productivity (Kg/ha)
Rice	6248	15520	2300
Groundnut	1777	2153	1559
Urad	692	376	477
Red gram	579	248	433
Cotton (lint)	796	1528	2104
Coconut	1003	7077	8243
Cashew	796	1528	2104

Table 5.3 b: Marine catch in coastal India	
Sector	Production
Marine fish	29.2 lakh tonnes
Shrimps	144.4 thousand tonnes
Scampi	42.8 thousand tonnes

Apart from the crops, production from marine fisheries and fresh water fish and aqua culture provide the bulk of agricultural output from coastal districts. In these analyses for crop production, 69 districts having the seacoast as part of their boundary are considered as coastal districts. Farming, crop production and fisheries in this area form components of agriculture. (see Table 5.3b).

5.4.2 Projected impacts of climate change on crops in 2030s

Rice: Climate change is projected to affect the yields of irrigated rice by about 10% in majority of coastal districts. However, in some coastal districts of Maharashtra, northern Andhra Pradesh and Orissa, irrigated rice yields are projected to marginally increase (<5%). On the other hand, rain-fed rice yields are projected to increase up to 15% in many of districts in the east coast, but reduce by up to 20% in the west coast. (Figure 5.2a).

Maize: Impacts of climate change on irrigated maize in coastal districts are projected to be much higher with projected yield loss between 15 to 50%, whereas in case of rain-fed maize, the projected yield loss is up to 35%. In some districts of coastal Andhra Pradesh, rain-fed maize yields are likely to increase by 10%. Projected increase in seasonal maximum temperature in these areas is less than 1°C in 2030's scenario. (Figure 5.2b).

Coconut: Yields of coconut are projected to increase in the west coast of India up to 30% (provided current level of water is made available in future scenario as well), while in the east coast, the north coastal districts of Andhra Pradesh, yields may increase by about 10%. In all other coastal districts in the eastern coast and those in Gujarat coast are projected to lose coconut yields up to 40%. It may be noted that in India, coconut production mainly comes from Kerala (~45%), Tamil Nadu (~22%), Karnataka (~ 12%) and Andhra Pradesh (~10%). Projected decrease in yields in east coast of Andhra Pradesh, Orissa, Gujarat and parts of Tamil Nadu and Karnataka may be due to existing high summer temperatures which are projected to increase relatively more than in the west coast region. The current temperatures are lower in the west coast than in the east coast of India. Thus crop growth is favoured in the west coast even up to about 3°C increase over current temperatures. On the other hand, due to the existing high temperatures, the crop growth in the eastern coast is affected even with an increase of 1°C. (Figure 5.2c).

5.4.3 Impact of climate change on coastal fisheries

Fisheries play an important role in food supply, food security and livelihood security of millions of fishermen and associated fish supply chains living in coastal areas. Over the last few years, fish production in India has increased at a higher rate compared to food grains, milk and other food items. The Fisheries

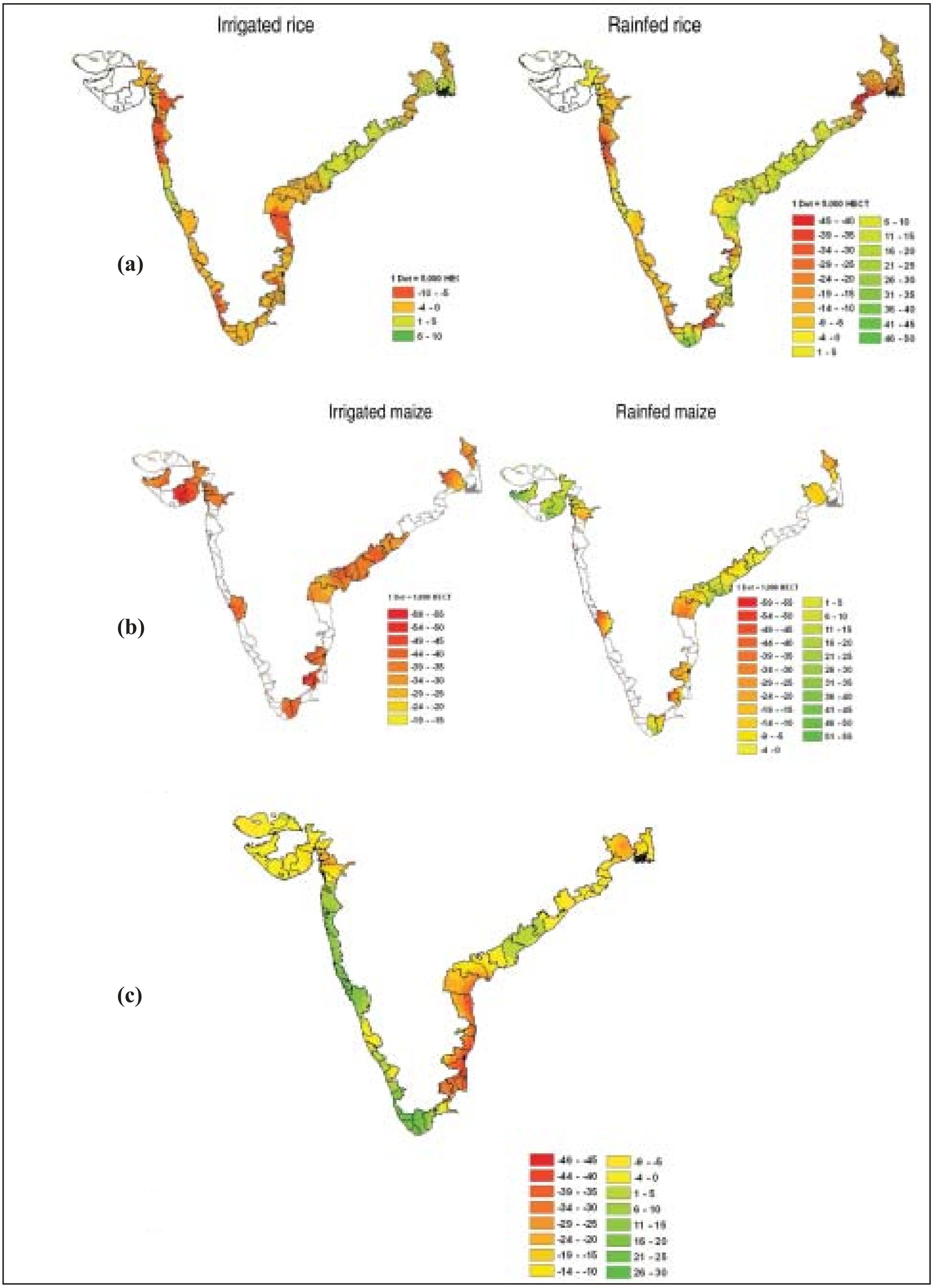


Figure 5.2: Impacts of climate change in the Coastal region in 2030s on (a) Rice, (b) Maize and (c) Coconut

sector contributes more than 5% to the agricultural GDP. Off late there has been a gradual shift in the production scenario from marine to inland fisheries.

Temperature is known to affect fish distribution and migration. Unlike with crops, there are no significant studies where the impacts of 2030 scenarios have been studied in fisheries. This is largely due to the absence of simulation models in the fish sector unlike crops where reasonably well-developed, calibrated and validated crop models are available. Much of the information on impacts of climate change on the fish sector therefore comes from the analysis of past data and its interpretation in relation to changes in weather and sea-surface temperatures in those periods. These studies can be used to infer the direction of change in the 2030's.

Many tropical fish stocks are already exposed to high extremes of temperature tolerance and hence, some may face regional extinction, while others may move towards higher latitudes (Perry *et al*., 2005). At shorter time-scales of a few years, increasing temperatures may have negative impacts on the physiology of fish because oxygen transport to tissues will be limited at higher temperatures. This constraint in physiology will result in changes in distributions, recruitment and abundance.

Changes in the timing of life history events (phenological changes) are expected with climate change. Species with short life spans and rapid turnover of generations such as plankton and small pelagic fish are most likely to experience such changes. At intermediate time scales of a few years to a decade, the changes in distributions, recruitment and abundance of many species will be acute at the extremes of species' ranges. Changes in abundance will alter the species' composition and result in changes in the structure and functions of the ecosystems. At long time scales of multi-decades, changes in the net primary production and its transfer to higher trophic levels are possible. Most models show decreasing primary production with changes of phytoplankton composition with high regional variability.

The tropical fisheries are characterised by several fast growing (von Bertalanffy's annual growth coefficient: 0.5 to 1.0) and multiple spawning species. Low levels of spawning take place throughout the year for most of the species with one or two distinct spawning peaks in a year (Vivekanandan *et al*., 2010). The eggs of most of the species are pelagic, directly exposed to higher temperatures and currents. As temperatures increase, the development duration of eggs decreases, as does the size of emerging larvae (Vidal *et al*., 2002). In the warmer years, the adults may grow faster, but there will be a point where growth rates would start to decrease as metabolic costs continue to increase. In some marine organisms, it has been found that the average life span will decrease as a function of increased growth rate, and the individuals will mature younger at a smaller size (Jackson and Moltschaniwskyj, 2001). This will, in turn, reduce the absolute fecundity, as smaller individuals produce lesser number of eggs. The scale of these organism-level changes on recruitment, biomass and fishery may depend on changes in the climatic parameters.

Generally, the more mobile species should be able to adjust their ranges over time, but less mobile and sedentary species may not. Depending on the species, the area it occupies may expand, shrink or be relocated. This will induce increases, decreases and shifts in the distribution of marine fish, with some areas benefiting while others lose.

The following responses to climate change by marine fish are discernible in the Indian seas:

(i) Extension of distributional boundary of small pelagics;
(ii) Extension of depth of occurrence; and
(iii) Phenological changes.

Some evidence for the responses in terms of extension and distributional boundary of small pelagics is discussed below:

Oil sardine: The oil sardine *Sardinella longiceps* and the Indian mackerel *Rastrelliger kanagurta* are tropical coastal and small pelagic fish, forming massive fisheries (21% of marine fish catch of India). They are governed by the vagaries of ocean climatic conditions, and have high population doubling time of 15 to 24 months. They are a cheap source of protein, and form a staple sustenance and nutritional food for millions of coastal people. These small pelagics, especially the oil sardine, were known for their restricted distribution between latitude 8°N and 14°N and longitude 75°E and 77°E (Malabar upwelling zone along the southwest coast of India) where the annual average sea surface temperature ranges from 27 to 29°C. Until 1985, almost the entire catch of oil sardine was from the Malabar upwelling zone. The catch from latitudes north of 14°N along the west coast was either very low or none at all (Figure 5.3). In the last two decades, however, the catches from latitude 14°N - 20°N are consistently increasing, contributing about 15% to the all-India oil sardine catch in the year 2006 (Vivekanandan *et al*., 2009). The surface waters of the Indian seas are warming by 0.04°C per decade, and the warmer tongue (27-28.5°C) of the surface waters is expanding to latitudes north of 14°N, enabling the oil sardine to extend their distributional range to northern latitudes. Another notable feature is the extension of oil sardine distribution to the east coast of India as well. Until the mid-1980s, the oil sardine did not form fisheries along the southeast coast. In the 1990s, oil sardine emerged as a major fishery along the southeast coast, with the annual catch recording more than 1 lakh tonnes.

It is also found that the catches from the Malabar upwelling zone have not decreased, indicating distributional extension and not a distributional shift. These observations indicate that the abundance of oil sardine has increased over the decades. Being an upwelling system, the southwest ecosystem is highly productive. The catch of small pelagics, especially that of the oil sardine has increased from 1,554 tonnes in 1994 to 2,50,469 tonnes in 2007 in the upwelling zone off Kerala. Time series data on different climatic and oceanographic parameters gathered from different sources show that, corresponding to the annual SST (Fig.5.4a), the annual average scalar wind speed increased from 3.58 m/s to 6.05 m/s and from 1.15 m/s to 2.93 m/s respectively (Fig.5.4b) during the years 1967– 2007 off Kerala (Manjusha et al., 2010). The zonal wind speed during the southwest monsoon season (June-September) increased from 3.34 m/s in 1967 to 5.52 m/s in 2005, with speed exceeding 5 m/s in several years during 1992-2005. The monsoonal CUI (Coastal Upwelling Index) is a measure of the volume of water that upwells along the coast. It identifies the amount of offshore transport of surface waters due to geostrophic wind

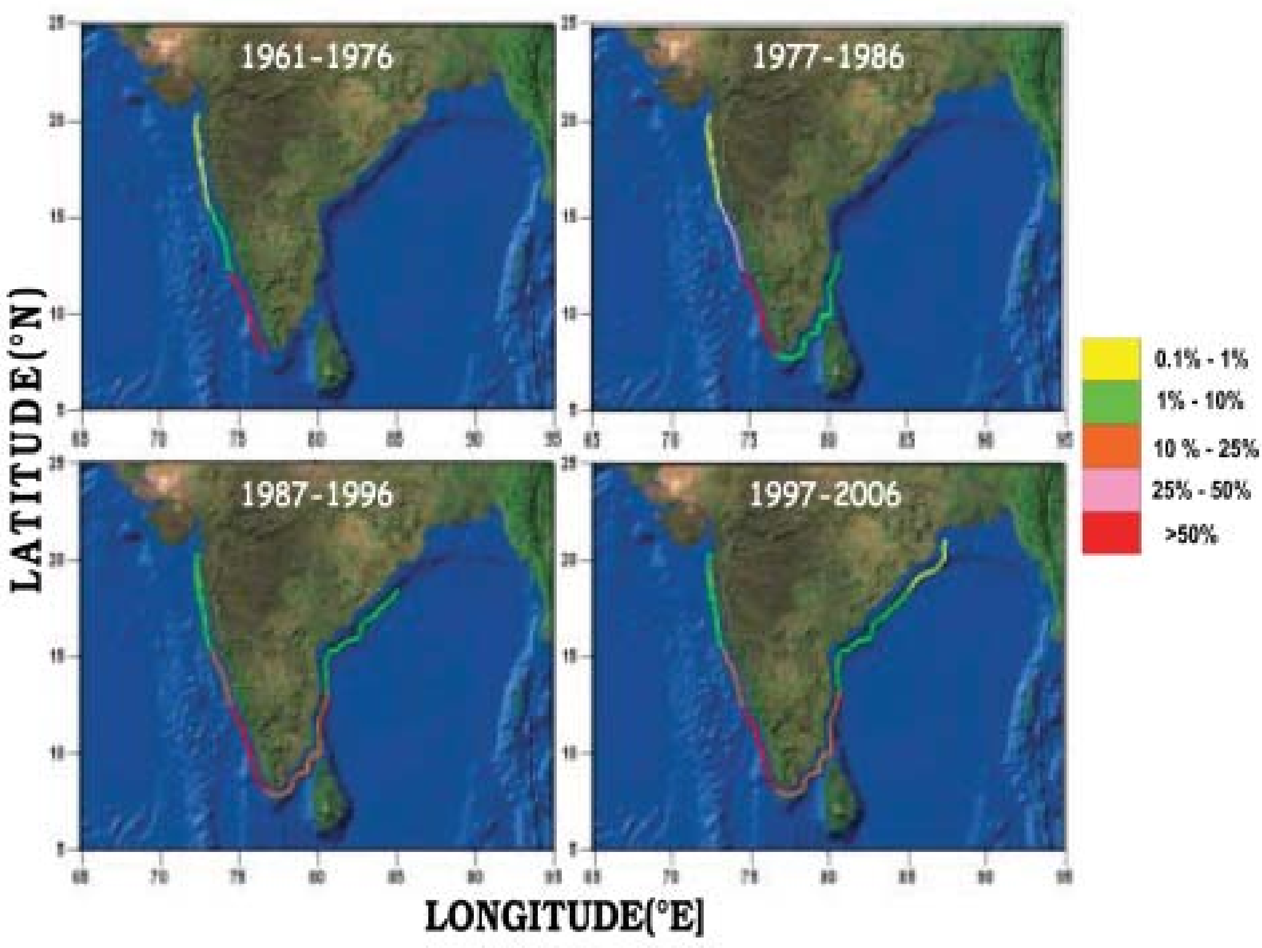


Figure 5.3 . Extension of distributional boundary of oil sardine along the Indian coast; the coloured lines indicate the percentage contribution of catch by each maritime state to the all India oil sardine catch during the corresponding time-period (from Vivekanandan *et al*., 2009c)

fields. Indices are in units of cubic meters per second along each 100 meters of coastline. Positive numbers indicate offshore transport for the upwelling index product and southward transport for the along-shore product increased by nearly 50% from 485 to 713 m^3/s during 1997-2007 (Fig. 5.4c).

This substantial increase in CUI elevated the chlorophyll-*a* concentration from 4.54 mg/m^3 (1997) to 13.85 mg/m^3 (2007) during monsoon (Fig. 5.4d). The high concentration coupled with increasing trend of chlorophyll-*a* during the monsoon resulted in increase of over 200% in annual average chlorophyll-*a* concentration. The increasing CUI and chlorophyll-*a* during monsoon sustained an increasing catch of oil sardine especially during post-monsoon season (Fig.5.4e). The peak spawning activity of oil sardine is during the southwest monsoon. If the direction and speed of wind are ideal, the larvae are dispersed to favourable destinations where they find enough food and fewer predators. Egg development and growth of post-larvae are rapid, and the fish reach 10 cm length in about three months. Thus the individuals, which spawn during the southwest monsoon are recruited to the fishery during the post-monsoon period. It may be concluded that elevated SST, favourable wind (and perhaps current) and increasing CUI have induced higher chlorophyll-*a* concentration during southwest monsoon, which has resulted in increasing the recruitment and catches of oil sardine during post-southwest monsoon season along the Kerala coast (Fig. 5.4d). This trend indicates that the current warming is beneficial to herbivorous small pelagics.

Indian mackerel: The Indian mackerel *Rastrelliger kanagurta* are also found to extend the distribution to the northern latitudes of the Indian seas. Compared to the oil sardine, the Indian mackerel had wider distribution along the Indian coast, but the catches and abundance were predominantly along the southwest coast. The annual production of mackerel in India is about 1.4 lakh tonnes (5% of the total marine fish production). It has a crucial role in marine ecosystems as a plankton feeder and as food for larger fish and also as staple sustenance and nutritional food for millions.

During 1961-76, the mackerel catch along the northwest coast of India contributed about 7.5% to the all-India mackerel catch, which increased to 18% during 1997-06 In the northeast coast, the mackerel catch contributed 0.4% to the all-India mackerel catch during 1961-76, which increased to 1.7% during 1997-06. Similarly along the southeast coast, the mackerel catch during 1961-76 was found to be 10.6% of the all-India mackerel catch, which increased to 23.2% during 1997-06. Along the southwest coast, the mackerel catch contributed about 81.3% to the all-India mackerel catch during 1961-76, which decreased to 56.1% during 1997-06.

The Indian mackerel, in addition to extension of northern boundaries, are found to descend to deeper waters in the last two decades. The fish normally occupy surface and sub-surface waters. The mackerel was conventionally caught by surface drift gillnets by artisanal fishermen. In recent years, however, the fish is increasingly getting caught in bottom trawl nets operated by large mechanised boats at about 50 to 100 m depth. During 1985-89, only 2% of mackerel

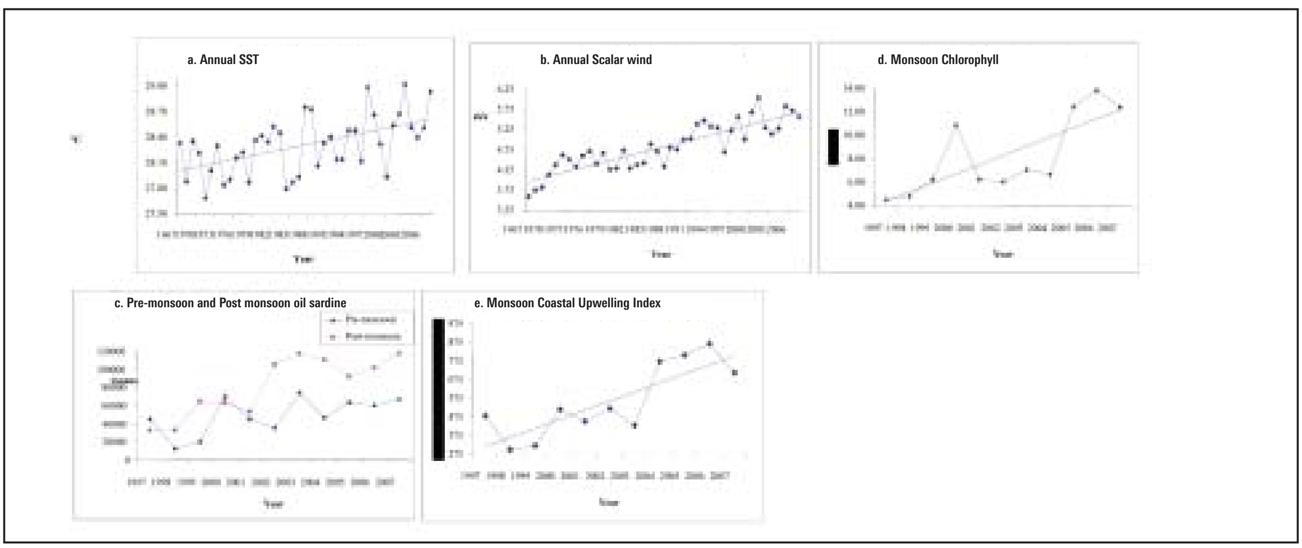


Fig. 5.4. Changes in oceanographic parameters off Kerala during 1967-2007; and their effect on chlorophyll concentration and oil sardine catch

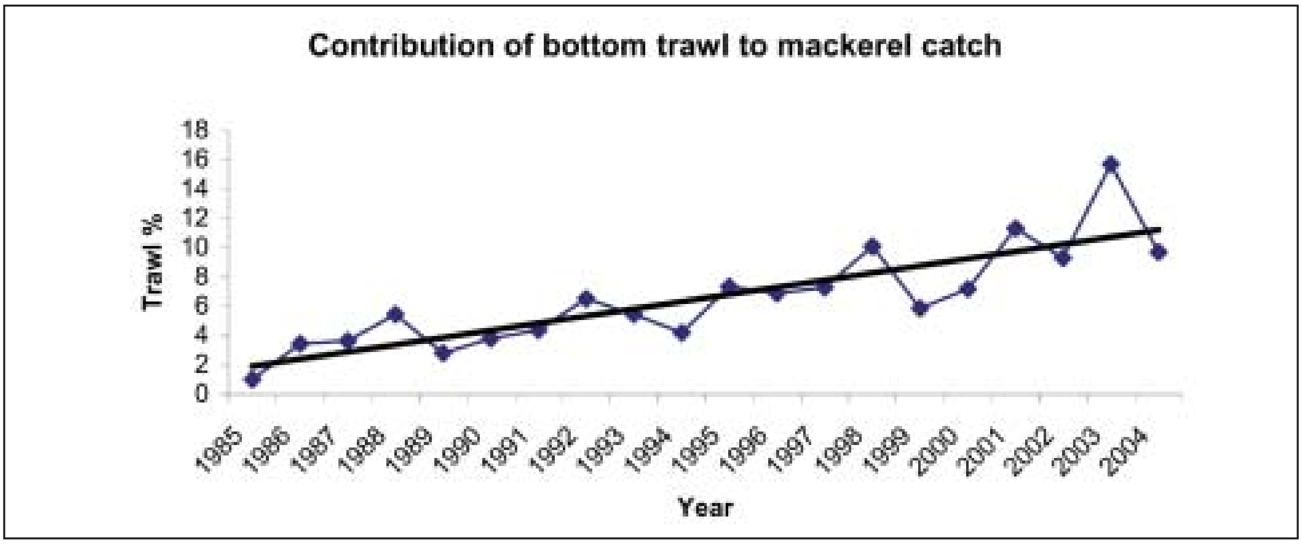


Fig. 5.5 . Increasing contribution of bottom trawlers to Indian mackerel catch during 1985 – 2004 along the Indian coast

catch was from bottom trawlers (Fig.5.5), and the rest of the catch was contributed by pelagic gear such as drift gillnet. During 2003-2007, it is estimated that 15% of mackerel catch was contributed by bottom trawlers along the Indian coast.

There could be two explanations for this: (i) The mackerel are being displaced from the pelagic realm due to warming of the surface waters. (ii) Global climate change models have shown that sea bottom temperatures are also increasing. The mackerel, being a tropical fish, are expanding the boundary of distribution to depths as they are able to advantageously make use of increasing temperature in the sub-surface waters. The latter explanation appears more reasonable as the catch quantities of the mackerel from the pelagic gear such as drift gillnet and ring seine are also increasing. It appears that the distribution of mackerel in the sub-surface has increased, and hence the recent trend may be a vertical extension of distribution, and not a distributional shift.

Considering the catch as a surrogate of distribution and abundance, it is found that the two most dominant fish are able to find temperature to their preference especially in the northern latitudes and deeper waters in recent years, thereby establishing fisheries in the extended coastal areas. Assuming further extension of warmer SST tongue in the future, it is expected that the distribution may extend further north of latitude 20°N. However, it should be cautioned that if the SST in the Malabar upwelling zone increases beyond the physiological optimum of the fish, it is possible that the populations may shift from the southern latitudes in the future.

Phenological changes Threadfin breams: Fish have strong temperature preferences to spawning. The process of spawning is known to be triggered by pivotal temperatures. The annually recurring life cycle events such as timing of spawning can provide particularly important indicators of climate change. Though sparsely investigated, phenological changes such as seasonal shift in spawning season of fish are now evident in the Indian seas.

The threadfin breams *Nemipterus japonicus* and *N. mesoprion* are distributed along the entire Indian coast at depths ranging from 10 to 100 m. They are short-lived (longevity: about 3 years), fast growing, highly fecund and medium-sized fish (maximum length: 30 to 35 cm). Data on the number of female spawners collected every month off Chennai (southeast coast of India) from 1981 to 2004 shows that the percent occurrence of spawners of the two species decreased during the warm months of April-September, but increased in the relatively cooler months of October-March (Vivekanandan and Rajagopalan, 2009). In the early 1980s, about 40% of the spawners of *N. japonicus* occurred during April-September, which gradually reduced to 15% in the early 2000's (Fig.5.6). On the other hand, 60% of the spawners occurred during October-March in the early 1980s, which gradually increased to 85% in the early 2000's. Data collected from ICOADS show that the annual average sea surface temperature off Chennai increased from 29.0°C (1980-1984) to 29.5°C (2000-2004) during April-September and from 27.5°C (1980-1984) to 28.0°C (2000-2004) during October-March. It appears that SST between 27.5°C and 28.0°C may

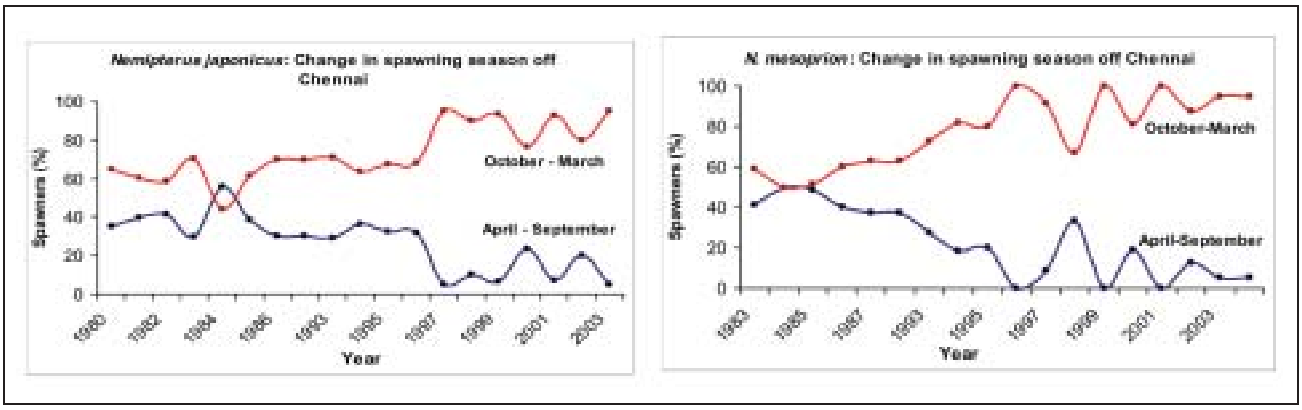


Fig 5.6 . Change in spawning season of *Nemipterus japonicus* and *N. mesoprion* off Chennai (from Vivekanandan and Rajagopalan, 2009)

be the optimum and when the SST exceeds 28.0°C, the fish are adapted to shift the spawning activity to seasons when the temperature is around the preferred optima.

These distributional and phenological changes may have an impact on the nature and value of fisheries. If small-sized, low-value fish species with rapid turnover of generations are able to cope with changing climate, they may replace large-sized high-value species, which are already showing declining trends due to fishing and other non-climatic factors. Such distributional changes would lead to novel mixes of organisms in a region, leaving species to adjust to new prey, predators, parasites, diseases and competitors, and result in considerable changes in ecosystem structure and function.

Currently, it is difficult to find out how much of catch fluctuation is due to changes in fish distribution and phenology. A time-series analysis on stock biomass of different species does not exist along the Indian coasts. Long-term records of abundance are limited to historical commercial landings. Availability of time-series data on climatic and oceanographic parameters and fish catches in India may be too short to detect displacements of stocks or changes in productivity. Moreover, these records are often influenced by economic factors such as the relative price paid for different types of fish, and changes in fishing methods or fishing effort. For instance, introduction of mechanized craft in the 1960s, motorized craft, high opening trawl net, mini-trawl and ring seine in the 1980s, and large trawlers for multi-day fishing in the 1990s substantially increased the fish catch. These non-climatic factors often obscure climate-related trends in fish abundance. Hence, to know the influence of climate change, the impact of non-climatic factors should be removed by de-trending analysis.

5.5 North Eastern region

5.5.1 Agricultural practices in the North Eastern region

North-Eastern India, comprising of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura has a total cropped area of 5.3 million hectares and a population of around 39 million. Assam, the largest state (26.7 million hectares) of North-Eastern India, is predominantly rural and its economy is primarily agrarian in nature, with almost 70% of population directly dependent on agriculture and another 15% dependent on allied activities for its living (Bujarbarua and Barua, 2009). The region is rich in biodiversity and major areas are under sustenance agriculture.

North-Eastern India in general and Assam in particular are known as the centre of diversity for many crops.

Table 5.4: Important Crops in the North Eastern Region

CROP	Area ('000ha)	Production ('000 t) Yield (Kg/ha)	Production ('000 t) Productivity (Kg/ha)
Tea	284	443	1211
Arecanut	82	75	947
Rice	3259	5195	1636
Wheat	78	98	1433
Rapeseed & Mustard	278	151	612

Assam possesses a rich diversity in several grain legumes such as about 61 lines of green gram, 59 lines of black gram, 44 lines of lentil, 12 lines of arhar and 29 lines of fieldpea. Apart from these, 12 wild species of sugarcane are found in the state of Assam. Over two thousand lines of tea and rice are identified. Tea, jute, cotton, potato, sugarcane, and oilseeds are the major cash crops in this area, of which, tea dominates all other cash crops. Orange, banana, pineapple, areca nut, coconut, guava, mango and jackfruit are major horticulture crops.

Tea, by far, is the major agriculture-based industry of Assam, which contributes to 55% of India's total tea output, and 15.6% of world tea production. Other agro-based industries are sugar, jute, paper and rice.

The agricultural practices in the region are broadly of two distinct types, viz., (i) settled farming practiced in the plains, valleys, foothills and terraced slopes and (ii) shifting cultivation (*Jhum*) practiced on the hill slopes. In the hills, agricultural operations are carried out up to a maximum elevation of 5000 m with 'slash and burn' method.

The North-East region is prone to floods and soil erosion, hence agriculture is vulnerable to flood effects. Cloudbursts also cause flash floods resulting in loss of life and agricultural produce. During the period of 45 years between 1953 and 2004, the seven states of the region suffered together a loss of Rs.1729.2 crore due to flood damage to crops, houses and public utility while 1.25 million hectares of land were affected due to floods. Vast areas in the region have been affected by erosion viz. 1 million hectares in Assam; 815,000 hectares in Meghalaya; 508,000 hectares in Nagaland; 108,000 hectares in Tripura; and 14,000 hectares in Manipur (Venkatachary *et al*., 2001). The total flood prone area in the Brahmaputra valley is estimated at 32 lakh hectares, which accounts for 9.6% of the country's total area. Apart from floods, droughts also affected several districts of Assam for two years in 2005 and 2006, causing a loss of more than Rs.100 crore due to crop failure and other peripheral effects.

5.5.2 Projected impacts of climate change on crops in 2030s in the North Eastern region

Simulation analysis indicates that the climate change may bring change in the irrigated rice yields by about –10% to 5%, while the impacts on rain-fed rice are likely to be in the range of –35% to 5% in A1B 2030 climate scenarios in NE regions (see figure 5.7a).
In the case of wheat, the yields are projected to reduce by up to 20%. Potato yields are likely to be marginally benefited up to 5% in upper parts of NE region due to climate change influence, but in the central part, the yields are projected to reduce by about 4% while in the southern parts of NE region, the negative impacts will be much higher. Maize crop yields are projected to reduce by about 40% in NE region (see figure 5.7b). Maize and mustard are also likely to experience decrease in productivity in the entire region (see figure 5.7c).

Adaptation measured can offset the negative impacts of climate change on irrigated wheat and rice but in the case of rain-fed rice, growing of tolerant and high-input efficiency rice varieties with better management and assured irrigation only can reduce the climate change impacts. With such adaptation strategies, the positive impacts can be improved further.

5.6 Himalayan region

5.6.1 Crop Production practices in the Himalayan region

Agriculture in the mountains is broadly defined to cover all land-based activities such as cropping, animal husbandry, horticulture, forestry, and their linkages and support system, and is a prime source of sustenance for most mountain communities (Kamal 2003). In the western Himalaya, five major farming system are prevalent, namely: (i) cereal-based production system (rice, wheat, millets, maize) (ii) Horticulture or agri-horti-based production system, (iii) Vegetables, floriculture and mushroom-based production system, (iv) Livestock-based production system and (v) agri-horti-silvi-pastoral-based production system.

Food grains, oil seeds, vegetables, fruits such as apples and livestock produce are the major products consumed by the inhabitants of western Himalaya. The response of agricultural crop production in different agro-ecological regions to climate change varies according to crop composition, edaphic conditions, and the cropping pattern. A wide range of variation in edaphic, topographic and climatic conditions and selection procedures over centuries of cultivation has cumulatively resulted in the preservation of an immense crop genetic diversity.

5.6.2 Observed changes

With warming of temperature, upward shifts in

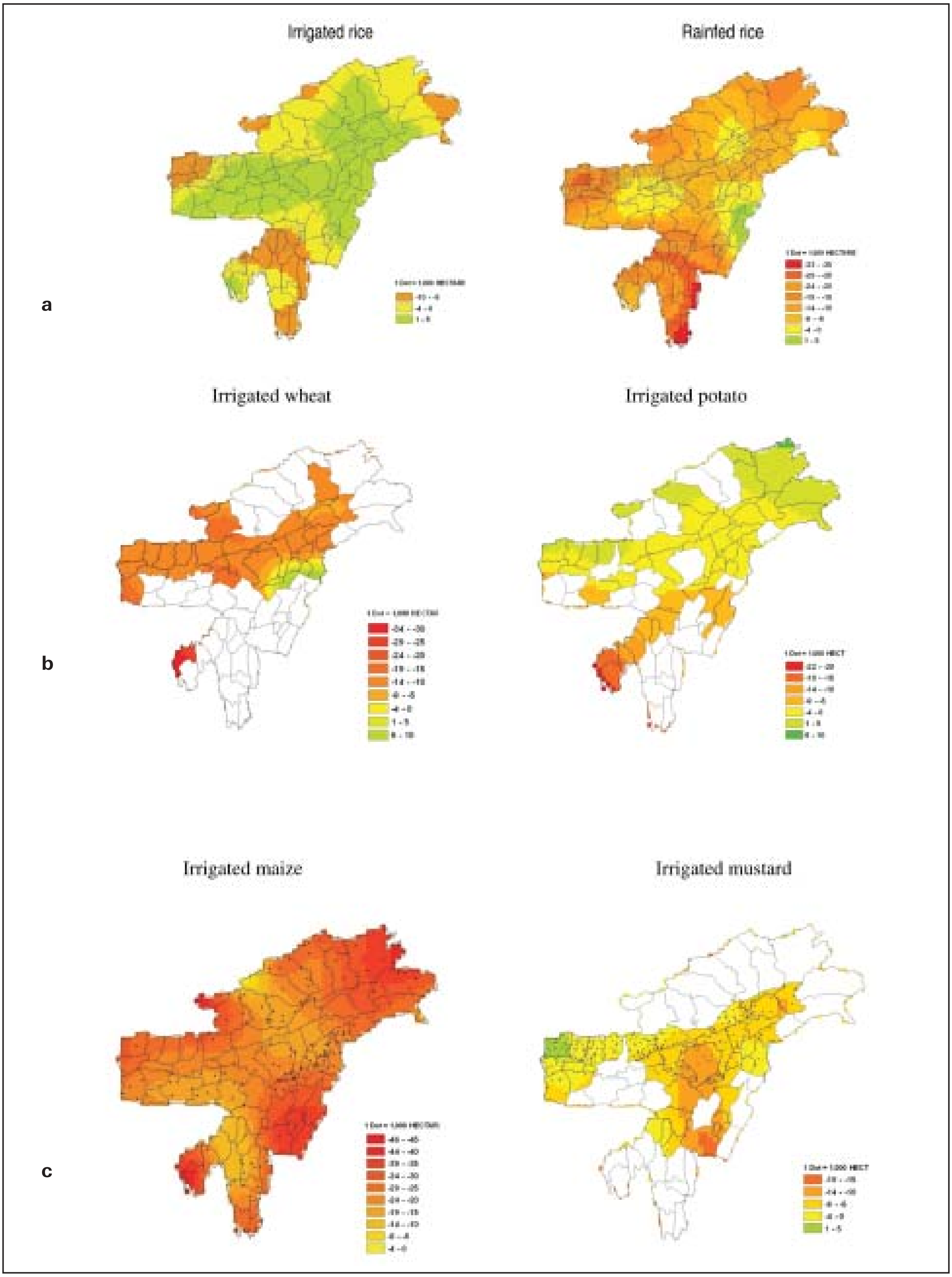


Figure 5.7: Impacts of climate change on crop production in 2030s in North Eastern Region (a) Rice, (b) Wheat and Potato, and (c) Maize and Mustard

agriculture may result in loss of permanent pastures and grassland (*Bugyals*) to arable cultivation, which is already very low. This may cause lower availability of fodder and can adversely affect livestock sector and agriculture. Due to rapid changes in land use caused by socio-cultural and economic changes and various environmental perturbations, the crops biodiversity of the buffer zone agriculture has changed steadily. The land use change in the reserve is significant and affects a whole range of issues. These encompass concerns such as global warming and climate change, biodiversity depletion, biological invasion, growing human population, imposition of conservation policies, land degradation and hydrological imbalances (Maikhuri *et al*., 2001).

In western Himalaya, the traditional farming operation is a complex product of crop husbandry, animal husbandry and forest resources constituting interlinked diversified production systems. However, with changing land use, the area under cultivation of many traditional crops has been reduced and some others are at the brink of extinction. Deficit in food production is growing in recent times in Jammu & Kashmir. With the reduction in rainfall, the rain-fed agriculture will suffer the most. Horticultural crops like apple are also showing decline in production and areal coverage particularly due to decline in snowfall.

A remarkable increase in the area under off-season vegetable cultivation has been noticed in the present cropping pattern in Bajaura Valley (1500-2200m). The area under food crops and fruits has shifted to off-season vegetable cultivation. Decline in area under apple and other fruit was comparatively higher in marginal and small farms. Productivity of apple has recorded a decrease of about 2 to 3% over the past years and the maximum decrease of about 4% has been noticed in marginal farms.

The total farm income on an average has shown a marginal reduction of about 4% in the present period. Off-season vegetables have shared more than 84% of the area under field crops in Theog Region (above 2000m). The area under cereals has declined to the extent of 80%. In this region, the total area under apple and other fruits has recorded no change over the period; however, across different categories of farmers, the decline in area was more in marginal farms (33.33%) than small (5.59%) and large farmers (4.91%). Two to three percent decline in the yield of apple has been observed.

The total income of an average farm remained stagnant but for the large category farmers, it has registered an increase of more than 17% due to more income from off-season vegetables. The share of the fruits crops, mainly apple has come down to 33% at present from 59% in past. In Lahaul valley (above 2500 m MSL) the area under cash crops, mainly potato and peas, in the present cropping pattern increased to the extent of about 8 to 9%. The area under apple has also recorded a remarkable increase of more than 122%. The productivity of cash crops like potato and peas has declined by more than 11 to 15% over a decade period. The productivity of apple has also recorded a marginal decline of 1 to 2% in the present period. The total farm income of the farmers has registered an increase of about 32% over the period. The percentage increase in the income was much higher for small and large farmers than the marginal farmers.

5.6.3 Changing apple productivity in the Himalayan region

Apple is a cash crop in Himachal Pradesh and accounts for 46% of the total area under fruit crops and 76% of the total fruits production. Apple trees develop their vegetative and fruiting buds in the summer, and as winter approaches, the already developed buds become dormant in response to shorter day lengths and cooler temperatures. This dormancy or sleeping stage protects these buds from the oncoming cold weather. Once buds have entered dormancy, they will be tolerant to temperatures much below freezing and will not grow in response to mid-winter warm spells. These buds remain dormant until accumulate sufficient Chilling Units (CU) of cold weather. Temperatures of approximately 35.1° to 55°F provide most of the chilling effect needed by fruit plants; however, the most efficient temperature at which a plant receives chilling is 45.1°F. Temperatures of 32°F and lower, contribute little or nothing to the actual chilling being received by the plant. The daily temperatures of 69.8°F and higher for 4 or more hours, can actually negate chilling that was received by the plant during the previous 24 to 36 hours. The chilling hours requirement for a standard variety of apple is 800-1100°F.

When enough chilling accumulates, the flower and leaf buds are ready to grow in response to warm temperatures. If the buds do not receive sufficient chilling temperatures during winter to completely release dormancy, trees will express delayed foliation, reduced fruit set and increased buttoning. These physiological symptoms consequently affect the yield and quality of the fruit. A recent study by Bhagat *et al*. (2009) has studied the impact of recent temperature changes, their impact on Chilling Units in Himachal and consequent changes in apple production and land use of Himachal Pradesh.

The apple crop is grown in almost all the districts of Himachal Pradesh (Fig.5.8) Three sites in apple growing districts viz. Kullu, Shimla and Lahaul & Spiti representing different elevations and with large areas under apple cultivation was selected for this study. The first study site, located in Kullu district 1200-2500 m above mean sea level represents 16.04% of the total geographical area of Himachal Pradesh. The region represents mid to high hills and receives snowfall in high hills during winter months. The ambient temperature ranges between 46.2° to 78.1°F. The second study site is located in the district Shimla and represents elevation above 2200-3250m MSL (the area is having mid to high hills). Mean annual temperature of the region is 59.7°F. Lahaul & Spiti, the northern part of the state at a considerably higher elevation, represents the third site. It consists of Lahaul and Spiti, Chamba, part of Kullu, Shimla and Kinnuar district and its annual mean temperature is below 57.2°F.

The climatic elements trends for these locations were analysed from the past 13-23 years weather database. Snowfall trends in the past two decades were also calculated for 21 sites representing different elevations ranging from 1500 to 4000 MSL and located in Satluj basins of Himachal Pradesh. The apple productivity trends for past two decades of apple growing areas and total productivity of Himachal Pradesh were also analysed.

The analysis of weather data recorded at Katrain (Kullu district) showed 77.0 mm increase of rainfall during November to May. Increase in precipitation and decreased snowfall during winter months consequently reflected in the low chilling hours in the region. Trend analysis indicated that snowfall is decreasing at the rate of 82.7 mm annually in the entire region.

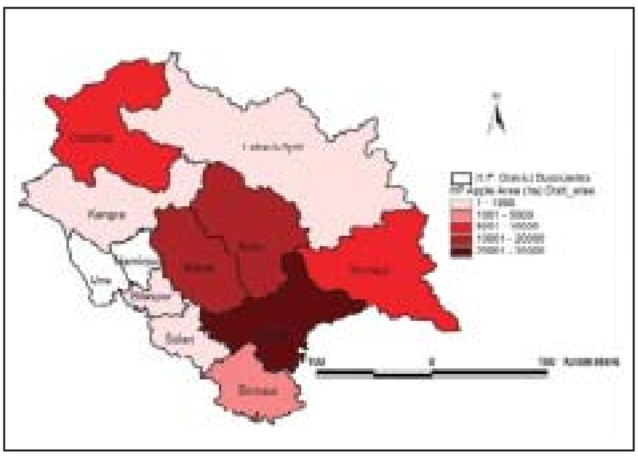


Fig. 5.8: Apple growing areas in Himachal Pradesh.

The increase in maximum temperature reduced the total chilling hours in the region (Fig 5.9). Data on cumulative chill units of coldest months showed a decline of more than 9.1 units per year in the last 23 years. This reduction was more during November and February months. At Bajaura, decrease in annual chill units was at the rate of 11.9 chill units during November to February months. The Utah model also showed decrease of more than 17.4 chill units every year due to increase in surface air temperature at Bajaura. For Shimla, the data exhibited same trends in decrease of chill units. The decrease was 19.0 chill units per year at Theog region.

The apple productivity trends in the last two decades studied for Shimla, Kullu and entire Himachal Pradesh (Figure 5.10), showed a decreasing trend. In recent years, the area under apple has fallen from 92,820 ha in 2001-02 to 86,202 ha in 2004-05 in the entire state, whereas, the area in Lahaul & Spiti and Kinnaur district which lie above 2500 m MSL showed an increase every year in the last ten years. The area increased from 334.0 ha in 1995-96 to 533 hectare in 2004-05 in Lahaul & Spiti and from 5516 ha in 1995-96 to 7700 ha in 2004-05 in Kinnaur district.

5.7 Thermal stress effects on livestock productivity

Temperature-Humidity Index (THI) has been used to represent thermal stress due to the combined effects of air temperature and humidity. THI is used as a weather safety index to monitor and reduce heat-stress related losses (National Research Council, 1971). THI > 75 affects milk production of high producing European crossbreds and buffaloes. THI > 80 severely impacts livestock health and productivity.

In this document, THI for different locations of India has been calculated using average THI mathematically and is represented as:

$$THI = 0.72 (T_{db} + T_{wb}) + 40.6 \ldots\ldots\ldots\ldots (1)$$

Here T_{db} represents Dry bulb temperature and T_{wb} is the wet bulb temperature and have been obtained from CRIDA, Hyderabad. In absence of information

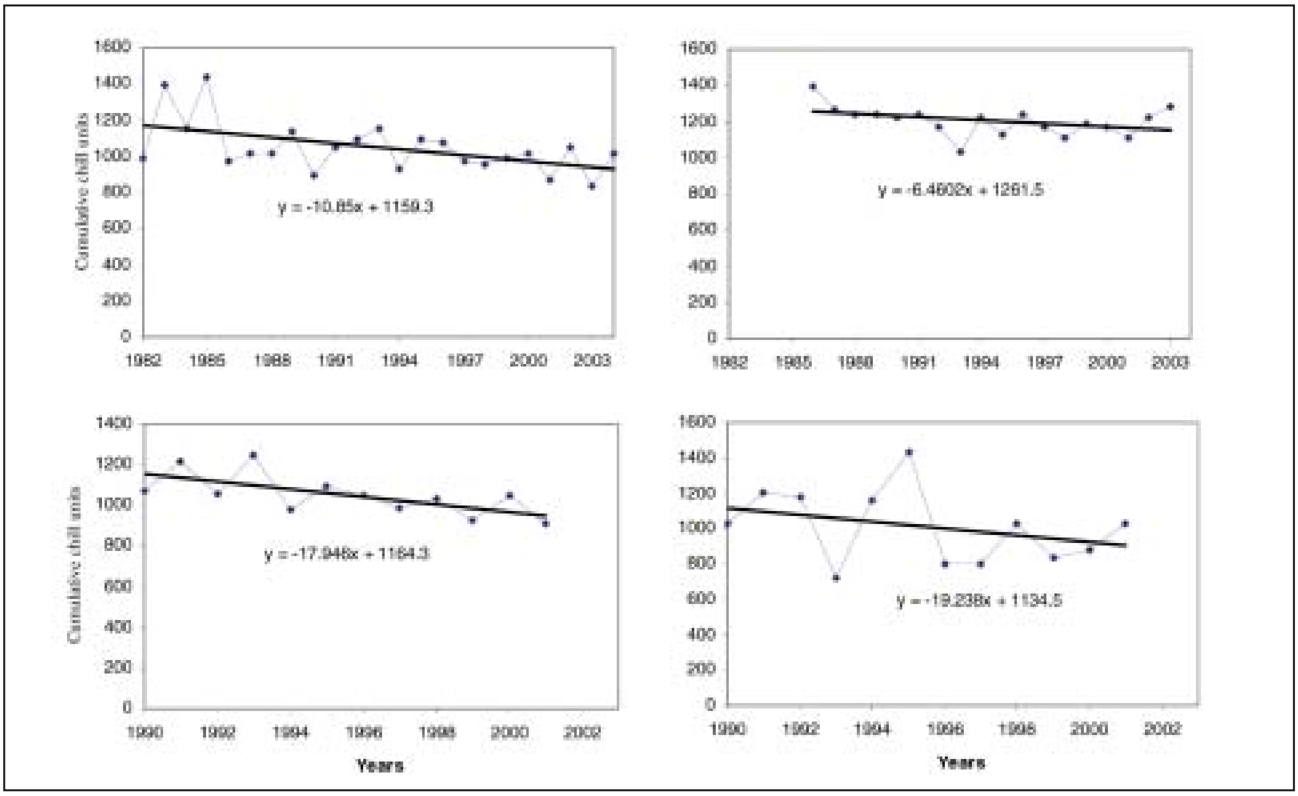


Fig. 5.9 Cumulative chill units trends for Shimla for different months.

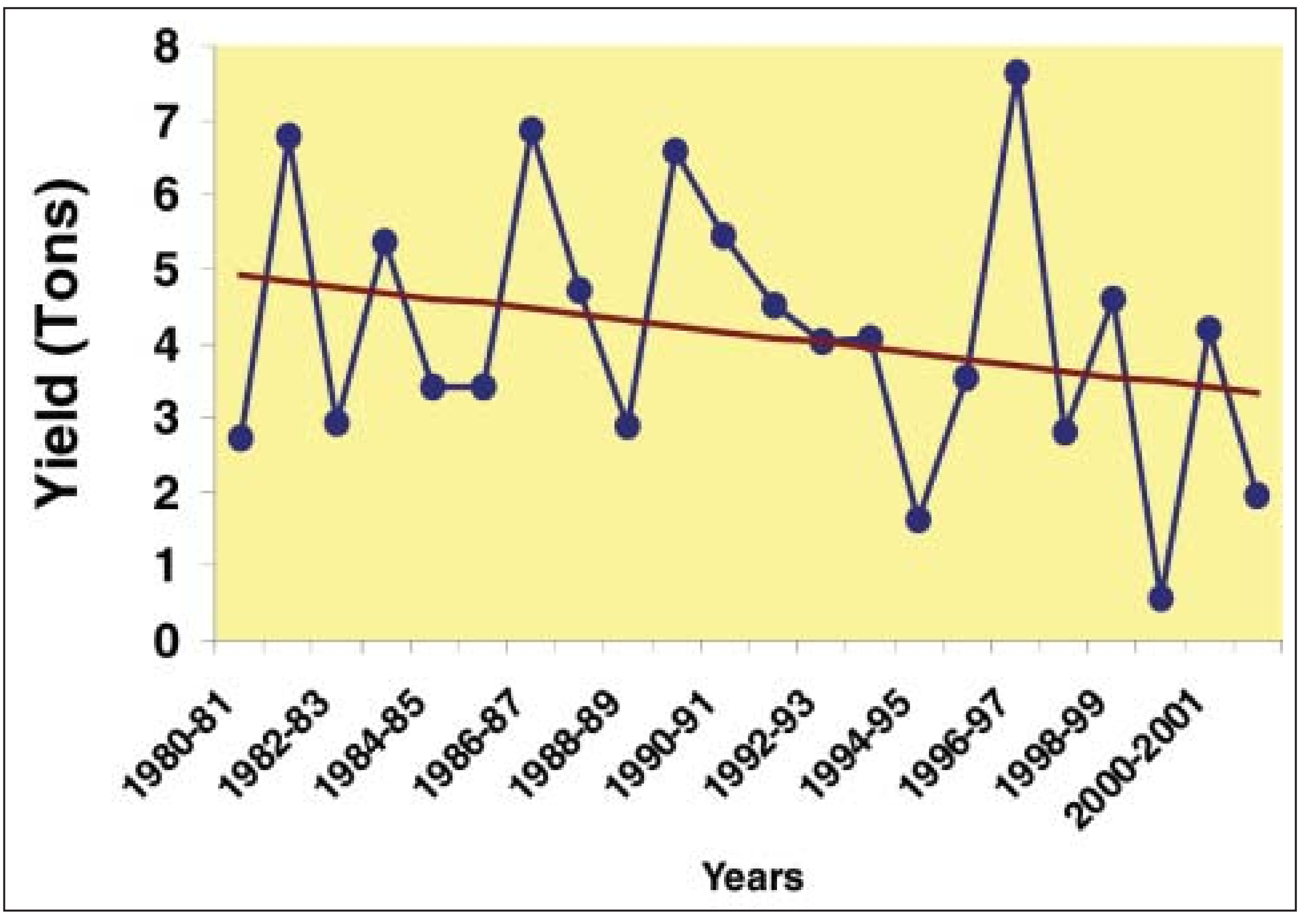


Fig.5.10: Apple productivity trends in Himachal Pradesh.

on T_{db} and T_{wb}, the THI is calculated using T_{max} and T_{min} and it is observed that the variation in THI was less and ranged 3-7% for different months for all locations and therefore was comparable. The THI for different locations for base and 2030 scenarios were calculated using T_{max} and T_{min}.

The Temperature Humidity Index analysis indicated that the congenial THI for production is .70 and is achieved during the months of January and February in most places in India. Only about 10-15% places have optimum THI for livestock productivity during summer and hot humid season. The present analysis indicates that majority of places in India have THI > 75 and more than 85% places in India experience moderate to high heat stress during April, May and June, wherein the value of THI ranges between 75-85 at 2.00p.m when the heat is at its peak. At about 25% places in India, during May and June the THI exceeds 85 i.e. severe stress levels are experienced. The night temperatures remain high and provide no relief from heat stress and morning THI is high. On an average, THI exceeds 75 at 75-80% places in India throughout the year.

The TH Index distribution over the Indian region is shown in Figure 5.11. The THI changes in four distinct regions - the Himalayan region, the North-East region, the Coastal region and the Western Ghats - have also been analysed (see Figures 5.12a, b, c, d, e, f) for the months of January, February, March, May, June and July. The regions defined for this analysis include Jammu & Kashmir, Himachal Pradesh and Uttaranchal in the Himalayan region; the North-East region includes parts of Arunachal Pradesh, Assam, Manipur, Mizoram, Meghalaya, Nagaland and Tripura; the Western Ghats include parts of Gujarat, Maharashtra, Karnataka and Kerala; and the Coastal region includes parts of Orissa, Andhra Pradesh and Tamil Nadu in the east and Maharashtra in the west. There is an all-round increase in THI in all the regions, which may impact the economic viability of livestock production systems in these regions. The highest impact is likely to be in the Coastal zones and the North-East regions where livestock rearing may become a cost-intensive affair for the marginal farmers. This change is also likely to alter the livestock production systems in Western Ghats, which is one of the biodiversity hotspots in India. The regional description of behaviour of THI in 2030's is as follows:

Himalayan region: The analysis for the baseline period and the 2030 scenario has shown the likely increase in THI in many parts of Himalayan region between March-September with a maximum rise between April- July. In the Himalayan region for 2030 scenario, thermal discomfort is likely to increase with THI > 80 compared to the baseline scenario, thereby indicating that in the 2030's, most places in this region are likely to remain under high temperature stress as compared to the baseline period.

North-Eastern region: In this region, the THI is likely to increase between April-October months with THI > 80.

Western Ghats: The likely increase in THI compared to the baseline scenario is highest for the September-April months and is likely to remain under highly stressful conditions in the 2030's period. The heat-stress days per annum are likely to increase with THI above 80 in 2030 in the Western Ghats.

Coastal region: The Coastal regions are likely to remain affected throughout the year in 2030 scenario with THI above 80.

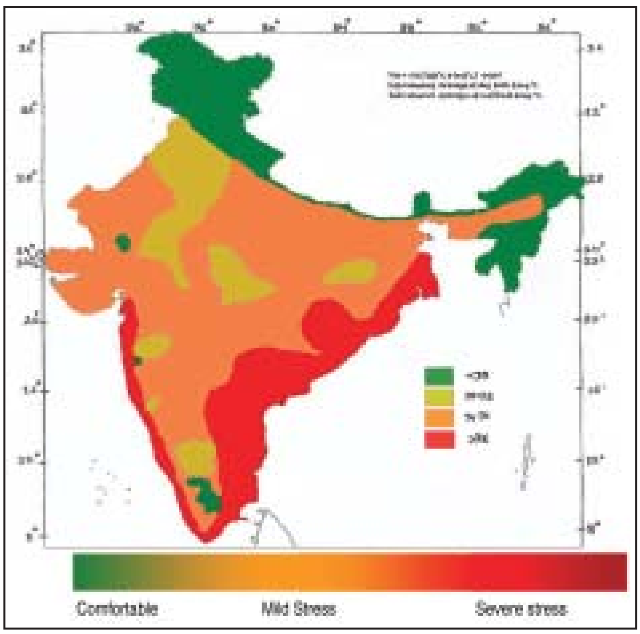


Figure 5.11: Temperature and Humidity Index (THI) map of India

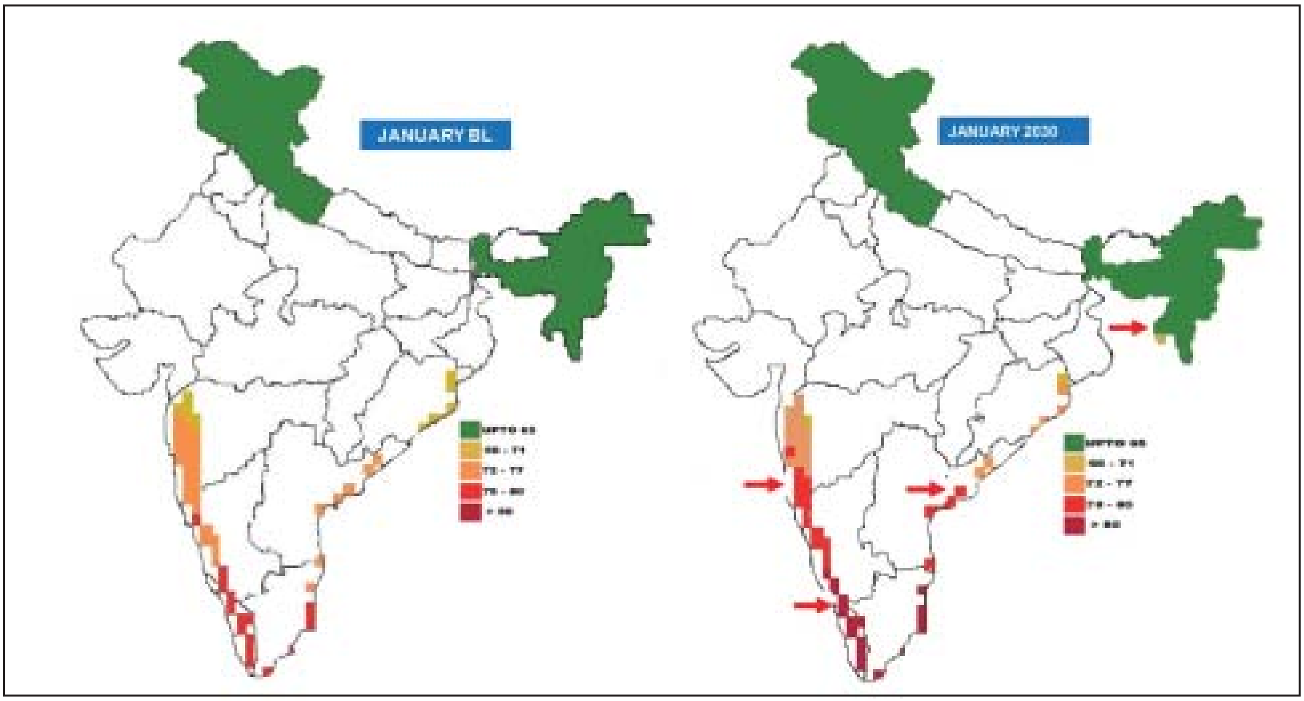


Fig.5.12a: Projected changes in thermal stress for 2030 over parts of India calculated from the RCM Projections under the A1B emission scenario. The thermal stress is likely to remain unchanged for the Himalayan and the North-East region with severe changes expected in the parts of Western Ghats and the Coastal region in the month of January for baseline (left) and the 2030 (right) time slice.

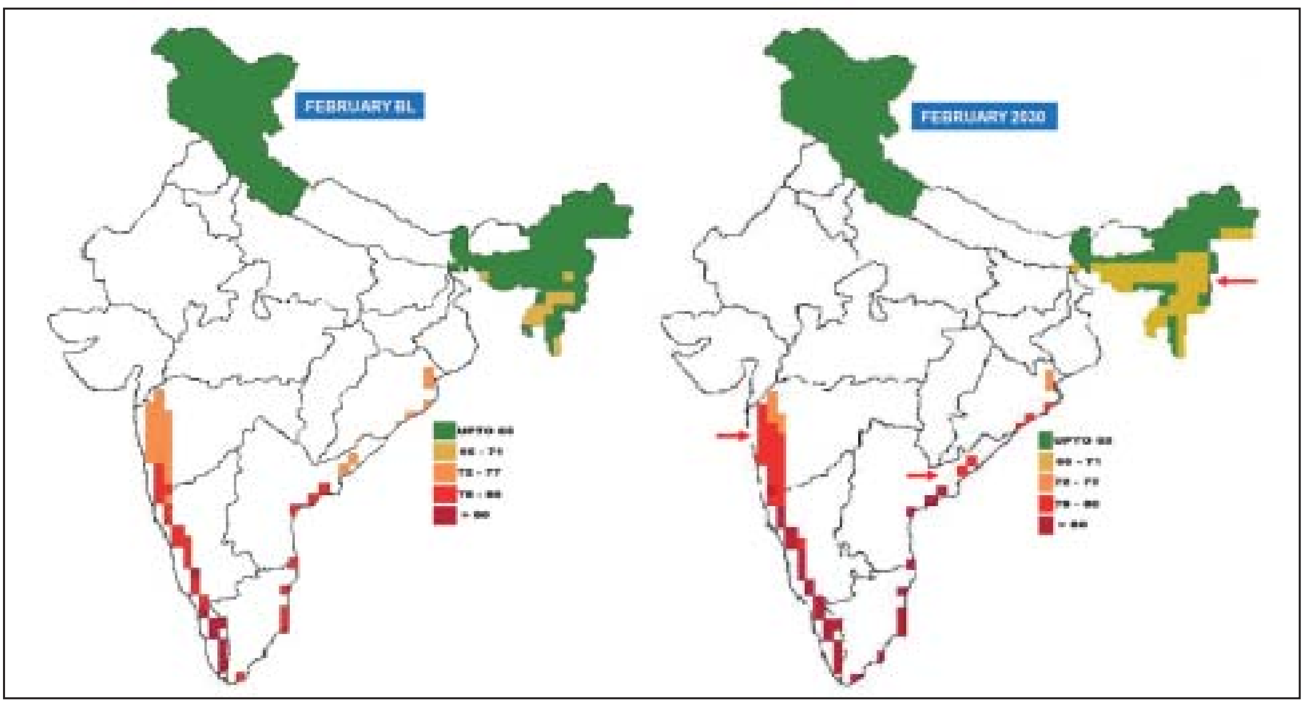


Fig.5.12b: Projected changes in thermal stress for 2030 over parts of India calculated from the RCM Projections under the A1B emission scenario for the month of February. The Himalayan region is likely to remain unaffected but changes in thermal stress are expected in most parts of North-East region. A more severe change is expected over most parts of Western Ghats and the Coastal region over the baseline period (right) for this month.

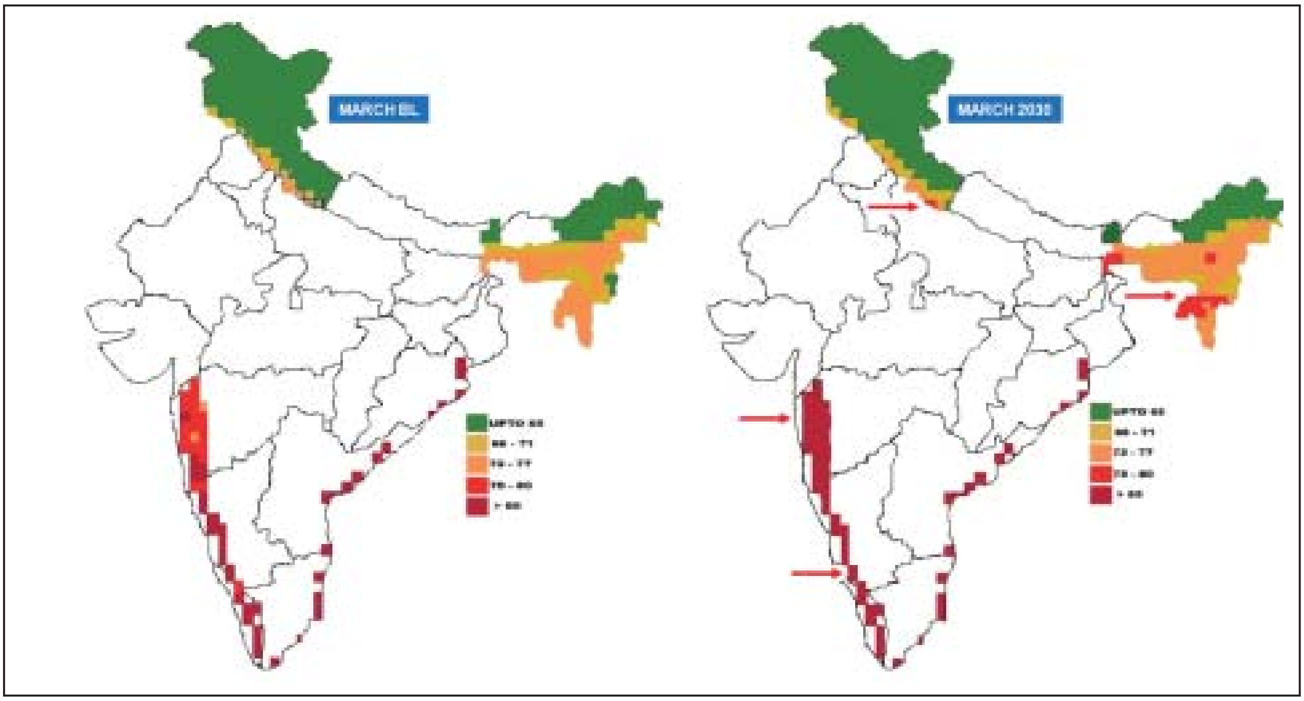


Fig.5.12c: Projected changes in thermal stress for 2030 (right) relative to the baseline period (left) over parts of India calculated from the RCM Projections under the A1B emission scenario for the month of March. Mild to moderate changes are expected in the Himalayan foothills and most parts of North-East region. Severe thermal discomfort is expected in most parts of Western Ghats and the Coastal region in March for 2030 time period.

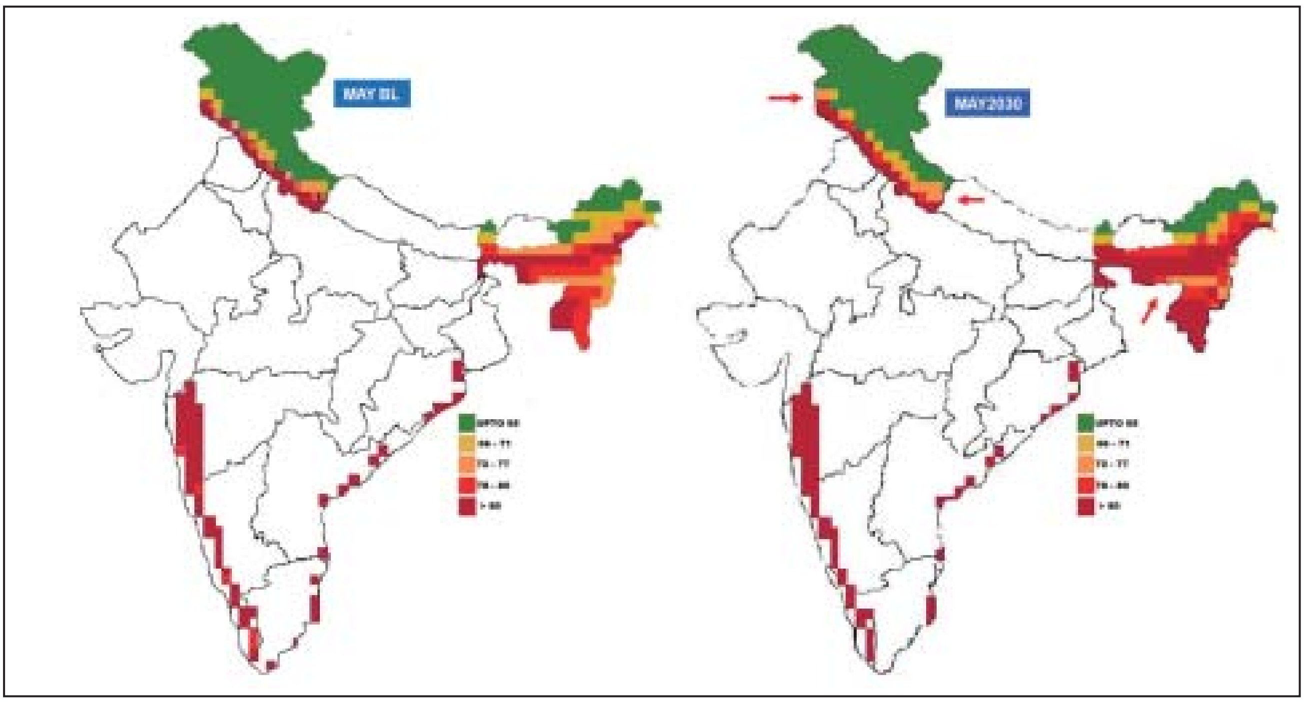


Fig.512d: Projected changes in thermal stress for 2030 (right) relative to the baseline period (left) over parts of India calculated from the RCM Projections under the A1B emission scenario for the month of May. The thermal stress is likely to increase in the Himalayan and North-East regions with THI > 80. A severe thermal discomfort is expected with THI > 80 in most parts of Western Ghats and the Coastal region in the month of May.

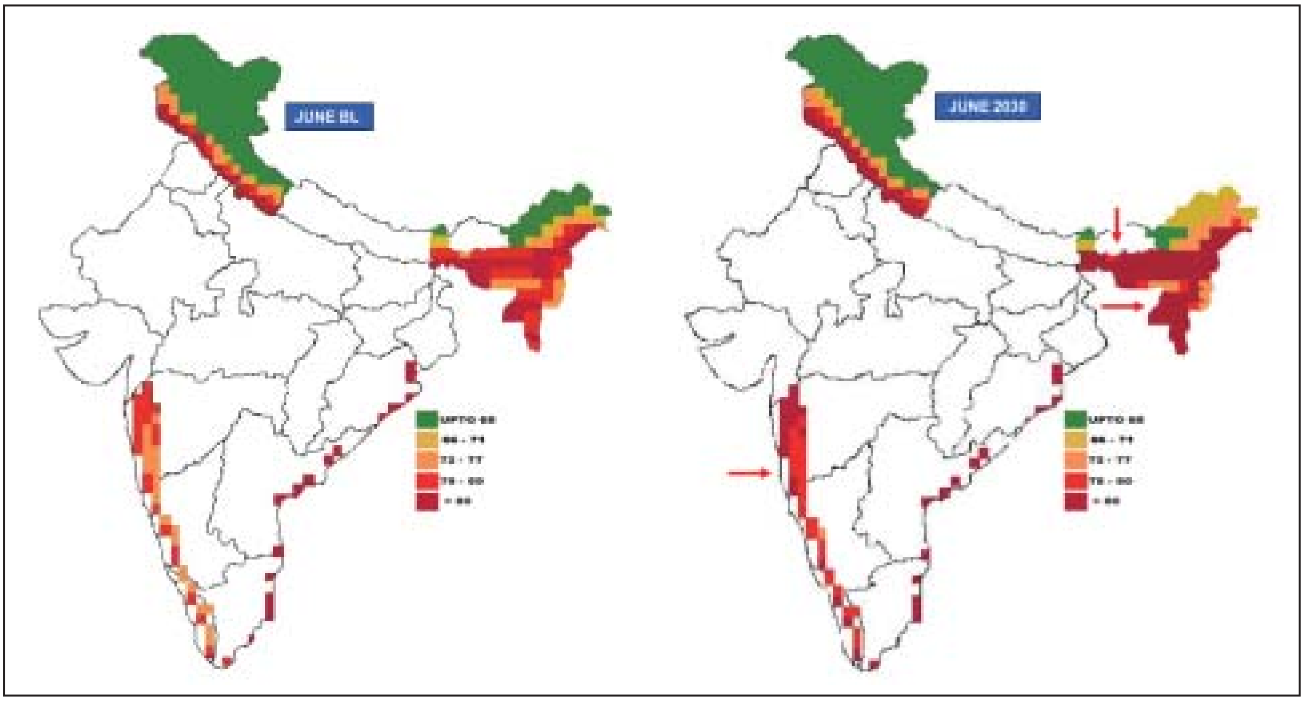


Fig.5.12e: Projected changes in thermal stress for 2030 (right) relative to the baseline period (left) calculated from the RCM Projections under the A1B emission scenario for the month of June. Severe changes in Temperature Humidity Index are expected in all the four regions- the Himalayanregion, the North-East region, of the Western Ghats and the Coastal region. These regions are likely to experience severe thermal discomfort.

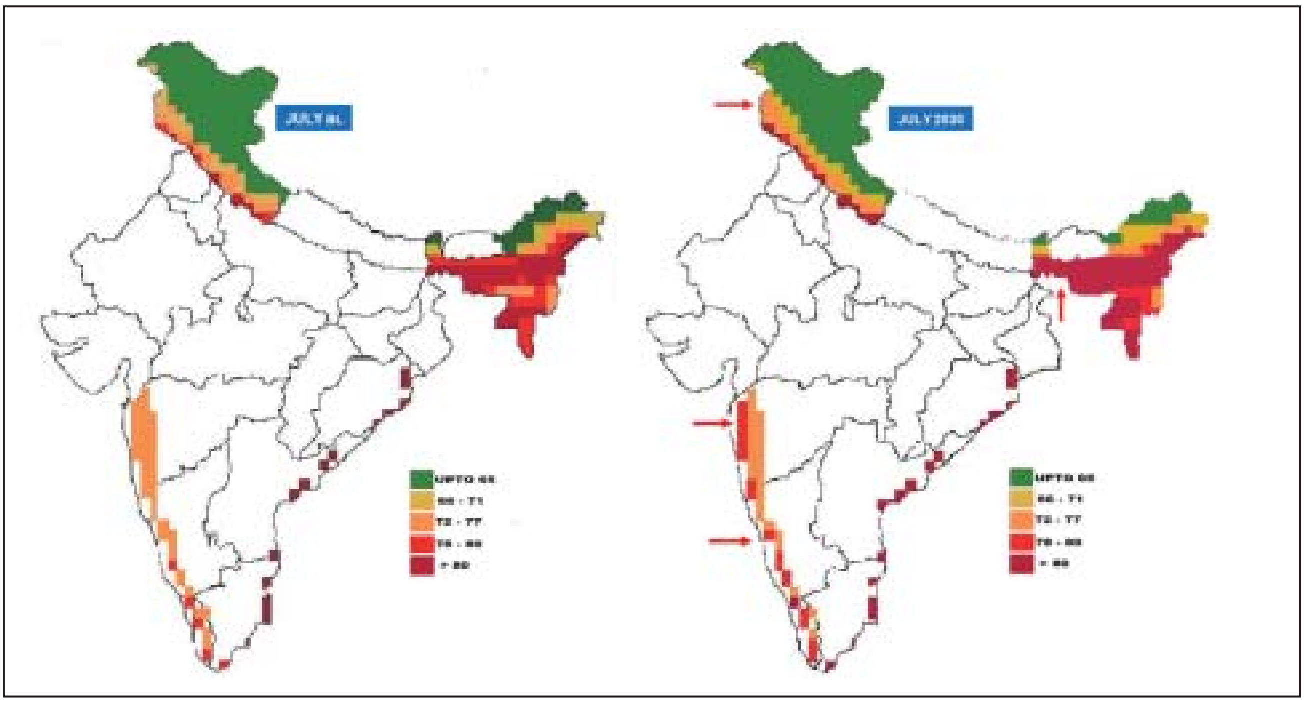


Fig. 5.12f: In the Himalayan and North-East region changes are likely to be more pronounced and thermal stress increase over base-line scenario. Most parts in Western Ghats and Coastal region are likely to experience mild to moderate thermal stress due to increased temperature during 2030 scenario

6

Natural Ecosystems and Biodiversity

6.1 Introduction

Climate is one of the most important determinants of global patterns of natural ecosystems and biodiversity along with the physical diversity of the region. In India, the varied climate regimes, the large geographical area, varied topography, long coastline and the possession of oceanic islands have endowed it with a diversity of natural biomes—from deserts to alpine meadows, from tropical rainforests to temperate pine forests, from mangroves to coral reefs and from marshlands to high-altitude lakes. About one-fifth to one-fourth of the country's geographical area comprises "natural" ecosystems, excluding forests that constitute of mangroves, wetlands and coral reefs and mountain ecosystems amongst others. [Fig.6.1 (a); Sukumar *et al*., 2004]. The forest cover is around 69.16 million ha (as of 2007), and it constitutes of tropical wet evergreen forests, tropical semi-evergreen forests, tropical moist deciduous forests, littoral and swamp forests, tropical dry deciduous forests, tropical thorn forests, tropical dry evergreen forests, subtropical broad-leaved hill forests, subtropical pine forests, subtropical dry evergreen forests, montane wet temperate forests, Himalayan moist temperate forests, Himalayan dry temperate forests, subalpine forests, moist alpine scrub, dry alpine scrub, plantations and tree outside forests (see Figure 6.1 (b); FSI, 2009).

The present chapter reviews the response of ecosystems to climate change. Further, it reviews the perceived changes in natural ecosystems, other than forests, in India due to climate change. Next, it reviews the modelling studies carried out so far to understand the response of forest vegetation to climate change at the middle and end of this century. This chapter limits itself to assessing the impact of climate change on the forests in four eco-sensitive regions of India for the 2030's. Such an assessment is likely to assist in developing and implementing adaptation strategies to ensure sustained flow of ecosystem services, including conservation of biodiversity from the forests. The four regions for which the study has been carried out include: 1) the Western Ghats, 2) the Himalayas, 3) the coastal regions, 4) the North-Eastern part of

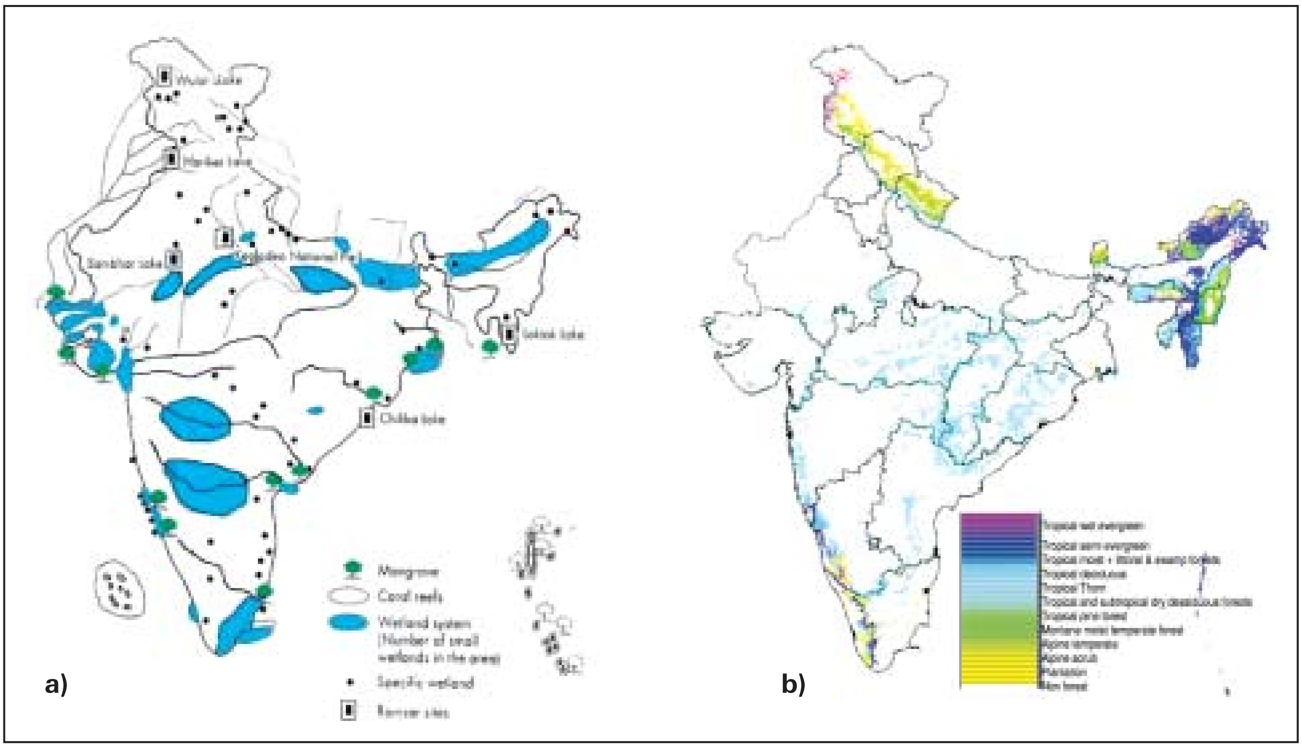


Figure 6.1: (a) Natural ecosystem map of India depicting natural inland lakes, mangroves, coral reefs, and wetland systems, (b) Forest strata map of India

Source: Sukumar *et al*., 2004; and FSI, 2009

India. Currently, much of these regions are covered with moderate to dense forests, except the coastal regions (FSI, 2009). For more details on the forest cover types, forest density and afforestation rates of these regions, please refer to FSI (2009).

6.2 What is known

6.2.1 Ecosystems- their response to climate change and key issues

An ecosystem can be practically defined as a dynamic complex of plant, animal and microorganism communities and the non-living environment, interacting as a functional unit (Millennium Ecosystem Assessment, Reid *et al*., 2005). Ecosystems are well-recognised as critical in supporting human well-being (Reid *et al*., 2005), and the importance of their preservation under anthropogenic climate change is explicitly highlighted in Article 2 of the UNFCCC (UNFCCC, 1992).

Ecosystems are expected to tolerate some level of future climate change and, in some form or another, will continue to persist (e.g., Kirschbaum and Fischlin, 1996; Gitay *et al*., 2001), as they have done repeatedly with palaeoclimatic changes (Jansen *et al*., 2007). A primary key issue, however, is whether ecosystem resilience (understood as the disturbance an ecosystem can tolerate before it shifts into a different state, e.g., Scheffer *et al*., 2001; Cropp and Gabrica, 2002; Folke *et al*., 2004) inferred from these responses (e.g., Harrison and Prentice, 2003) will be sufficient to tolerate future anthropogenic climate change (e.g., Chapin *et al*., 2004; Jump and Peñuelas, 2005). The implications of possibly transient increases in productivity for resilience are also very relevant. These may occur in certain terrestrial ecosystems through likely atmospheric CO2-fertilisation effects and/or modest warming (e.g., Baker *et al*., 2004; Lewis *et al*., 2004b; Malhi and Phillips, 2004), and demonstrated consequences of increased radiation due to reduced tropical cloudiness (Nemani *et al*., 2003).

Ecosystems are increasingly being subjected to other human-induced pressures, such as extractive use of goods, and increasing fragmentation and degradation of natural habitats (e.g., Bush *et al*., 2004). In the medium-term (i.e. decades) especially, climate change will increasingly exacerbate these human-induced pressures, causing a progressive decline in biodiversity (Lovejoy and Hannah, 2005). However, this is likely to be a complex relationship that may also include some region-specific reductions in land-use pressures on ecosystems (e.g., Goklany, 2005; Rounsevell et al., 2006). Another issue involves exceeding critical thresholds and triggering non-linear responses in the biosphere that could lead via positive feedback to novel states that are poorly understood.

Projected future climate change and other human-induced pressures are virtually certain to be unprecedented (Forster *et al*., 2007) compared with the past several hundred millennia (e.g., Petit *et al*., 1999; Augustin *et al*., 2004; Siegenthaler *et al*., 2005). An understanding of time-lags in ecosystem responses is still developing, including, for example, broad-scale biospheric responses or shifting species geographical ranges. Many ecosystems may take several centuries (vegetation) or even possibly millennia (where soil formation is involved) before responses to a changed climate are played out (e.g., Lischke *et al*., 2002). A better understanding of transient responses and the functioning of ecosystems under continuously changing conditions is needed to narrow uncertainties about critical effects and to develop effective adaptation responses at the time-scale of interest to human society.

Species extinctions, and especially global extinction as distinct from local extinctions are key issues that need to be addressed, as the former represents irreversible change. This is crucial, especially because of a very likely link between biodiversity and ecosystem functioning in the maintenance of ecosystem services (Duraiappah *et al*., 2005; Hooper *et al*., 2005; Diaz *et al*., 2006; Worm *et al*., 2006), and thus extinctions critical for ecosystem functioning, be they global or local, are virtually certain to reduce societal options for adaptation responses.

6.2.2 A review of impacts of climate change on ecosystems and biodiversity in India

Impacts on grassland, mangroves, wetland, coral reefs: According Sukumar *et al*. (2004), increasing atmospheric CO_2 levels are projected to favor C3 plants over C4 grasses, but the projected increase in temperature would favour C4 plants[1]. The outcome of climate change in India would thus be

1 *C3 plants include cool, temperate grasses and practically all woody dicots, while C4 plants include warm, tropical grasses, many types of sedge and some dicots. The C4 plants that constitute much of the biomass of tropical grasslands, including the arid, semi-arid and moist grasslands in India, thrive well under conditions of lower atmospheric CO2 levels, higher temperatures and lower soil moisture, while C3 plants exhibit the opposing traits.*

region-specific and involve a complex interaction of factors. Sea-level rise along the Indian coast would submerge the mangroves as well as increase the salinity of the wetland. This would favour mangrove plants that tolerate higher salinity. Increased snowmelt in the western Himalayas could bring larger quantities of freshwater into the Gangetic delta. This would have significant consequences for the composition of the Sundarbans mangroves, favouring mangrove species that have the least tolerance to salinity. The projected sea-level rise of 0.18m minimum to a maximum of 0.59m (IPCC, 2007a) is well within the ability of Sunderbans mangrove ecosystem to adapt which presently face tidal amplitudes up to 5m (Untawale, 2003). This may not be true for other mangroves such as the Pichavaram and Muthupet where tidal amplitudes are much lower at 0.64m and much of the inland areas are already developed for agriculture. Changes in local temperature and precipitation will also influence the salinity of the mangrove wetlands and have a bearing on plant composition. Increase in temperature will lead to bleaching of corals. Coral reefs could also be potentially impacted by sea-level rise. Healthy reef flats seem able to adapt through vertical reef growth of 1cm per year (observed during the Holocene; see Schlager, 1999). that is within the range of projected sea-level rise over the next century. However, the same may not be true for degraded reefs that are characteristic of densely populated regions such as South and South-East Asia (Bryant *et al*., 1998).

Himalayan ecosystem: Following on from the experiences of other mountains, with current level of increase in mean annual temperature over various parts of the Himalayas, an upward movement of plants is expected (Grabherr *et al*., 1994; Pauli *et al*., 2001). Researches carried out elsewhere have shown that the community composition has changed at high alpine sites, and tree line species have responded to climate warming by invasion of the alpine zone or increased growth rates during the last decades (Paulsen *et al*., 2000). Several field studies in different parts of the world indicate that climate warming earlier in the twentieth century (up to the 1950s and 1960s) has caused advances in the tree limit (Kullman, 1998).

Yet another study has reflected climate sensitivity of high-altitude forests of the western Himalayas. The study by Borgaonkar *et al*., (2010) has reported an unprecedented enhancement in growth during the last few decades in the five tree-ring width chronologies of Himalayan conifers (*Cedrus deodara D.Don*.; *Picea smithiana Boiss*) from the high-altitude areas of Kinnaur (Himachal Pradesh) and Gangotri (Uttarakhand) regions. Analysis of surface air temperature data over the region indicates significant and increasing trend during the last century, with recent noticeable enhanced warming in the past four decades. The time series of annual highest values of daily maximum and minimum temperatures also show an increasing trend. As such, the study partially attributes the accelerated tree-ring growth during the last few decades to the overall warming trend seen over the region.

Change in plant phenology may be one of the earliest observed responses to rapid global climate change and could potentially have serious consequences for the plants and animals that depend on periodically available resources. The phenology and development of most organisms generally follow a timescale, which is temperature dependent (Allen, 1976). The overall development and pattern of plant growth is important and directly affects productivity. Literature reports indicate that climatic conditions are more useful "predictors" than the calendar dates (Parella, 1985). Species in some ecosystems are so strongly adapted to the long-prevailing climatic pattern that these are vulnerable even to modest changes. Little is known about the reproductive cycle and ecological factors necessary for flowering and reproduction in individual species. Increase in the level of carbon dioxide in the atmosphere and consequent global warming may also have a profound effect on the flowering time of plants.

Climate change signatures have already begun to appear in the Indian Himalayan Region (IHR) in the form of shift in the arrival of monsoon, long winter dry spells (5–6 months as experienced in 2008–09), increased frequency of forest fires during winter, the early flowering/fruiting of native trees, such as *Rhododendron spp.* and *Myrica esculenta*, etc. One systematic study, which deals with the impact of climate change on the phenophases of 11 multipurpose tree species, pertains to Himachal Pardesh (western Himalayas). The experiment site represents a transitional zone between the subtropical and the sub-temperate regions, located between 30°51′ N and 76°11′ E, with an elevation of 1,200 metres above sea level (m asl). The tree species included *Grewia optiva, Morus alba, Bauhinia variegate, Robinia pseudoaccacia, Melia azedarach, Dalbergia sisoo, Toona ciliate, Celtis australis, Gmelina arborea, Sapindus mukurosii and Albizia stipulate.*

The study concluded that the substantial shift in

Table 6.1 : Observations on ecological, structural, functional and phylogenetic aspects of microbes of Indian Himalayan Region

S. No.	Brief description of the findings	Reference
1.	Occurrence of negative rhizosphere effect along with greater colonization by antagonistic microorganisms with many plant species	Pandey and Palni, 2004; 2007
2.	Decrease in microbial population with increasing altitude	Pandey and Palni, 1998; 2007
3.	Inability of tropical plant growth promoting bioinoculants against suitability of psychrotolerant plant growth promoting bacteria in agricultural fields at higher altitudes	Selvakumar *et al*., 2007
4.	Influence of biotic factors (e.g., temperature and mountain aspect) on phosphate solubilizing pseudomonads	Pandey *et al*., 2002; 2006; Selvakumar et al., 2009
5.	Occurrence of *bulbous sporangia*, at terminal ends, in *thermophilic Geobacillus spp*	Kumar *et al*., 2004; Sharma *et al*., 2009
6.	Occurrence of dark-septate mycelium in high altitude rhododendrons	Chaurasia *et al*., 2005
7.	Occurrence of psychrophiles, including new species, from glaciers of Uttarakhand and cold desert of Himachal Pradesh	Mayilraj, 2007; Shivaji, 2009
8.	Tolerance of wide range of pH and temperature by species of bacteria and fungi, isolated from extreme low and high temperature environments	Pandey *et al*., 2006; 2008; Rinu and Pandey, 2010
9.	Occurrence of new species of Pythium with inflated sporangia and coiled antheridium from Kashmir Himalaya	Paul and Bala, 2008
10.	Emergence of Begomovirus problems in sub-temperate and temperate Himalaya	Kumar *et al*., 2010
11.	Higher production of cellular metabolites including enzymes at suboptimal conditions	Malviya *et al*., 2009; Rinu and Pandey, 2010
12.	Dominance of species of spore forming bacteria, species of Bacillus, in extreme low and high temperature environments of Himalaya	Pandey *et al*., 2010

critical phenophases, including leaf emergence, flower initiation and growth period in a span of eight years seems to be associated with climate change and there is every reason to believe that advancement in phenophases of these tree species might be the result of climate change at the regional level

Impacts on Indian forest vegetation types: Studies by Ravindranath *et al*., (2004, 2006) made an assessment of the impact of projected climate change on forest ecosystems in India. This assessment was based on climate projections of the Regional Climate Model of the Hadley Centre (HadRM3) using the A2 (740 ppm CO_2) and B2 (575 ppm CO_2) scenarios and the BIOME4 vegetation response model. The main conclusion was that under the climate projection for the year 2085, 77% and 68% of the forested grids in India are likely to experience shift in forest types under A2 and B2 scenario, respectively. A recent assessment (Chaturvedi *et al*., 2010) of the impact of projected climate change on forest ecosystems in India was made using a Dynamic Global Vegetation Model (DGVM). Using climate projections of the HadRM3 and the DGVM IBIS for A2 and B2 scenarios, it has been projected that 39% of forest grids are likely to undergo vegetation type change under the A2 scenario and 34% under the B2 scenario by the end of this century. The study concluded that the impacts varied with the region and forest types. Thus there is need for regional studies particularly for the ecologically sensitive regions and for short-term periods such as the 2030's.

6.3 Projections for 2030s on forest vegetation - Methodology

The impacts of climate change on forests in India are assessed based on the changes in area under different forest types, shifts in boundary of forest types and net primary productivity (NPP). This assessment was based on spatial distribution of (i) current climatic variables, (ii) future climate projected by relatively high-resolution regional climate models for moderate SRES A1B climate change scenario, and (iii) vegetation types and NPP as simulated by the dynamic model IBIS v.2 (Integrated Biosphere Simulator). Detailed information about the methodology and models used is given in Chaturvedi *et al*. (2010).

6.3.1 Climate model

In this report, data from the HadCM3 GCM, downscaled by PRECIS model, a regional climate model for downscaling climate projections, is used. The combination of HadCM3 and PRECIS models is known as the HadRM3 model. Climate change projections were made:

- for monthly mean values of temperature (average, maximum, minimum)
- for monthly mean values of precipitation
- at grid-spacing of 0.4425° latitude by 0.4425° longitude.

6.3.2 Vegetation model

The dynamic vegetation model IBIS is designed around a hierarchical, modular structure (Kucharik et al. 2000). IBIS requires a range of input parameters including climatology as well as soil parameters. The main climatology parameters required by IBIS are: monthly minimum, maximum and mean temperature (C), monthly mean precipitation rate (mm/day), monthly mean relative humidity (%), wind speed (m/s) and monthly mean cloudiness (%). The main soil parameter required is the texture of soil (i.e. percentage of sand, silt and clay). The model also requires topography information. Observed climatology is obtained from Climate Research Unit (CRU).

6.3.3. Scenarios of Climate Change and period of assessment

In this report, the future period 2021–2050 under SRES scenario A1B (atmospheric CO_2 concentration of 490 ppm by 2035) is considered. The mid-year for this future period is 2035, and hence we refer to this assessment period as the '2035' scenario. It should be noted that scenario '2035' does not represent the exact year 2035: rather, it refers to the climate averaged over 2021–2050. We compare the results of our 2035 scenario with the "baseline" scenario, which represents the averaged observed climate over the period 1961–91. "Baseline" is also referred to as either the "reference" or "control" case.

6.3.4 Validation of the model

The model has been well-validated for the Indian region (Chaturvedi *et al*., 2010.). Comparison of simulated vegetation cover with the observed vegetation map (Figure 6.2) (Champion and Seth, 1968) shows fair agreement. Many important observed vegetation features are simulated by the model including (1) the placement of the tropical evergreen forest vegetation in the Western Ghats and the North-East; 2) simulation of desert and thorny vegetation types in the western and south central parts, 3) placement of tropical deciduous forests in most of its present day distribution except parts of western Madhya Pradesh where the model simulates savanna and shrublands and 4) presence of temperate evergreen conifer forests in the Himalayas and higher elevations of the North-East.

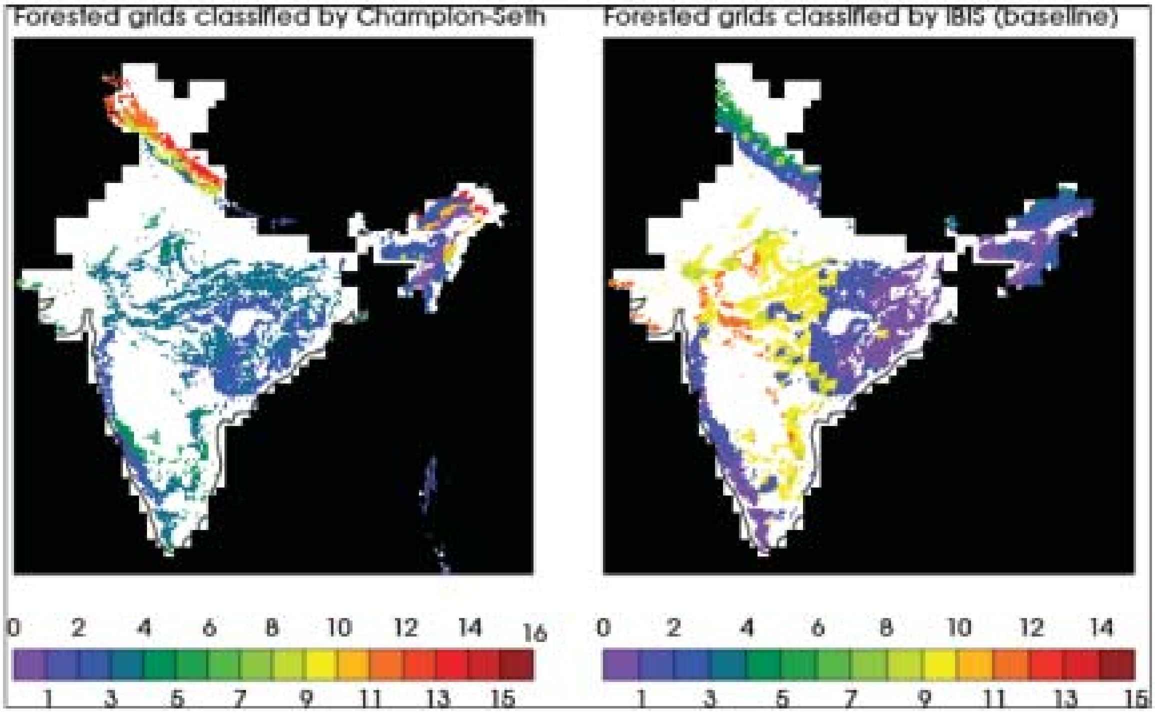
6.4 Impact of climate change on forests

The impacts of climate change are presented for the four eco-sensitive regions selected for the assessment. The impact is assessed with respect to the potential shift in vegetation types or Plant Functional Types and changes in NPP. The results are presented for the forest grids.

6.4.1. Western Ghats

We extracted the grids that lay inside this region of interest (see corresponding figure of the extent of Western Ghats in Chapter 2). The model simulated vegetation as well as grids that undergo vegetation change in this region are shown in Figure 6.3. The entire Western Ghats region is covered by 54 grids, out of which 10 (18%) of them are projected to undergo change. As discussed in previous literature (Ravindranath *et al*., 2006), the forests in areas where IBIS predicts vegetation shift are more vulnerable to climate change. This is because the future climate may not be optimal to the current vegetation in those places. In other words, 18% forested grids in the region are projected to be vulnerable to climate change.

The projection of the NPP for the Western Ghats region is shown in Figure 6.4. The region is projected to have approximately 20% increase in NPP on an



Key: 1.Tropical wet evergreen forests, 2. Tropical semi-evergreen forests, 3. Tropical moist deciduous forest, 4.Tropical dry deciduous forest, 5. Tropical thorny/scrub forests, 6.Tropical dry evergreen forest, 7. Littoral and swampy forest, 8. Subtropical broad-leaved hill forests, 9. Subtropical pine forests, 10.Subtropical dry evergreen forests, 11. Montane wet temperate forests, 12. Himalayan wet/moist temperate forests, 13. Himalayan dry temperate forests, 14. Subalpine forests, 15. Moist alpine forests, 16. Dry alpine forests

Key: 1: Tropical evergreen forest/woodland, 2: Tropical deciduous forest/woodland, 3: Temperate evergreen broadleaf forest/woodland, 4: Temperate evergreen conifer forest/woodland, 5: Temperate deciduous forest/woodland, 6: Boreal evergreen forest/woodland, 7: Boreal deciduous forest/woodland, 8: Mixed forest/woodland, 9: Savanna, 10: Grassland/steppe, 11: Dense shrubland, 12: Open shrubland, 13: Tundra, 14: Desert, 15: Polar desert/rock/ice

Figure 6.2: Model generated (Chaturvedi *et al*, 2010) current vegetation distribution (right panel) compared with observed vegetation distribution (left panel, Champion and Seth, 1968)

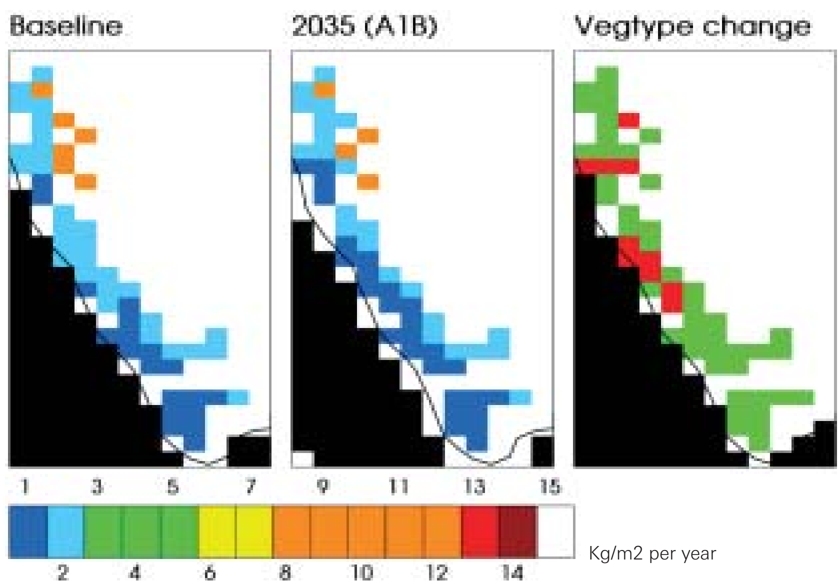


Figure 6.3: Simulated dominant vegetation in the Western Ghats region for the baseline (left panel) and 2035 (middle panel). The grids where a change in vegetation is projected are shown in red in the right panel.

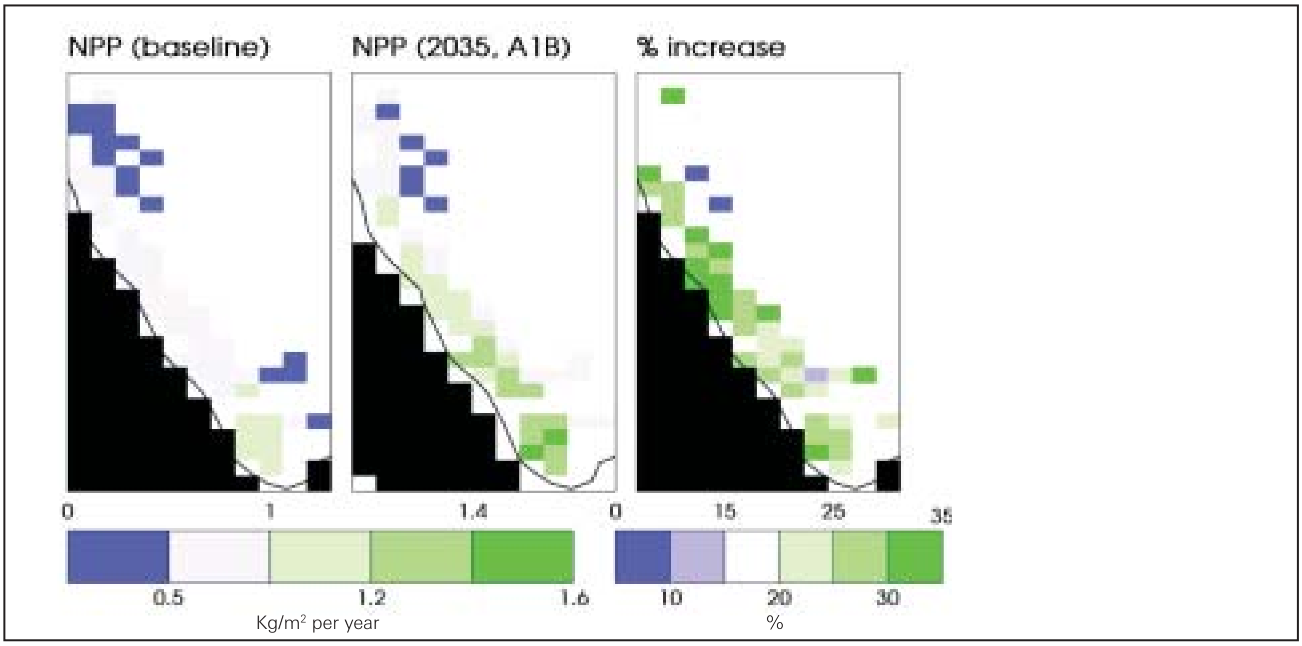


Figure 6.4: Simulated NPP projections in the Western Ghats region for the baseline (left panel) and 2035 (middle panel). The projected percent increase in NPP is shown in the right panel.

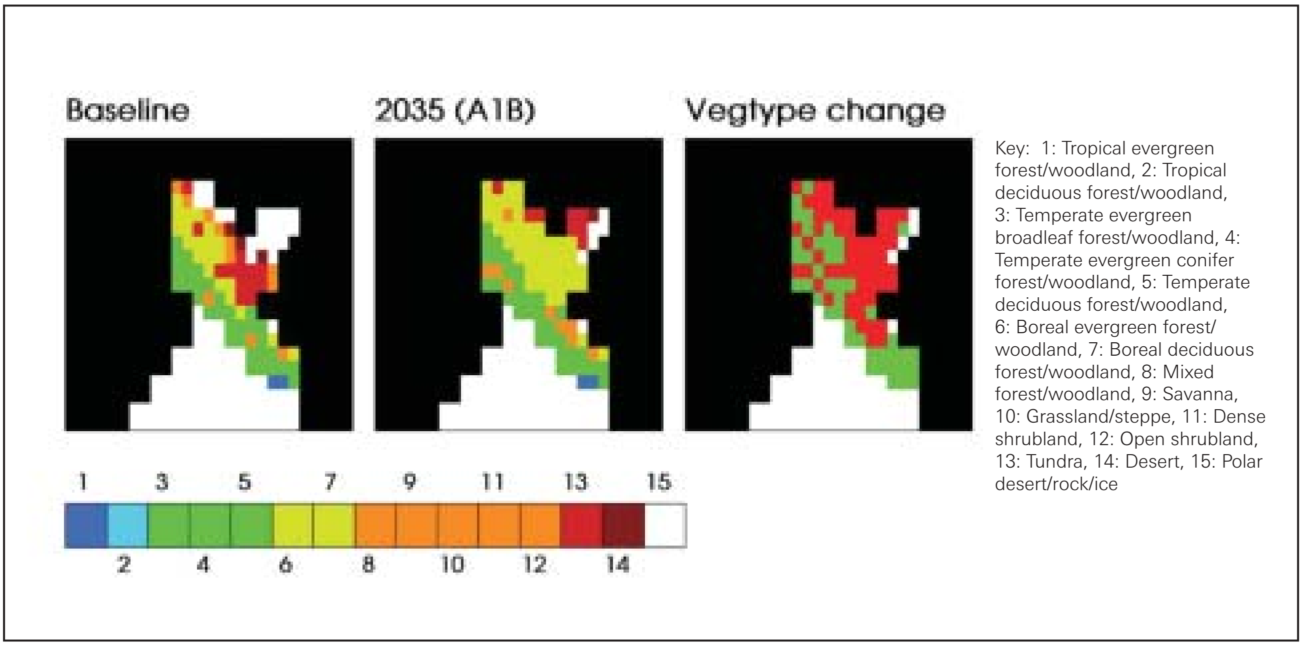


Figure 6.5: Simulated dominant vegetation in the Himalayan region for the baseline (left panel) and 2035 (middle panel). The grids where a change in vegetation is projected are shown in red in the right panel.

average. This may not be realised as the IBIS model does not have representation for nitrogen limitations in soil, changes in frequency of forest fires and pest incidences.

6.4.2 Himalayas

In our study, this region is defined by forests that lie in the states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand. Much of the dense forests of these areas are part of the Himalayan biodiversity hotspot as defined by Conservation International (CI, 2010).

The model simulated vegetation as well as grids that undergo vegetation change for the Himalayan region are shown in Figure 6.5. The entire Himalayan region is covered by 98 IBIS grids, out of which 55 (56%) are projected to undergo change. Thus, over half of

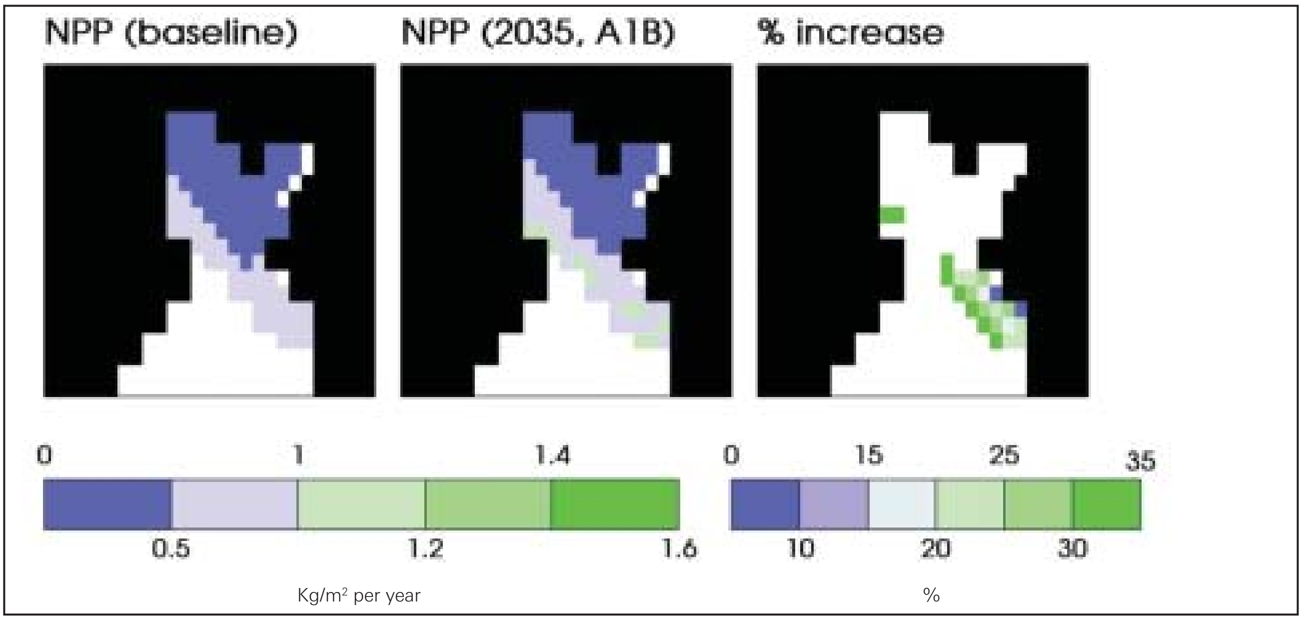


Figure 6.6: Simulated NPP in the Himalayan region, for the baseline (left panel) and 2035 (middle panel). The projected percent increase in NPP is shown in the right panel.

the forests are likely to be adversely impacted in the Himalayan region by 2030's.

Projection of NPP for the Himalayan region is shown in figure 6.6. NPP is projected to increase in the region by about 57% on an average by 2030s

6.4.3 Coastal regions

The coastal region is defined by all districts that lie on the Indian coast (adjoining the sea). We extracted the grids that lay inside this region of interest. The model simulated vegetation as well as grids that undergo vegetation change for the coastal region are shown

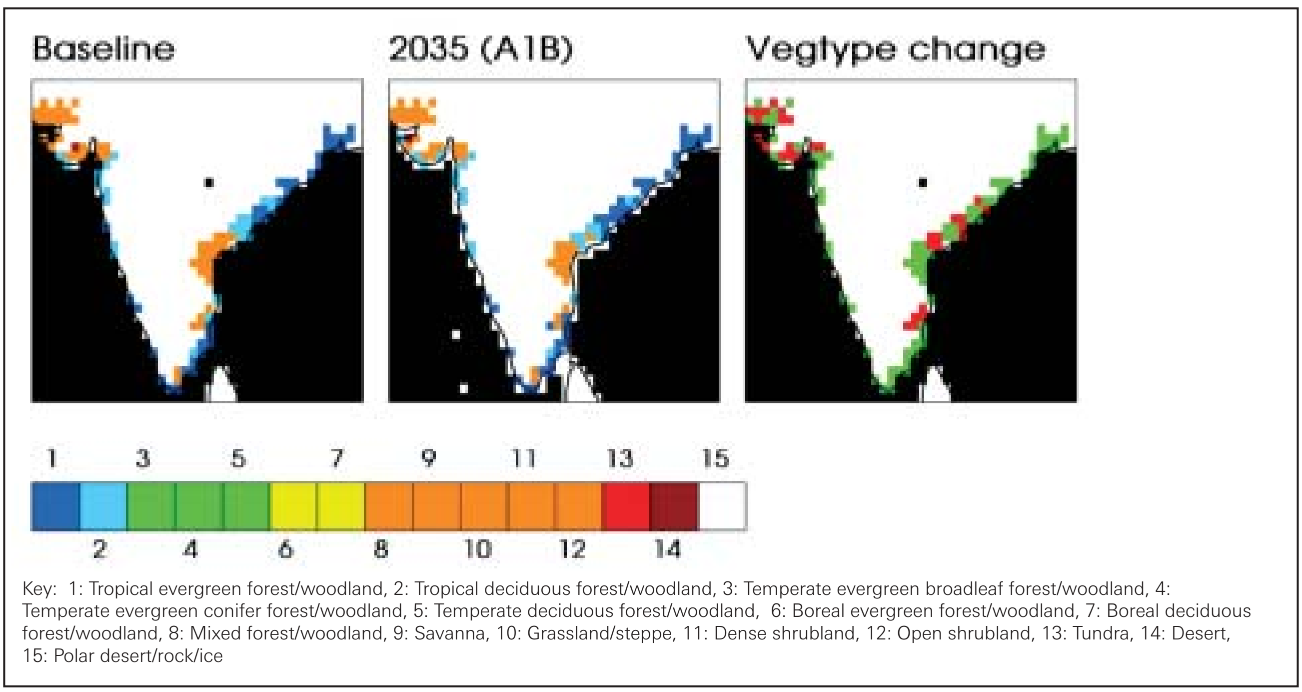


Figure 6.7: Simulated dominant vegetation in the coastal region for the baseline (left panel) and 2035 (middle panel). The grids where a change in vegetation is projected are shown in red in the right panel.

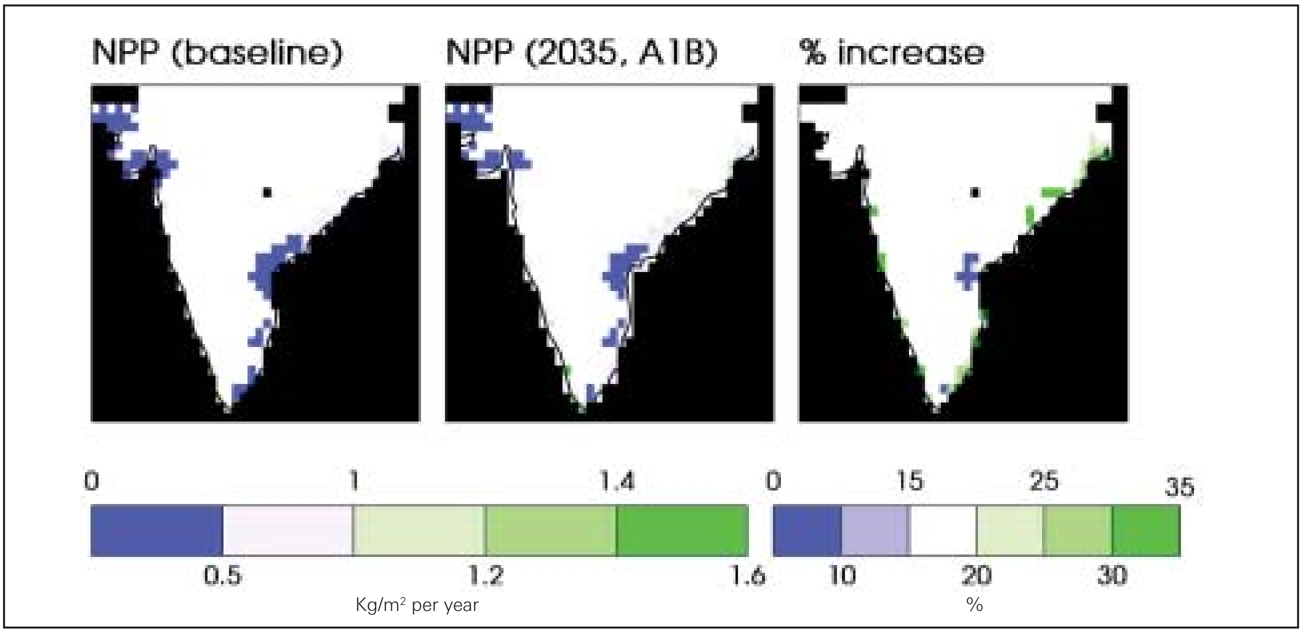
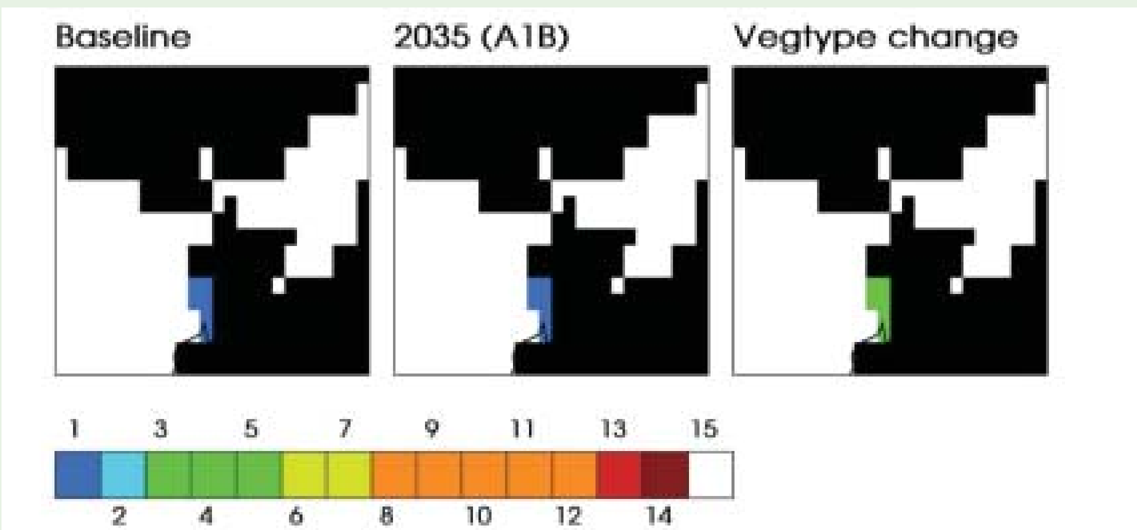


Figure 6.8: Simulated NPP in the coastal region for the baseline (left panel) and 2035 (right panel). The projected percent increase in NPP is shown in the right panel.

Box 6.1: A case study of the Sunderbans:

The Sundarbans (a part of the Indian coast) is a large block of tidal mangrove forests, covering about 10,000 square km (of which about 6,000 square km are in Bangladesh). It became inscribed as a UNESCO world heritage site in 1997. The single-largest threat to the Sunderbans is by projected rise in sea level. But, in this report, we study the effect of projected climate change on this area. The entire Sundarbans is covered by 7 grids, out of which none are projected to undergo change within this short period. Thus vegetation or forest type shift may not be a major threat for the Sundarbans.



Key: 1: Tropical evergreen forest/woodland, 2: Tropical deciduous forest/woodland, 3: Temperate evergreen broadleaf forest/woodland, 4: Temperate evergreen conifer forest/woodland, 5: Temperate deciduous forest/woodland, 6: Boreal evergreen forest/woodland, 7: Boreal deciduous forest/woodland, 8: Mixed forest/woodland, 9: Savanna, 10: Grassland/steppe, 11: Dense shrubland, 12: Open shrubland, 13: Tundra, 14: Desert, 15: Polar desert/rock/ice

Figure: Simulated dominant vegetation in the sunderbans region for the baseline (left panel) and 2035 (middle panel). The grids where a change in vegetation is projected is shown in red in the right panel (no vegetation type change is projected here) in Figure 6.8. The entire coastal region is covered by 96 grids, out of which 29 (30%) of them are projected to undergo change. Forested grids of the Western Ghats are excluded here. Projections of NPP for this region are shown in Figure 6.8. The NPP in the region is projected to increase by 31% on an average.

6.4.4 North-east region

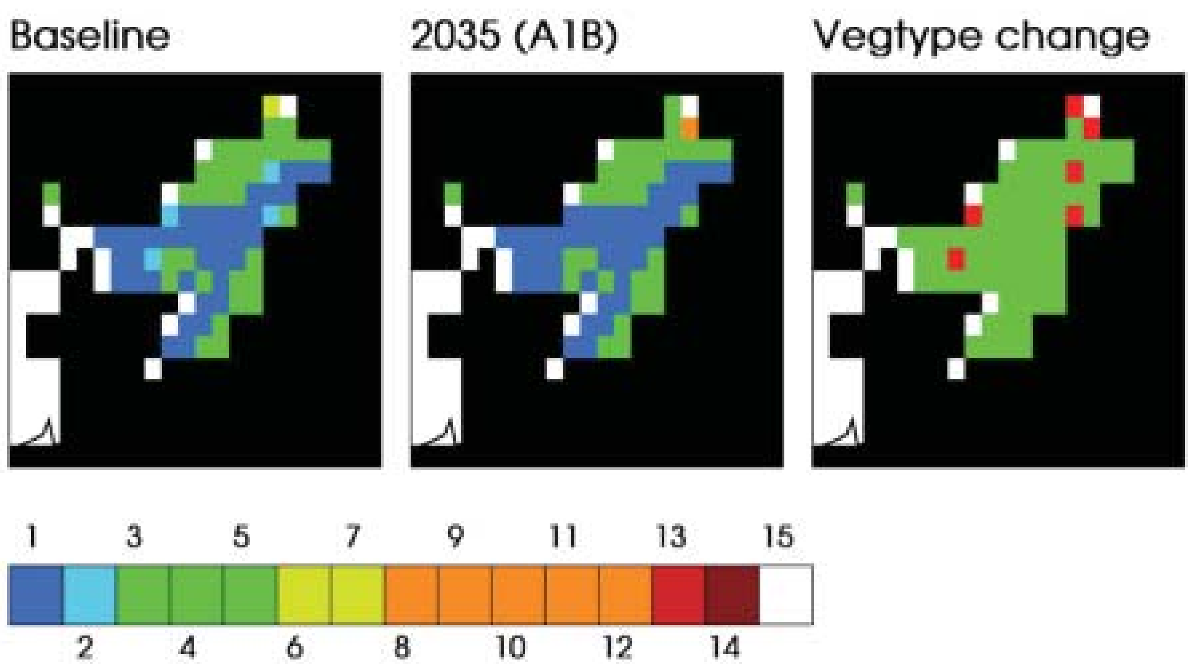
The North-East is defined to include the states of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Tripura and Sikkim. This region is dominated by forestland cover (FSI, 2009). Much of the dense forests of Assam, Nagaland and Arunachal Pradesh are part of the Himalayan biodiversity hotspot as defined by Conservation International (CI, 2010). Because of these reasons, it is essential to conduct scientific studies on the projected impact of climate change on the forests of the North-East.

The model simulated vegetation as well as grids that undergo vegetation change for the North-Eastern region are given in Figure 6.9. In the North-Eastern region only about 8% of (or 6 out of 73) forested grids are projected to undergo change. Projections of NPP for this region are shown in Figure 6.10. The region is projected to witness a 23% increase in NPP on an average.

6.5 Comparison across regions

Table 6.2 shows projections of the percent of grids where vegetation-type change is projected in different regions. From the table, one can infer that the forest ecosystems of the Himalayan eco-region are the most vulnerable to climate change. The coastal regions and Western Ghats are moderately vulnerable to climate change. It is also inferred that forests in the North-Eastern region are projected to be minimally impacted by climate change in the short term.

It can be concluded that forests of the four eco-sensitive regions are vulnerable to projected climate change in the short to medium term, even under a



Key: 1: Tropical evergreen forest/woodland, 2: Tropical deciduous forest/woodland, 3: Temperate evergreen broadleaf forest/woodland, 4: Temperate evergreen conifer forest/woodland, 5: Temperate deciduous forest/woodland, 6: Boreal evergreen forest/woodland, 7: Boreal deciduous forest/woodland, 8: Mixed forest/woodland, 9: Savanna, 10: Grassland/steppe, 11: Dense shrubland, 12: Open shrubland, 13: Tundra, 14: Desert, 15: Polar desert/rock/ice

Figure 6.9: Simulated dominant vegetation in the North-Eastern region, for the baseline (left panel) and 2035 (middle panel). The grids where a change in vegetation is projected are shown in red in the right panel.

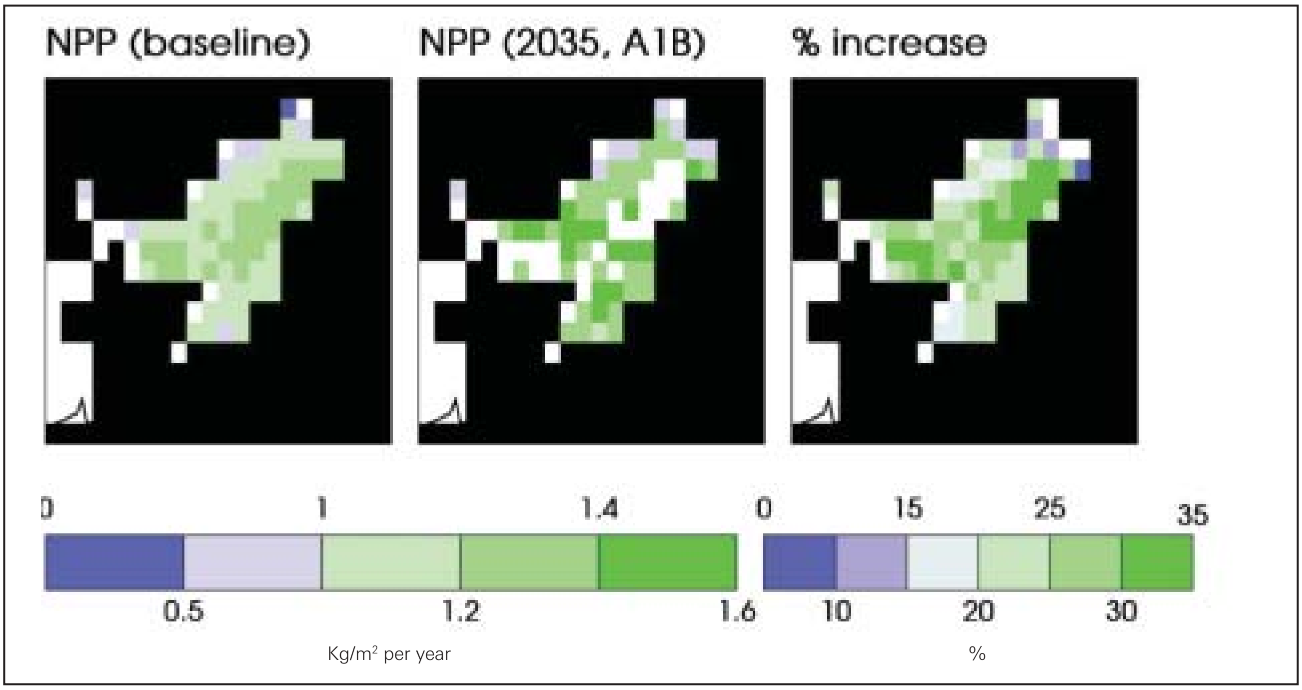


Figure 6.10: NPP projections in the North-Eastern region for the baseline (left panel) and 2035 (middle panel). The projected percent increase in NPP can be seen in the rightmost panel.

Table 6.2: Region-wise projections of the percent of grids where vegetation-type change is expected under A1B climate scenario by 2035.				
Region	Total number of grids	Number of grids projected to change	% projected to change	Remarks
Himalayas	98	55	56.0	Most vulnerable
Coastal region	96	29	30.0	Moderately vulnerable
Western Ghats	54	10	18.0	Moderately vulnerable
North-East	73	6	8.2	Least vulnerable

moderate climate change scenario. The impacts vary from region to region. The impacts and vulnerability could be higher for other climate change scenarios and in the longer period.

It is cautioned that we have made the impact assessment based on a single GCM (HadCM3) and a single regional climate model (PRECIS) for the short to medium term. The magnitude and spatial patterns of climate projections could vary for different GCMs and regional models and in the long term (say by 2100). Therefore, further studies involving downscaled data from multiple GCM ensembles and regional climate model projections are required in the future to increase the confidence in these regional projections.

7

Human Health

7.1 Introduction

Climate plays a key role in propagation of most diseases, impacting either directly or indirectly through interaction with ecological systems (see table 7.1). The direct health impacts can be in the form of heat strokes.Indirect impacts include diarrhoeal risk from water contamination via flooding, or higher risk of mortality from the impact of large-scale loss of livelihoods. Other indirect health impacts can be in terms of deterioration in nutritional health arising due to crop failure, which is caused by droughts and especially by high night temperatures that result in reduced cereal yields. With projected increase in surface temperature, increase in frequency and intensity of extreme events such as increase in night temperatures, increase in number of warm days, extreme heat and heavy precipitation etc. in the future due to anthropogenic causes, human health impacts are likely to escalate with respect to their virulence and spread to hitherto disease-free areas. For example, with increase in average surface temperatures, it is apprehended that windows of transmission for vector-borne diseases will open in areas where they were hitherto closed due to low temperatures.

Though India's overall population health has improved greatly since Independence - its life expectancy has doubled from 32 years in 1947 to 66 years in 2004 - nevertheless, many threats to health and life expectancy still remain. Climate change can further increase the burden of disease, especially amongst the set of population which has a lower capacity to combat the impacts *vis-a -vis* their access to medical facilities. Research on health impacts of climate change in India is at an early stage and the studies that are available are for malaria transmission projections. Large-scale collaborative work between public health institutes, meteorologists, earth scientists and economists is needed at the national level to develop climate-health impact models that will project future health effects. Keeping this limitation in view, the present assessment first makes an attempt to takestock of the typical climate parameters affecting public health and the climate-sensitive diseases that may proliferate due to climate change in the various regions that are under consideration in the present assessment.

This chapter focuses on vector-borne diseases, especially malaria, which is climate sensitive as the development of the parasite takes place in a mosquito (extrinsic incubation period). Being a cold-blooded creature, the mosquito is sensitive to climatic conditions such as temperature, rainfall, relative humidity and wind velocity. There is evidence of increasing malaria prevalence throughout India (NVBDCP, 2007). This is thought to stem partially from economic development (which changes vector dynamics and human migration patterns) and partially from climate change, where recent models predict the spread of malaria into new regions in the 2050's and 2080's (Bhattacharya *et al*., 2006). Any spread of malaria in India will expose large populations to the disease. (Hays *et al*., 2004). A recent estimate suggests an annual incidence of malaria as high as 83 million cases per year (Korenromp, 2005).

However, long term projections are of little value in developing preparedness plans to address the issue, as, in addition to climate parameters, the transmission dynamics of malaria is affected by other local factors like agricultural practices, urbanization, water scarcity, socio-economics etc. which vary from region to region and cannot be projected for a long timeline beyond 30 years. In view of this, the present assessment undertakes a near-future assessment for the 2030's, of the likely projection of malaria in the very eco-sensitive regions such as the Himalayas, North-Eastern region, Western Ghats and coastal areas of India.

7.2 Public health in India and Climate Change

Public health depends on availability of enough food, safe drinking water, a decent home protection against disasters, a reasonable income and good social and community relations (WHO, 2003). Climate change is projected to affect all of those factors (Rahman A, 2008). This could include direct health impacts such as heatstroke and indirect impacts such as increased diarrhoea risk from water contamination via flooding, or higher risk of mortality from the impact of large-scale loss of livelihoods. Major nutritional health impacts are projected via crop failure caused by drought, loss of rain-dependent non-irrigated crops and especially from high night temperatures reducing cereal yields. These impacts are projected to adversely affect a very large number of people because a significant portion of India's GDP derives from agriculture (World Bank, 2010).

The projected rise in sea level, together with the increase in storms around India's coastal regions is projected to increase mortality due to drowning and water-borne diseases.Damage to agriculture and livelihoods (crop losses, loss of coastal trade, agriculture and industry), could increase poverty and malnutrition. Population displacement from these impacts and from drought could adversely affect social cohesion and health. It could also increase India's urbanization still further, with associated risks of mortality from non-communicable chronic disease.

However, positive health impacts are also likely. It is expected that increase in rainfall could benefit the populations of some regions by improving crop yield and survival in areas where rain is currently scarce, leading to better food availability. However, it could also cause floods in other areas, which may increase morbidity and mortality risk from drowning, from malaria because of more persistent standing water, and from water-borne diseases due to contamination of fresh water supplies. Table 7.1 summarises the climate parameters, the resources that it impacts and the consequent health impacts that may arise due to climate change in various regions in India.

7.3 Climate change and malaria

7.3.1 Inter-relationship between climate, mosquito vector and malaria transmission

The epidemiological triangle of malaria involves 1) man as host, 2) Plasmodium, the causative organism and 3) anopheline mosquito vector as transmitting agent with the interaction of environment playing a key role. The parasite has to complete its life cycle in a female mosquito (extrinsic incubation). As mosquitoes are cold-blooded creatures, their life cycle and the development of the parasite in their body are affected by climatic conditions like temperature, rainfall, relative humidity, frost and wind velocity etc.

The role of climatic factors has been studied extensively in the epidemiology of malaria due to its global public health importance. The minimum temperature required for development of *P. vivax* parasite in anopheline mosquitoes is 14.5 –16.5^{0}C while for *P. falciparum* it is 16.5 –18^{0}C (Martens *et al*. 1995). At 16^{0}C it will take 55 days for the *P. vivax* to complete sporogony, while at 28^{0}C, the process can be completed in 7 days, and at 18^{0}C it will take 29 days (WHO 1975). The duration of sporogony in Anopheles mosquitoes decreases with increase in temperature from 20 to 25^{0}C (Table 7.2).

From 32^{0}C to 39^{0}C, there is high mortality in mosquitoes (Martens, 1997) and at 40^{0}C, their daily survival becomes zero (Martens, 1997). The interplay between temperature and mosquitoes has recently been reviewed by Dhiman *et al*.(2008). At increased temperatures, the rate of digestion of blood meal increases. This in turn accelerates the ovarian development, egg laying, reduction in duration of the gonotrophic cycle and higher frequency of feeding on hosts, thus increasing the probability of transmission (Martens *et al*., 1995). Reduction in duration of the gonotrophic cycle and the sporogony are related with increased rate of transmission (Macdonald 1957; Detinova 1962; Molineaux 1988). Two entomological indices i.e. vectoral capacity and Entomological Inoculation Rates (EIR) are directly affected by the density of vectors in relation to number of humans in a given local situation, daily survival rate, feeding rate of vector mosquitoes and the duration of the sporogonic cycle. These are sensitive to changes in environmental temperature (Lindsey and Birley, 1996; Martens 1998; Martens *et al*. 1999) and reduce with increase in temperature.

Table7.2 Average duration of sporogony of human Plasmodium at different temperature

Parasite species	No of days required for sporogony at different temperatures	
	20^0 C	25^0 C
P. falciparum	22-23	12-14
P. vivax	16-17	9-10
P. malariae	30-35	23-24
P. ovale	not known	15-16
(Adapted from WHO, 1975)		

Table7.1: Potential impacts of climate change on health in various regions in India			
Regions	**Climate parameters**	**Probable impacts on ecosystems**	**Emerging Impacts on health**
Himalayan Region	• Increase in temperature by 0.9°C to 2.6°C by 2030s with respect to 1970s • Increase in intensity by 2-12% in 2030s with respect to 1970s	• Increase in Forest fires • Increased glacier melt	• Loss in forest litter & wood used for heating purposes in the cold season – morbidity due to extreme cold • Flash floods leading to large scale landslides and hence loss of agriculture area affecting food security • Increase in incidence of malaria due to opening up of transmission windows at higher latitudes • Increase in morbidity due to unprecedented rise in temperature
Western Ghats	• Temperature may rise by 1.7° to 1.8°C in 2030s wrt 1970s • Northern areas to experience increase in rainfall while southern areas will remain unaffected • Decrease in rainfall over tropical montane cloud forests of Gavi, Periyar, High Ways and Venniyar	• Adverse effect on cash crops such as coffee and tea. • Large scale flooding and soil erosion as a result of increased rainfall.	• Increase in morbidity and mortality due to flooding • Reduction in employment due to impact on cash crops leading to negative impacts on health and life expectancy.
Coastal Zone	• In the west coast temperature may rise by 1.7° to 1.8°C in 2030s wrt 1970s • In the east coast the surface annual air temperature is set to rise by 1.6 to 2.1°C. • Increase in sea surface temperatures • Increase in rain fall intensity • Rising sea levels • Increase in intensity of cyclones and storm surges, especially in the east coast	• Decrease in coconut production • Increase in salinity due to incursion of coastal waters due to rise in sea level affecting habitats, agriculture and availability of fresh water for drinking • Changes in distribution and productivity of marine as well as fresh water fisheries • Submergence of habitats and special ecosystems such as the mangroves	• Increase in morbidity and mortality due to increase in water borne diseases associated with cholera epidemics and increase in salinity of water • Loss of livelihoods due to effect on agriculture, tourism, fisheries and hence impacting health and life expectancy • Forced migration, loss of housing and drowning will result due to sea-level rise.
North-East India	• Surface air temperature is projected to increase between 0.8 to 2.1°C • Decrease in winter precipitation • Increase in intensity of summer precipitation • Increase in night-time temperatures	• Cereal production likely to be benefited, but yield of paddy will be negatively affected due to projected increase of night-time temperature. • Tea plantations to be affected due to soil erosion • Increase runoff and land slides during summer precipitation • Decrease in yields in winters	• Loss of employment and adverse effect on health • Expected to face an increase in incidence of Malaria due to temperature and humidity increase.

7.3.2 Sensitivity and vulnerabilities of current climate on Malaria vector and disease in India

Malaria is a climate-sensitive disease and its transmission dynamics are greatly affected by climatic conditions. The distribution map of India reveals that the highest endemicity is confined to Orissa, north-eastern states, Jharkhand and Chhattisgarh while the lowest is in Rajasthan, Uttar Pradesh, Himachal and Uttarakhand states. The reason of highest and lowest endemicity is linked with malaria stability or instability. In stable malaria, transmission continues almost throughout the year as the temperature, rainfall and resultant relative humidity are suitable for all the 12 months. The states having unstable malaria experience winters during which transmission does not take place. Areas with unstable malaria are epidemic prone depending on favourable conditions provided by unusually high rains at the threshold of the transmission season.

Distribution of malaria and its endemicity, is the reflection of suitable climatic conditions and availability of mosquito vectors in different parts of the country

7.4 Methodology for determination of transmission windows of malaria

Based on the data extracted from the PRECIS model, and exported to excel sheets, Transmission Windows(TW) were determined and categorised. Transmission windows of malaria are determined, keeping in view the lower cut-off temperature as 18^0C and upper cut-off as 32^0C (Craig *et al* 1999) and RH from >55%. (Bruce Chwatt, 1980). Keeping in view the climatic suitability for the number of months transmission may remain open, transmission windows were categorised as follows:

- Category I: not a single month is open
- Category II: 1-3 months open
- Category III: 4-6 months open
- Category IV: 7-9 months open
- Category V:10-12 months are open continuously for malaria transmission

Transmission of malaria is possible if TW is open for 3 months continuously, therefore, for analyses at the regional level, a new category i.e. TW open for 1-2 month was also created to differentiate it from 3 continuous months. TW open for 6 months or more indicate stability of malaria transmission. Transmission windows have been determined based on temperature alone as well as with combination of temperature and RH and for Baseline (1960-1990) and for the projection year 2030s. The inputs were fed in ArcGIS 9.3 software for generation of region/area-wise maps with district boundaries.

7.5 Projections of Malaria transmission at national level

Based on minimum required temperature for ensuing transmission of malaria, a district-wise map of India was generated to show the distribution of different categories of transmission windows under baseline and by the year 2030s (Fig 7.1). The climate projections for 2030s are derived from the PRECIS, regional model developed by the Hadley centre and forced by the GHG emission scenarios arising out of the IPCC defined A1B socio-economic scenario for the future (see chapter 3 for details of the climate scenario). Data for 42 pixels mainly from northern part of India were not available. It is seen that in the regions below the Vindhyas, the transmission window is open for 10-12 months in the baseline scenario. In the 2030's with increase in temperature, the regional spread of 10-12 month category shrinks and remains confined to the Western Ghat region and some districts adjoining the ghats. In the region, above the Vindhyas and below the Himalayan region, extending from Rajasthan in the west to West Bengal in the east, the transmission windows are open for 7-9 months in the baseline scenario and continue to do so in the 2030's with increase in temperature, except in the north-western parts of Rajasthan where the windows tend to open only for 4-6 months in the 2030's. Also in the 2030's in the North-Eastern region and upper reaches of the Himalayan region, the windows tend to open for 7-9 to 10-12 months with respect to baseline scenario. The transmission windows in some parts of the Himalayan region i.e. Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh however, continue to have only 0-2 months open for transmission even in the 2030's.

When the Transmission windows were determined based on temperature and RH combined, categories IV and V of open transmission are reduced to a greater extent remaining confined to the Southern parts of India. The projected scenario (Fig. 7.2) shows slight reductions in the extent of category V while the same increasing in north-eastern parts of India. In central and northern India, mainly category III, i.e. 4-6 months, open TWs are seen in both the scenarios.

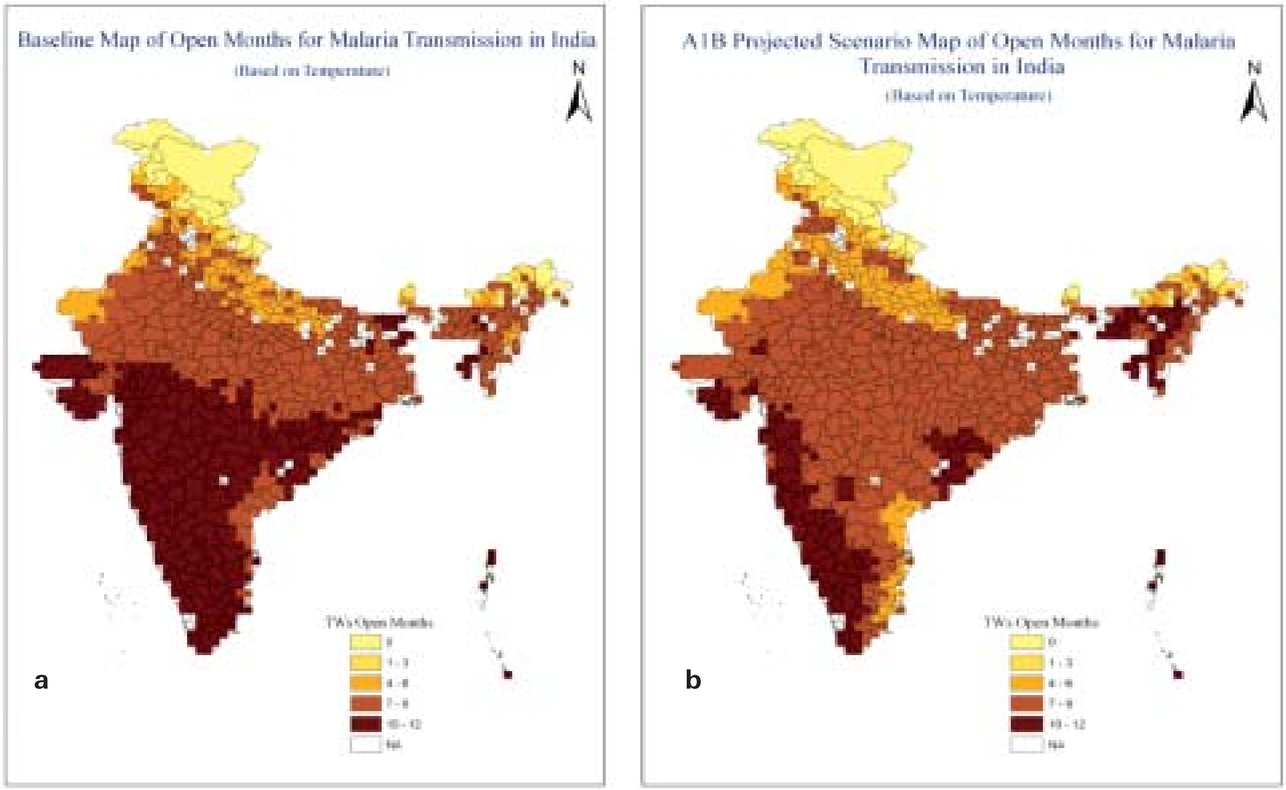


Fig7.1: Transmission Window of malaria based on Temperature. (a) Baseline (1960-1990), and (b) by the year 2030.

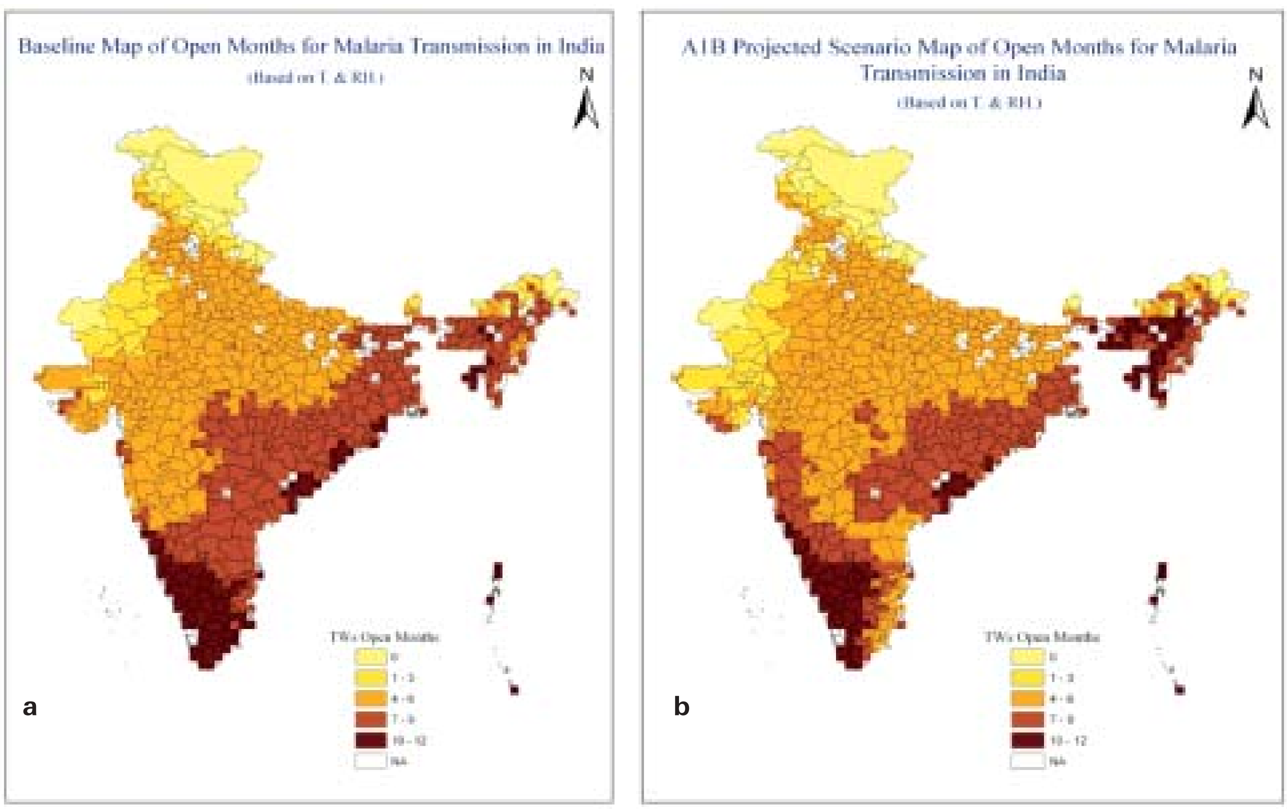


Fig7.2: Transmission Window of malaria based on minimum required Temperature and RH – (a) Baseline (1960-1990) and (b) for 2030s.

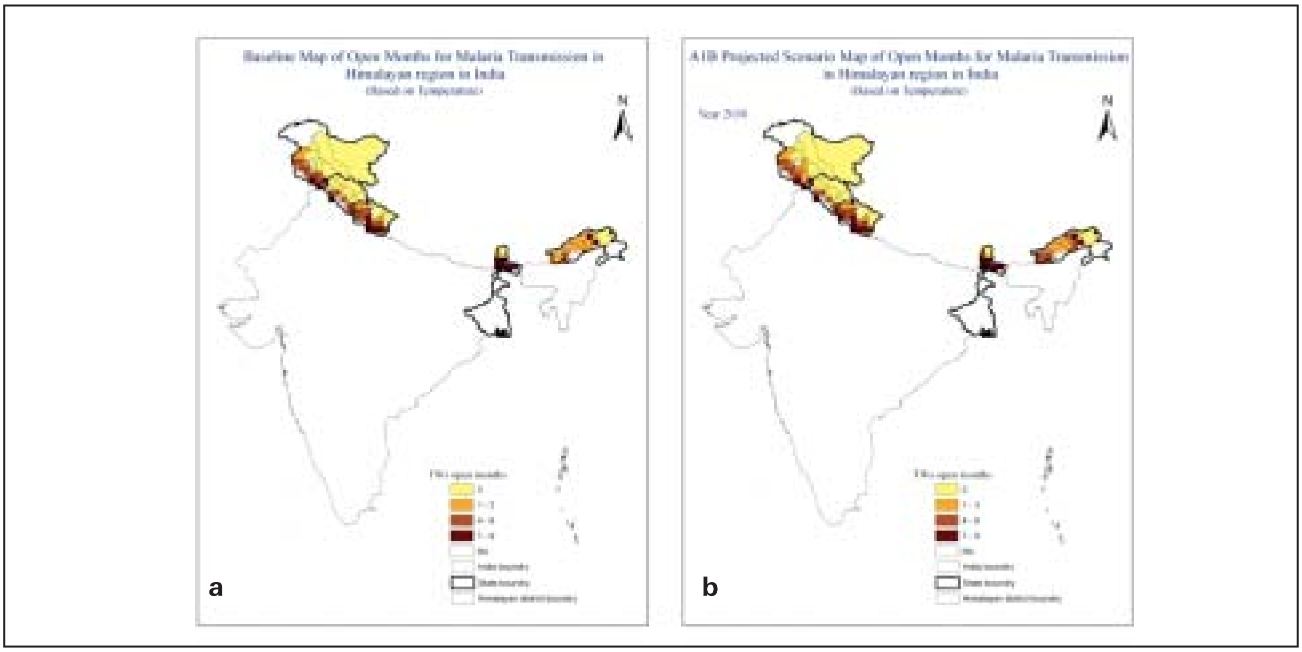


Fig7.3: TWs of malaria based on minimum required T under (a) baseline and (b) projected scenario (2030) in the Himalayan Region.

Table – 7.3 TWs of Malaria in Himalayan region based on temperature (A1B Baseline and projected scenario by 2030)									
State	**No. of Districts**	**No. of months open for Malaria Transmission**							
			0	**1-2**	**3**	**4-6**	**7-9**	**10-12**	**Data not available**
Jammu & Kashmir	15	Baseline	7	0	1	4	2	0	1
		Projection	6	1	2	3	2	0	1
Himanchal Pradesh	12	Baseline	4	0	0	5	1	0	2
		Projection	4	0	0	5	1	0	2
Uttarakhand	13	Baseline	2	2	0	5	3	0	1
		Projection	2	1	1	4	4	0	1
Sikkim	4	Baseline	1	0	1	1	0	0	1
		Projection	1	0	0	2	0	0	1
Arunanchal Pradesh	9	Baseline	3	2	2	1	1	0	0
		Projection	3	1	1	3	1	0	0
West Bengal	2	Baseline	0	0	0	0	2	0	0
		Projection	0	0	0	0	2	0	0
6	**55**	**Baseline**	**17**	**4**	**4**	**16**	**9**	**0**	**5**
		Projection	**16**	**3**	**4**	**17**	**10**	**0**	**5**

7.6 Regional projection scenarios

7.6.1 Himalayan region

In this assessment, 55 districts in the states of Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, West Bengal and Arunachal Pradesh have been considered in the Himalayan region. Using the temperature criteria for determining the transmission windows (see Fig 7.3), 2 districts show an opening in transmission windows for the period 0-3 months in Jammu & Kashmir in projected scenario. In Uttarakhand also, one district is set to have an opening of TW for 3 months. In Sikkim and Arunachal Pradesh, the transmission windows are set to increase from 3 months in the baseline scenario to 4-6 months

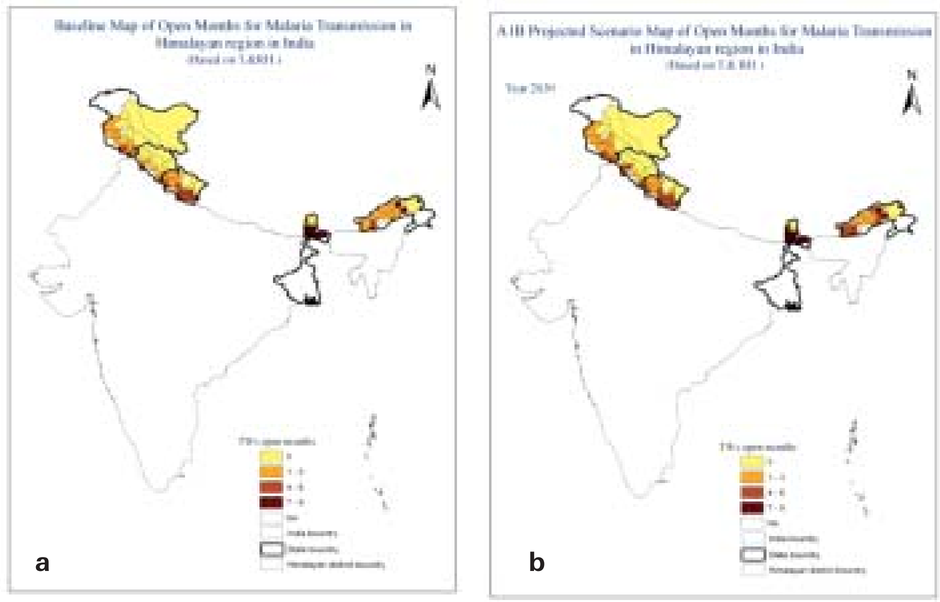


Fig7.4: TWs of malaria based on minimum required T and RH under (a) baseline and (b) projected scenario (2030) in the Himalayan Region.

Table – 7.4 TWs of Malaria based on T and RH in Himalayan region (A1B Baseline and projected scenario by 2030)

State	No. of Districts	No. of months open for Malaria Transmission							
			0	1-2	3	4-6	7-9	10-12	Data not available
Jammu & Kashmir	15	Baseline	7	1	4	2	0	0	1
		Projection	6	3	3	2	0	0	1
Himanchal Pradesh	12	Baseline	4	0	3	3	0	0	2
		Projection	4	0	2	4	0	0	2
Uttarakhand	13	Baseline	3	1	1	7	0	0	1
		Projection	2	2	1	7	0	0	1
Sikkim	4	Baseline	1	0	1	1	0	0	1
		Projection	1	0	0	2	0	0	1
Arunanchal Pradesh	9	Baseline	3	2	2	1	1	0	0
		Projection	3	1	1	3	1	0	0
West Bengal	2	Baseline	0	0	0	0	2	0	0
		Projection	0	0	0	0	2	0	0
6	**55**	**Baseline**	**18**	**4**	**11**	**14**	**3**	**0**	**5**
		Projection	**16**	**6**	**7**	**18**	**3**	**0**	**5**

in the 2030's (Table 7.3). There is no district, which has transmission windows open for 10-12 months. In Jammu & Kashmir and West Bengal there is no change in transmission windows under projected scenario with respect to baseline. When transmission windows were determined in combination with relative humidity, transmission windows are not open beyond 6 months (see Fig 7.4 and Table 7.4).

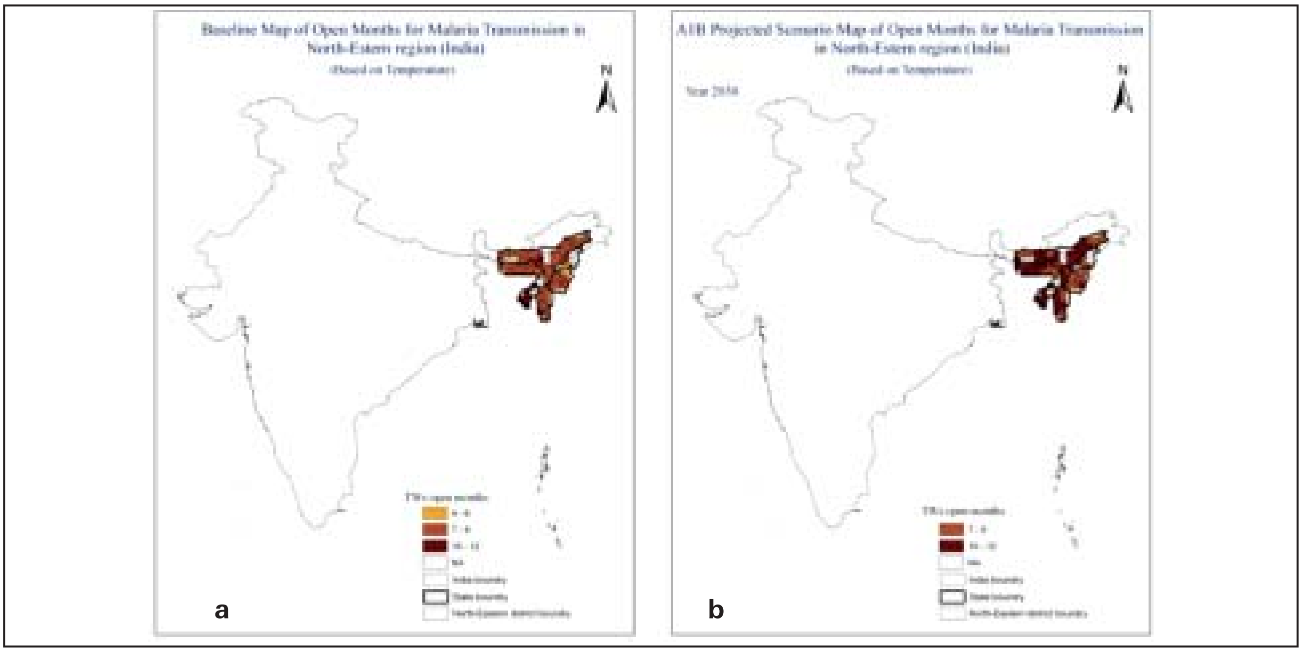


Fig7.5: TWs of malaria based on minimum required T under (a) baseline and (b) projected scenario (2030) in the North Eastern Region.

Table -7.5 TWs of Malaria in North-Eastern region based on temperature (A1B Baseline and projected scenario by 2030)									
State	**No. of Districts**	**No. of months open for Malaria Transmission**							
			0	**1-2**	**3**	**4-6**	**7-9**	**10-12**	**Data not available**
Assam	23	Baseline	0	0	0	0	18	1	4
		Projection	0	0	0	0	5	14	4
Mizoram	8	Baseline	0	0	0	0	6	1	1
		Projection	0	0	0	0	3	4	1
Manipur	9	Baseline	0	0	0	1	6	0	2
		Projection	0	0	0	0	6	1	2
Meghalaya	7	Baseline	0	0	0	0	7	0	0
		Projection	0	0	0	0	3	4	0
Nagaland	8	Baseline	0	0	0	1	4	0	3
		Projection	0	0	0	0	5	0	3
Tripura	4	Baseline	0	0	0	0	0	3	1
		Projection	0	0	0	0	0	3	1
6	**59**	**Baseline**	**0**	**0**	**0**	**2**	**41**	**5**	**11**
		Projection	**0**	**0**	**0**	**0**	**22**	**26**	**11**

7.6.2 North-Eastern region

In this assessment, 59 districts in 6 states, namely Assam, Meghalaya, Mizoram, Manipur, Tripura and Nagaland have been included. The states of Arunachal Pradesh and Sikkim have been considered in the Himalayan region. Using only the temperature criteria for defining transmission, the baseline scenario indicate that only for southern parts of Tripura, the transmission windows are open for 10-12 months. In the rest of the region, the transmission windows are open for 7-9 months and only in Mizoram, some districts have the transmission window open for only 4-6 months (Fig 7.5a and Table 7.5.). In the 2030's, however, with increase in temperature, majority

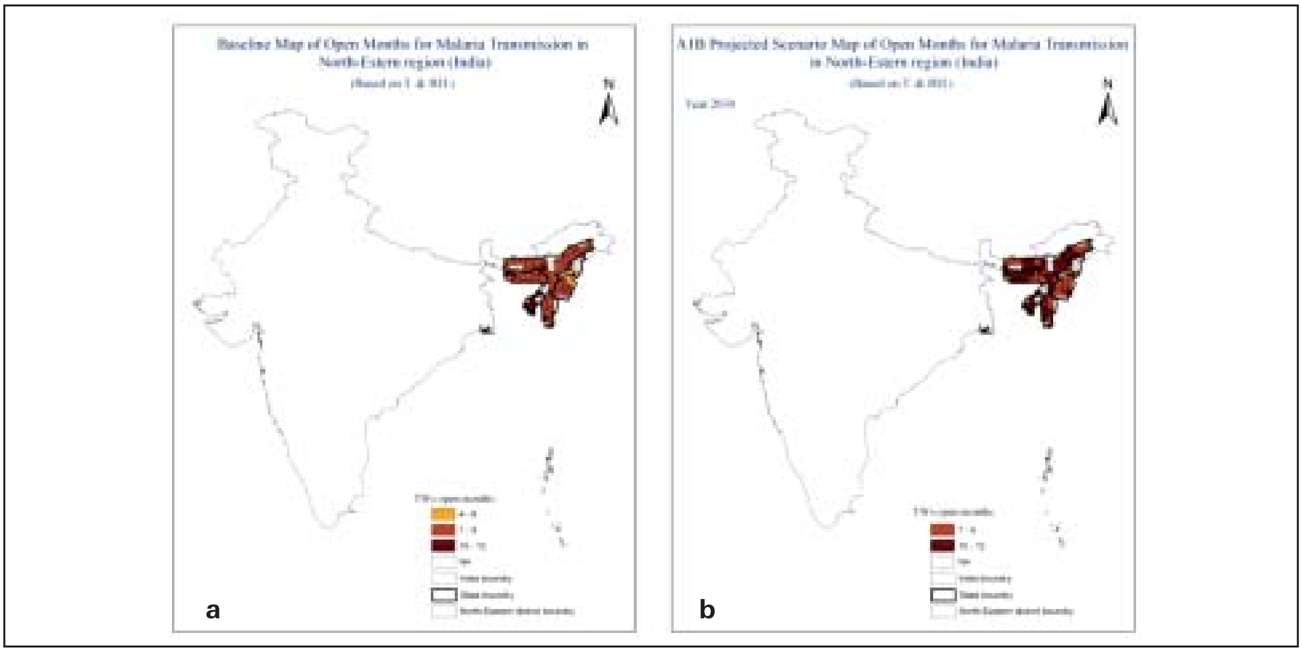


Fig7.6: TWs of malaria based on minimum required T and RH (a) baseline and (b) projected scenario (2030) in the North-Eastern Region.

Table 7.6 TWs of Malaria in North-Eastern region based on temperature and RH (A1B Baseline and projected scenario by 2030)

State	No. of Districts	No. of months open for Malaria Transmission							
			0	1-2	3	4-6	7-9	10-12	Data not available
Assam	23	Baseline	0	0	0	0	17	2	4
		Projection	0	0	0	0	5	14	4
Mizoram	8	Baseline	0	0	0	0	6	1	1
		Projection	0	0	0	0	3	4	1
Manipur	9	Baseline	0	0	0	1	6	0	2
		Projection	0	0	0	0	6	1	2
Meghalaya	7	Baseline	0	0	0	0	6	1	0
		Projection	0	0	0	0	3	4	0
Nagaland	8	Baseline	0	0	0	1	4	0	3
		Projection	0	0	0	0	5	0	3
Tripura	4	Baseline	0	0	0	0	0	3	1
		Projection	0	0	0	0	0	3	3
6	**59**	**Baseline**	**0**	**0**	**0**	**2**	**39**	**7**	**11**
		Projection	**0**	**0**	**0**	**0**	**22**	**26**	**11**

of the districts in this region have transmission windows open for 10-12 months, and very few have transmission windows open for 7-9 months, indicating more stability of malaria transmission in these states (see Fig7.5b). When the assessment is made for transmission windows that combine temperature and relative humidity both, the projections are similar (Fig 7.6b and Table 7.6).

7.6.3 Western Ghats

In this region, 30 districts in the states of Maharashtra, Karnataka, Kerala and Gujarat have been assessed. Here the transmission windows are open for 10-12 months and continue to do so in the 2030's when transmission windows are determined on the basis of

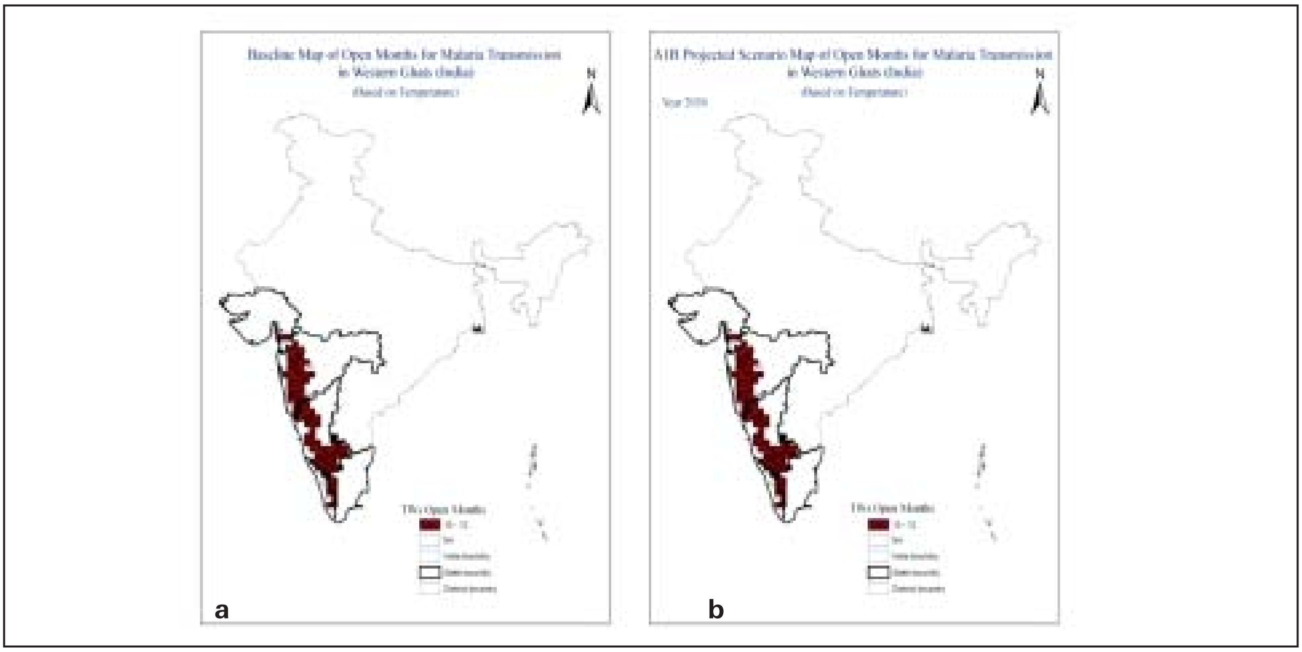


Fig7.7: TWs of malaria based on minimum required T (a) baseline and (b) projected scenario (2030) in the Western Ghats.

Table 7.7 TWs of Malaria in Western Ghats based on temperature (A1B Baseline and projected scenario by 2030)									
State	**No. of Districts**	**No. of months open for Malaria Transmission**							
			0	**1-2**	**3**	**4-6**	**7-9**	**10-12**	**Data not available**
Gujarat	2	Baseline	0	0	0	0	0	1	1
		Projection	0	0	0	0	0	1	1
Maharashtra	6	Baseline	0	0	0	0	0	6	0
		Projection	0	0	0	0	0	6	0
Karnataka	15	Baseline	0	0	0	0	0	15	0
		Projection	0	0	0	0	0	15	0
Kerala	5	Baseline	0	0	0	0	0	4	1
		Projection	0	0	0	0	0	4	1
Tamil Nadu	2	Baseline	0	0	0	0	0	2	0
		Projection	0	0	0	0	0	2	0
5	**30**	**Baseline**	**0**	**0**	**0**	**0**	0	**28**	**2**
		Projection	**0**	**0**	**0**	**0**	0	**28**	**2**

temperature only (compare panel a and b of Fig 7.9 showing baseline and projected scenario for 2030's respectively and Table 7.7). When transmission windows are determined in combination of temperature and relative humidity requirements for malaria transmission, for the base year, in the northern parts of western ghats, the transmission windows are open in 25% of the districts for 4-6 months, and 180% of the northern districts in western ghats have transmission windows open for 7-9 months. In the southern parts of the western ghat region, the transmission windows still open for the entire 10-12 months. In the projected scenario for 2030's, the duration of the transmission windows in the southern part of the western ghat remains the same, but in Maharashtra 50% of the districts show increase in open months of transmission windows from 4-6 months to 7-9 months (Fig7.8 and Table 7.8). If we compare the existing transmission of malaria in Gujarat and Karnataka, transmission continues for more than 7-9 months.

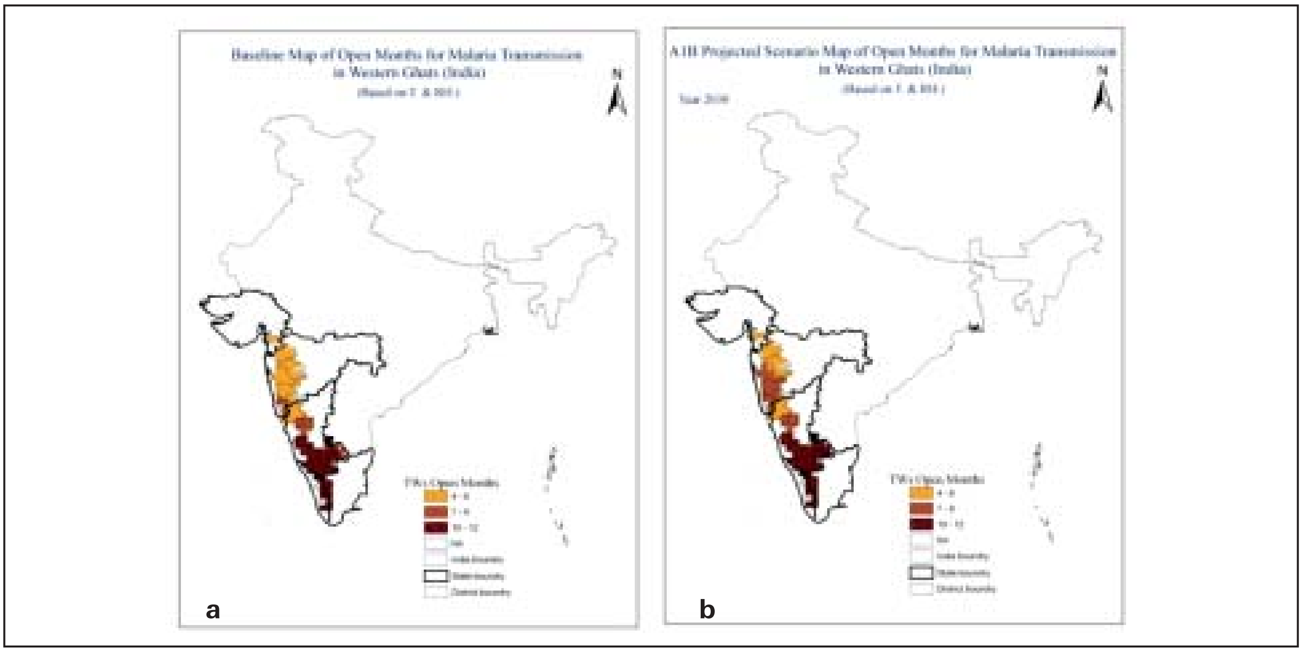


Fig7.8: TWs of malaria based on minimum required T and RH (a) baseline and (b) projected scenario (2030) in the Western Ghats.

Table 7.8 TWs of Malaria in Western Ghats based on minimum required temperature and RH (A1B Baseline and projected scenario by 2030)									
State	**No. of Districts**	**No. of months open for Malaria Transmission**							
			0	**1-2**	**3**	**4-6**	**7-9**	**10-12**	**Data not available**
Gujarat	2	Baseline	0	0	0	1	0	0	1
		Projection	0	0	0	1	0	0	1
Maharashtra	6	Baseline	0	0	0	5	1	0	0
		Projection	0	0	0	0	6	0	0
Karnataka	15	Baseline	0	0	0	1	4	10	0
		Projection	0	0	0	1	3	11	0
Kerala	5	Baseline	0	0	0	0	0	4	1
		Projection	0	0	0	0	0	4	1
Tamil Nadu	2	Baseline	0	0	0	0	0	2	0
		Projection	0	0	0	0	0	2	0
5	**30**	**Baseline**	**0**	**0**	**0**	**7**	**5**	**16**	**2**
		Projection	**0**	**0**	**0**	**2**	**9**	**17**	**2**

7.6.4 Coastal areas

This assessment includes 71 districts in 12 states. Climate data for Daman & Diu, Lakshadweep and Pondicherry were not available. In this region, malaria occurs for 4 to 12 months. Using only the temperature as criteria for determination of transmission windows of malaria, it is seen that in the baseline scenario, in the districts of Andaman & Nicobar Islands, Maharashtra, Dadra & Nagar Haveli, Goa, Karnataka and Kerala, the transmission windows are open for 10-12 months and continue to do so even in the 2030's (see Fig 7.9a and b and Table 7.9). There is reduction in months of transmission of malaria in 7-9 and 10-12 months categories in some districts of Gujarat, Tamil Nadu, Orissa and West Bengal due to increase in temperature by the year 2030. In the southern coastal districts of Andhra Pradesh and northern coastal districts of Tamil Nadu, the transmission windows are open only for 4-6 months in 2030's, with respect to 7-9 months in the baseline scenario. Similar changes are seen along the coastline when transmission windows are determined

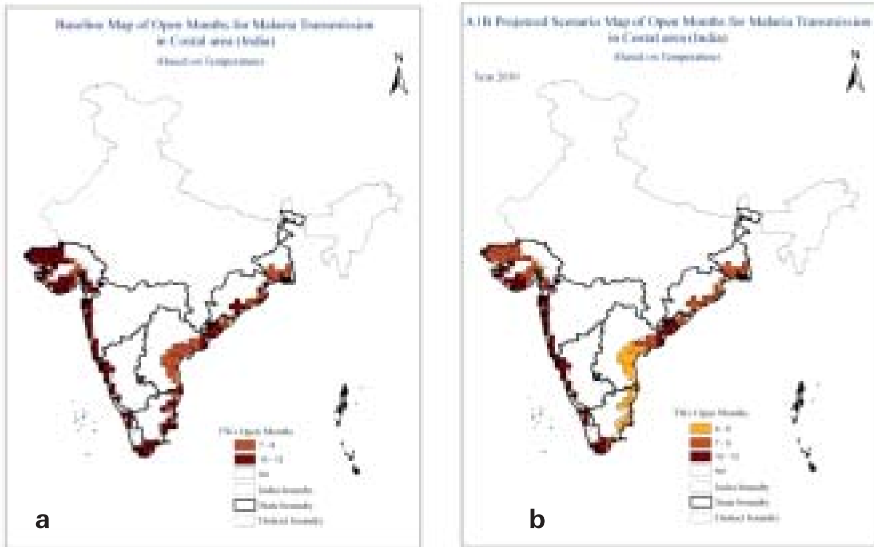


Fig 7.9 TWs of malaria in coastal area based on minimum required T (a) baseline and (b) projected scenario (2030)

Table 7.9 TWs of malaria in coastal area based on minimum required T (a) baseline and (b) projected scenario (2030).

State	No. of Districts	No. of months open for Malaria Transmission							
			0	1-2	3	4-6	7-9	10-12	Data not available
Gujarat	14	Baseline	0	0	0	0	1	12	1
		Projection	0	0	0	0	7	6	1
Maharashtra	5	Baseline	0	0	0	0	0	4	1
		Projection	0	0	0	0	0	4	1
Goa	2	Baseline	0	0	0	0	0	2	0
		Projection	0	0	0	0	0	2	0
Daman and Diu	2	Baseline	0	0	0	0	0	0	2
		Projection	0	0	0	0	0	0	2
Dadra and Nagar Haveli	1	Baseline	0	0	0	0	0	1	0
		Projection	0	0	0	0	0	1	0
Karnataka	3	Baseline	0	0	0	0	0	3	0
		Projection	0	0	0	0	0	3	0
Kerala	9	Baseline	0	0	0	0	0	6	3
		Projection	0	0	0	0	0	6	3
Tamil Nadu	13	Baseline	0	0	0	0	4	9	0
		Projection	0	0	0	7	4	2	0
Andhra Pradesh	9	Baseline	0	0	0	0	7	2	0
		Projection	0	0	0	1	6	2	0
Pondicherry	3	Baseline	0	0	0	0	0	0	3
		Projection	0	0	0	0	0	0	3
Orissa	7	Baseline	0	0	0	0	6	1	0
		Projection	0	0	0	0	7	0	0
West Bengal	3	Baseline	0	0	0	0	2	1	0
		Projection	0	0	0	0	3	0	0
Andaman Nicobar Islands	2	Baseline	0	0	0	0	0	2	0
		Projection	0	0	0	0	0	2	0
Lakshadweep Islands	1	Baseline	0	0	0	0	0	0	1
		Projection	0	0	0	0	0	0	1
14	**74**	**Baseline**	**0**	**0**	**0**	**0**	**20**	**43**	**11**
		Projection	**0**	**0**	**0**	**8**	**27**	**28**	**11**

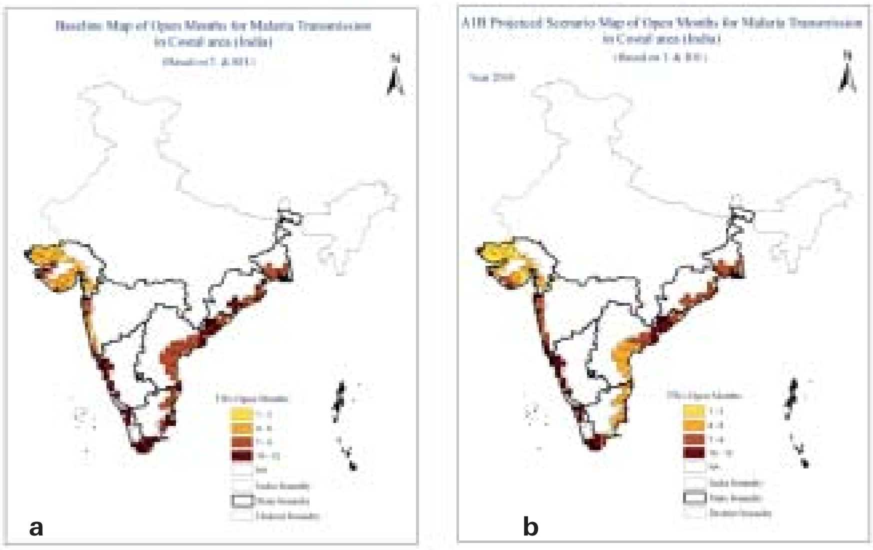


Fig 7.10 TWs of malaria in coastal Region based on minimum required T and RH (a) baseline and (b) projected scenario (2030)

Table 7.10 TWs of malaria in based on minimum required T and RH (a) baseline and (b) projected scenario (2030).

State	No. of Districts	No. of months open for Malaria Transmission							
			0	1-2	3	4-6	7-9	10-12	Data not available
Gujarat	14	Baseline	0	0	2	9	1	1	1
		Projection	0	1	4	4	2	2	1
Maharashtra	5	Baseline	0	0	0	0	4	0	1
		Projection	0	0	0	0	3	1	1
Goa	2	Baseline	0	0	0	0	1	1	0
		Projection	0	0	0	0	0	2	0
Daman and Diu	2	Baseline	0	0	0	0	0	0	2
		Projection	0	0	0	0	0	0	2
Dadra and Nagar Haveli	1	Baseline	0	0	0	1	0	0	0
		Projection	0	0	0	0	1	0	0
Karnataka	3	Baseline	0	0	0	0	0	3	0
		Projection	0	0	0	0	0	3	0
Kerala	9	Baseline	0	0	0	0	0	6	3
		Projection	0	0	0	0	0	6	3
Tamil Nadu	13	Baseline	0	0	0	1	6	6	0
		Projection	0	0	0	7	4	2	0
Andhra Pradesh	9	Baseline	0	0	0	0	7	2	0
		Projection	0	0	0	1	6	2	0
Pondicherry	3	Baseline	0	0	0	0	0	0	3
		Projection	0	0	0	0	0	0	3
Orissa	7	Baseline	0	0	0	0	6	1	0
		Projection	0	0	0	0	7	0	0
West Bengal	3	Baseline	0	0	0	0	2	1	0
		Projection	0	0	0	0	3	0	0
Andaman Nicobar Islands	2	Baseline	0	0	0	0	0	2	0
		Projection	0	0	0	0	0	2	0
Lakshadweep Islands	1	Baseline	0	0	0	0	0	0	1
		Projection	0	0	0	0	0	0	1
14	**74**	**Baseline**	**0**	**0**	**2**	**11**	**27**	**23**	**11**
		Projection	**0**	**1**	**4**	**12**	**26**	**20**	**11**

using the criteria of temperature and relative humidity together, except in some coastal districts of Gujarat where, transmission windows increase only in the 4-6 months categoryin the 2030's (Fig 7.10 a and b, Table 7.10). It does not match with the seasonality of malaria in Gujarat as reflected by current epidemiological data, which indicate transmission for more than 7-9 months. This observation indicates that mosquito vectors are finding micro-niche (e.g. accumulation of water) to get the required RH even if climatically the RH requirement is not satisfied for their transmission.

8

Water

8.1 Introduction

Water is the most critical component of life support systems. India shares about 16% of the global population but it has only 4% of the total water resource. The irrigation sector, which uses 83% of water, is the main consumer of this resource. The main water resources in India consist of precipitation on the Indian territory – estimated to be around 4000 cubic kilometres per year (km^3/year) – and transboundary flows, which it receives in its rivers and aquifers from the upper riparian countries. Precipitation over a large part of India is concentrated in the monsoon season during June to September/October. Due to various constraints of topography there is uneven distribution of precipitation over space and time. Precipitation varies from 100 millimetres (mm) in the western parts of Rajasthan to over 11,000mm at Cherrapunji in Meghalaya. Out of the total precipitation, including snowfall, the availability from surface water and replenishable groundwater is estimated at 1,869km^3. It has been estimated that only about 1,123km^3, including 690km^3 from surface water and 433km^3 from groundwater resources, can be put to beneficial use. Table 8.1 shows the water resources of the country at a glance (MoWR, 2010).

Further, extreme conditions of floods and droughts are a common feature, which affect the availability of water for various purposes. The Rashtriya Barh Ayog (RBA) estimates that 40 million hectares (mha) of area is flood-prone and this constitutes 12% of total the geographical area of the country. Droughts are also experienced due to deficient rainfall. It has been found that an area of 51mha is drought prone and this constitutes 16% of the total geographical area. Added to this is the growing demand for water. The population of the country has increased from 361 million in 1951 to 1.13 billion in July 2007. Accordingly, the per capita availability of water for the country as a whole has decreased from 5,177 cubic metres per year (m^3/year) in 1951 to 1,654m^3/year in 2007.

Gupta and Deshpande (2004) estimated that the gross per capita water availability in India will decline from about 1,820m^3/yr in 2001 to as low as about 1,140 m^3/yr in 2050. This, of course, does not include the impacts of climate change. According to India's Initial National Communication to United Nations Framework Convention on Climate Change (NATCOM, 2004), climate change is likely to adversely affect the water balance in different parts of India due to changes in precipitation and evapotranspiration and rising sea levels, leading to increased saline intrusion into coastal and island aquifers. Increased frequency and severity of floods may affect groundwater quality in alluvial aquifers. Increased rainfall intensity may lead to higher runoff and possibly reduced recharge.

Further, the National Water Mission, which is a part of the National Action Plan on Climate Change (MoWR, 2010), identifies the threat to water resources in India due to climate change in terms of

Table 8.1: Water Resources of India	
	Km^3
Estimated annual precipitation (including snowfall)	4000
Run-off received from upper riparian countries (Say)	500
Average annual natural flow in rivers and aquifers.	1869
Estimated utilisable water	1123
(i) Surface	690
(ii) Ground	433
Water demand _ utilization (for year 2000)	634
(i) Domestic	42
(ii) Irrigation	541
(iii) Industry, energy & others	51

Source: National Water Mission under National Action Plan on Climate Change, MoWR, GOI, 2010

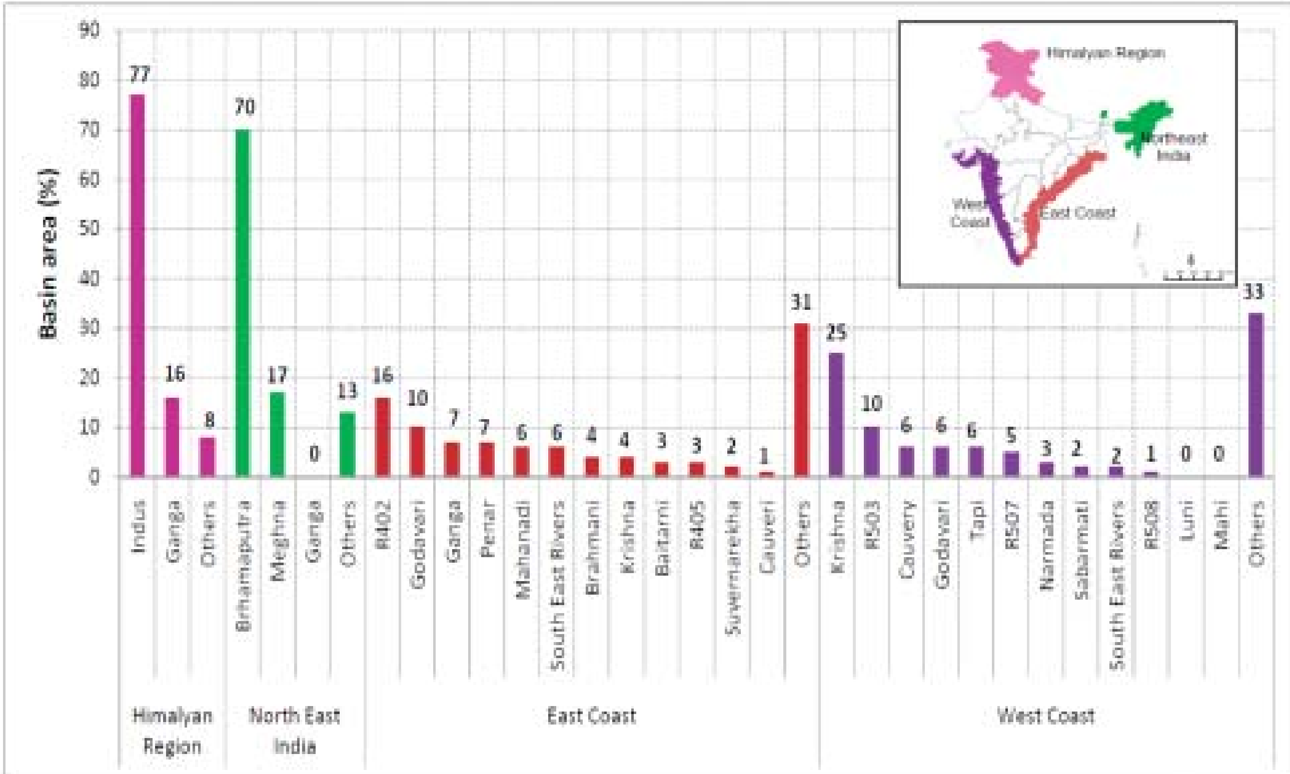


Figure 8.1: INCCA Regions showing proportion of river systems falling in them

the expected decline in the glaciers and snowfields in the Himalayas; increased drought-like situations due to the overall decrease in the number of rainy days over a major part of the country; increased flood events due to the overall increase in the rainy day intensity; effect on groundwater quality in alluvial aquifers due to increased flood and drought events; influence on groundwater recharge due to changes in precipitation and evapotranspiration; and increased saline intrusion of coastal and island aquifers due to rising sea levels. The National Water Mission has been, therefore, set up to undertake integrated water resources management for the conservation of water, minimizing wastage and ensuring equitable distribution both across and within the states.

Clearly the impact of climate change on water resources in India adds another dimension to the complexity of managing and using water resources. Climate change may alter the distribution and quality of natural resources, which will definitely affect the livelihood of its people. Considering that regional distribution of water resources within the country is variable and likely to change due to the changing climate, this assessment focuses on the water availability in the future in the four ecologically sensitive regions of the Himalayas, west coast, east coast and the North-East regions of India. Figure 8.1 shows the proportion of various river systems that compose these regions. Some of these river systems are designated by a number. This number is the river code number that has been assigned as part of the standardization process (refer http://gisserver.civil.iitd.ac.in/natcom).

8.2 Water Resources in India– The regional distribution

The annual precipitation (including snowfall), which is the main source of water in the country, is estimated at 4,000km^3. The resource potential of the country, which occurs as natural runoff in rivers, is about 1,869km^3, as per the basin-wise latest estimate of Central Water Commission, considering both surface and groundwater as one system. The majority of river runoff occurs during 3–4 months in a year during the monsoon. Inland water resources of the country are classified as rivers and canals, reservoirs, tanks and ponds, beels, lakes, derelict water and brackish water (Mall *et al*., 2007).

8.2.1 Rivers

The Ganga–Brahmaputra–Meghna system is the major contributor to the total water resource potential of the country. Its share is about 60% in total water resource potential of the various rivers. As per the

2001 census, the per capita freshwater availability is about 1,820m^3. Due to various constraints of topography, uneven distribution of resources over space and time, it has been estimated that only about 1,122km^3 of the total potential of 1,869km^3 – of which 690km^3 comes from surface water resources – can be put into beneficial use. In the majority of river basins, the present utilization is significantly high and is in the range of 50%–90% of utilizable surface resources. However, in rivers such as the Narmada and Mahanadi, the percentage utilization is quiet low and is 23% and 34%, respectively. Per capita gross water availability in the Brahmaputra and Barak basins is of the order of 14,057m^3 per annum and in Sabarmati basin, the water availability is as low as 307m^3 (MoWR, 2003).

Average water yield per unit area of the Himalayan rivers is almost double that of South Peninsular river systems, indicating the importance of snow and glacier melt contribution from the Himalayan region. The average intensity of mountain glaciation varies from 3.4% for the Indus to 3.2% for the Ganga and 1.3% for the Bramhaputra. The tributaries of this river system show maximum intensity of glaciation (2.5%–10.8%) for Indus, followed by the Ganga (0.4%–10%), and the Brahmaputra (0.4%–4%). The average annual and seasonal flow of these systems give a different picture, thereby demonstrating that rainfall contributions are greater in the eastern region, while the snow and glacier melt contributions are more important in the western and central Himalayan region. In recent decades the hydrological characteristics of the watersheds in the Himalayan region seem to have undergone substantial change as a result of land use (e.g. deforestation, agricultural practices and urbanization) leading to more frequent hydrological disasters, enhanced variability in rainfall and runoff, extensive reservoir sedimentation and pollution of lakes, etc. (Ramakrishnan, 1998).

Most of the rivers in the south like the Cauvery, the Narmada and the Mahanadi are fed through groundwater discharges and are supplemented by monsoon rains. So, these rivers have very limited flow during non-monsoon periods. The flow rate in these rivers is independent of the water source and depends upon the precipitation rate in the region. Therefore, in spite of being smaller, the rivers flowing into the west coast have a higher flow rate due to higher precipitation over that region.

8.2.2 Glaciers

Major glacier-fed Himalayan rivers, along with glaciated catchments, have regional importance—the water from the glacier melt sustains stream flow in these rivers through the dry season. The "frozen water" in the Himalayas is crucial for the people inhabiting the mountain areas as well as those inhabiting the downstream regions. The Indus and the Ganga – the two major rivers in western Himalayan region – directly impact the lives of a large population living in the northern part of India, and even beyond the national boundaries.

The Indus basin has 7,997 glaciers with a total glacier cover of 33,679km^2 and total ice volume of 363.10km^3. The Ganga basin has 968 glaciers with a total glacier cover of 2,857km^2 and total ice volume of 209.37km^3 (Table 8.2). The contribution of snow to the runoff of major rivers in the eastern Himalayas is about 10% (Sharma, 1993) but more than 60% in the western Himalayas (Vohra, 1981).

It is estimated that Himalayan mountains cover a surface area of permanent snow and ice of about 97,020km^2, with a volume of 12,930km^3. In these mountains, it is estimated that 10%–20% of the total surface area is covered with glaciers while an additional area ranging from 30%–40% has seasonal snow cover (Upadhaya, 1995; Bahadur, 1999). These glaciers, providing snow and glacial meltwaters, keep our rivers perennial. Bahadur (1999) reported that a very conservative estimate puts the snow and ice meltwater contribution to Himalayan streams at no less than 500km^3 per year, while another study reports about 515km^3 per year from the upper Himalayas. The most useful facet of glacier runoff is that glaciers release more water in a drought year and less water in a flood year.

8.2.3 Ground water

The other source of water is the groundwater resource, which has two components—static and dynamic. The static fresh groundwater reserve (i.e, aquifer zones below the zone of groundwater table fluctuation) of the country has been estimated at 10,812 billion m^3. The dynamic component, which is replenished annually, has been assessed as 432 billion m^3. As per the national water policy, development of groundwater resources is to be limited to utilization

Table 8.2 : Major glaciers in the three North-Western Himalayan States of India			
Basin	**No. of glaciers**	**Glacier covered Area (km²)**	**Ice volume (km³)**
A. Indus Basin			
Ravi	172	193	8.04
Chenab	1,278	3,059	206.30
Jhelum	133	94	3.30
Beas	277	579	36.93
Satluj	926	635	34.95
Upper Indus	1,796	8,370	73.58
Shyok	2,454	10,810	NA
Nubra	204	1,536	NA
Gilgit	535	8,240	NA
Kishenganga	222	163	NA
Total	**7,997**	**33,679**	**363.10**
B. Ganga Basin			
Yamuna	52	144	12.20
Bhagirathi	238	755	67.02
Alaknanada	407	1,229	86.38
Ghaghra	271	729	43.77
Total	**968**	**2857**	**209.37**
Source: Raina and Srivastava, 2008. NA: Data Not Available			

Table 8.3 : Recent retreat pattern of selected glaciers in the three North-Western Himalayan States of India						
Name of the Glacier	**State**	**Retreat of snout (m)**	**Observation Period**	**Trend**	**Avg. retreat rate (m/yr)**	**Reference**
Gangotri	Uttarakhand	954.14 564.99 12.10	1935-71 1971-2004 2004-2005	Retreating --do-- --do--	26.50 17.15 12.10	Bali et. al, 2009--do--Kumar *et. al*, 2008
Pindari	Uttarakhand	1600 1040 61 262	1845-1906 1906-1958 1958-1996 1966-2007	Retreating --do-- --do-- --do--	26.23 20.0 7.62 6.39	Bali *et. al*, 2009
Dokriani	Uttarakhand	550	1962–95	Retreating	16.67	Dobhal, *et. al.*, 2004
Durung Drung	Jammu & Kashmir	-	2004-07	No Change	-	Ganjoo, 2010
Kangriz	Jammu & Kashmir	-	1913-2007	No Change	-	Ganjoo, 2010
Siachin	Jammu & Kashmir	NA --do-- --do-- - NA -	1862-1909 1909-1929 1929-1958 1958-1985 1985-2004 2004-2005	Advancing Retreating Retreating No Change Retreating No change	15.42 2.5 14 - 3 -	Ganjoo, 2010
NA: Data Not Available						

of dynamic component of groundwater. The present development policy, therefore, forbids utilization of the static reserve to prevent groundwater mining. The total annual replenishable groundwater resource is about 43 million hectare metres (Mham). After making a provision of 7Mham for domestic, industrial and other uses, the available groundwater resource for irrigation is 36Mham, of which the utilizable quantity is 32.6Mham (Mall *et al*., 2007).

The Central Ground Water board has established about 15,000 network monitoring stations in the country to monitor the water level and its quality. The water level in major parts of the country generally does not show any significant rise or decline. However, certain blocks in 289 districts in the states of Andhra Pradesh, Assam, Bihar, Chhattisgarh, NCT Delhi, Jharkahand, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra. Orissa, Punjab, Rajasthan, Tamil Nadu, Tripura, Uttar Pradesh and West Bengal show a significant decline in groundwater.

8.3 Observed changes in glaciers in India

The glaciers in the region show fluctuations in retreat rates during the last century, possibly due to the mixed influence of variable topography, temperature and snowfall regime (see Table 8.3). The Gangotri glacier, which was earlier receding at the rate of around 26m/year between 1935 and 1971, has shown a gradual decline in the rate of recession. It had come down to around 17m/year between 1971 and 2004, and in recent years has shown a recession rate of about 12m/year during 2004–2005 (Kumar *et al*., 2008). The rate of recession of the Pindari glacier has come down to 6.5m/year in comparison to the earlier reported rate of 26m/year between 1996 and 2007. Similarly, the rate of recession of the Milam glacier has been observed as 16.5m/year in the last 150 years (Bali *et al*., 2009).

The snout of the Donagiri glacier has shown signs of moderate recession, and the Satopanth glacier, which had been receding at the rate of 22.86m/year earlier, has lately shown a recession rate of 6.5m/year during 2005–2006 (Nainwal *et al*., 2008). Between 1962 and 1995, the volume of ice in the Dokriani glacier has reduced by approximately 20%, and the frontal area has vacated by 10%, whereas the glacier has receded by 550m at an average rate of 16.6m/yr. However, the yearly monitoring of the snout position of the glacier during 1991–1995 revealed an average rate of recession of 17.4m/yr, and it has vacated an area of 3,957m^2. Detailed studies on Dokriani glacier have been summarized in Box 2. The estimated retreat of the Dokriani glacier in 1998 was 20m compared to an annual average of 16.5m over 1993–1998 (Mirza *et al*., 2002).

Studies conducted during last three decades by the National Institute of Hydrology, Roorkee, reveal that in Ladakh, Zanskar and the Great Himalayan ranges of Jammu and Kashmir are generally receding, and the glacier volume changes range between 3.6% and 97%, with the majority of glaciers showing a degradation of 17%–25% (Annual Report, NIH, 2008-09). The 23km long Durung Drung glacier in the Zanskar valley is highly affected by western disturbances (ablation rate variations between 0.75cm/day and 2.67 m/day during July and August); The studies, however, do not reveal any significant retreat during 2004–07 (Table 8.3).

The Nubra valley of Jammu and Kashmir has 114 small-sized glaciers varying between less than 5km and 10km in length. The glaciers of the valley do not show much change in their length and area during the period 1989–2001 (Mirza *et al*., 2002). However, variable decline in the glacial area of the Siachin glacier has been observed (Ganjoo & Kaul, 2009). The area has reduced from 994.99km^2 in 1969 to 932.90km^2 in 1989. However, small change in the area (932.90km^2 to 930km^2) has been noticed during the following decade (1989–2001). Recession patterns of 466 glaciers in the Chenab, Parbati and Baspa basins of the western Himalayas have been studied for the period 1962–2008. Here, a reduction in the glacial area from 2,077km^2 to 1,628km^2 and an overall deglaciation of 21% has been observed (Kulkarni *et al*., 2007).

Most of the glaciers in western Himalayas are receding (expect a few in Jammu and Kashmir, which do not show any change or are advancing). The processes controlling the rate of retreat of glaciers are complex and vary with location and topography of the area. However, the impact of rising temperature and reducing snowfall on glacier mass balance is reflected in these findings, which may require a sound long-term database for precise climate change assessment.

8.4 Review of Projections of climate change on water resources in India

Studies on impacts on climate change (Gosain *et al*., 2004, Gosain *et al*., 2006) on river runoff in various river basins of India indicate that the quantity of surface runoff due to climate change would vary across river basins as well as sub-basins in the 2050s. However, there is a general reduction in the quantity of available runoff. An increase in precipitation in the Mahanadi, Brahmani, Ganga, Godavari and Cauvery basins is projected under the climate change scenario of IS92a and A2 scenarios run on the Hadley Centre regional model. However, the corresponding total runoff for all these basins does not increase. This may be due to increase in evapotranspiration on account of increased temperatures or variations in the distribution of rainfall. In the remaining basins, a decrease in precipitation has been experienced. The Sabarmati and Luni basins show a drastic decrease in precipitation and consequent decrease of total runoff to the tune of two-thirds of the prevailing runoff. This may lead to severe drought conditions in the future. Flooding conditions may deteriorate in the Mahanadi and Brahmani river systems. Further, climate change may increase the severity of droughts and intensity of floods in the various parts of the country.

The snowline and glacier boundary are sensitive to changes in climatic conditions. The mean equilibrium line altitude at which snow accumulation is equal to snow ablation for glaciers is estimated to be 50–80m higher, relative to the altitude during the first half of the nineteenth century (Pender, 1995). A warming is likely to rapidly increase the rate at which glaciers are melting, leading to greater ablation than accumulation. Glacier melt is expected to increase under changes in climate conditions, which would lead to increased summer flows in some river systems for few decades, followed by a reduction in flow as the glaciers disappear (IPCC, 1998). Further, extreme precipitation events have geomorphological significance in the Himalayas where they may cause widespread landslides (Ives and Messerli, 1989). The response of hydrological systems, erosion processes and sedimentation in this region could alter significantly due to climate change.

The groundwater demand is projected to increase to 980 million cubic metres (MCM) in the 2050s, needing extra power to pump out water at about 100 gigawatt hour (GWh) electricity per billion cubic metres (BCM) groundwater. In order to meet the groundwater demand, intensive development of groundwater resources, exploiting both dynamic and static potential, will be required (Shukla et al., 2004).

8.5 Regional projections for 2030s

8.5.1 Methodology and data used

For the present analysis, all the river basins of these regions have been modelled using the hydrologic model SWAT (Soil and Water Assessment Tool). The model requires information on terrain, soil profile and land use of the area as input, which have been obtained from the global sources. These three entities are assumed to be static in the future as well. Information on weather conditions in the present and future is essential for the analysis. That data has been provided by the Indian Institute of Tropical Meteorology (IITM), Pune, as the output of a regional climate model (RCM-PRECIS) at daily interval at a resolution of about 50km.

Climate outputs from PRECIS regional climate model for the present (1961–1990, BL) and the near term (2021–2050, 2030s) for A1B IPCC SRES socio-economic scenario (characterized by a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies, with development balanced across energy sources) have been used. The potential impacts of climate change on water yield and other hydrologic budget components were quantified by performing SWAT hydrological modelling with current and future climates respectively for the regional systems.

The study determines the present water availability in space and time without incorporating any man-made changes like dams, diversions, etc. The same framework is then used to predict the impact of climate change on the water resources with the assumption that land use shall not change over time. A total of 60 years of simulation has been conducted; 30 years belonging to IPCC SRES A1B baseline (BL) and 30 years belong to IPCC SRES A1B near-term or 2030s climate scenario.

While modelling, each river basin in the region has been further subdivided into reasonable sized sub-basins so as to account for spatial variability of inputs in the baseline and greenhouse gases (GHG) scenario.

Detailed analyses have been performed to quantify the possible impacts on account of climate change.

To start with precipitation, the output of the PRECIS RCM model has been used as the input for the SWAT model. The output has been analysed to examine the projected changes in this core water resource. The detailed outputs of the SWAT hydrological model have been analysed with respect to the two major water balance components, that is, water yield and actual evapotranspiration, which are highly influenced by intensity and temporal distribution of precipitation and weather conditions dictated by temperature and allied parameters.

Furthermore, the analysis has also been extended to the detection of extreme events of droughts and floods that may be triggered on account of climate change and are of major concern to the local societies. All the analyses have been performed by aggregating the inputs/outputs at the sub-basin level, which are the natural boundaries controlling hydrological processes and have been depicted accordingly using the GIS. Knowledgeable users can draw their own additional conclusions using the base information provided.

The analysis is based on spatial data that includes Digital Elevation Model sourced from the Shuttle Radar Topography Mission (SRTM) of 90m resolution; Drainage Network sourced from Digital Chart of the World, 1992; Soil maps and associated soil characteristics (source: FAO Global soil); and land use (source: Global Land Use). The hydro-meteorological data pertaining to the river basin on daily rainfall, maximum and minimum temperature, solar radiation, relative humidity and wind speed are taken from PRECIS Regional Climate Model outputs for the baseline scenario simulated for the period 1961–1990 and near-term projections for the 2030s derived as the average of the projections made for the period 2021–2050 for A1B IPCC SRES scenario.

8.5.2 The Hydrologic Simulation with Baseline Scenario

The SWAT model has been used on each of the river basins separately using daily weather generated by the PRECIS RCM baseline scenario (1961–1990, IPCC SRES A1B). Although the model does not require elaborate calibration, yet, in the present case, any calibration was not meaningful since the simulated weather data is being used for the control period which is not the historical data corresponding to the recorded observed runoff. However, the SWAT model has been used in Indian catchments of varied sizes and it has been observed that the model performs very well without much calibration (Gosain *et al*., 2003). The model generates detailed outputs on a daily interval at the sub-basin level: outflow, actual evapotranspiration and soil moisture status are some of the useful outputs. Further, subdivisions of the total flow such as surface and sub-surface runoff are also available. It is also possible to evaluate the natural recharge to the groundwater on a daily basis.

8.5.3 The Hydrologic Simulation with Climate Change Scenario in 2030s

The model has been run using PRECIS GHG climate scenarios for the near-term (2021–2050, IPCC SRES A1B) with no change in land use. The outputs of these two scenarios have been analysed with respect to the possible impacts on the runoff, sediment yield and actual evapotranspiration. The aggregated picture is depicted by showing the variations through the GIS layers with the precipitation, water yield and evapotranspiration as the base entities.

The effect of climate change on water balance components has been analyzed spatially for each region. The spatial distribution of water yield, evapotranspiration and sediment yield, along with precipitation, has been analysed for the IPCC SRES A1B baseline and 2030s scenario.

The long-term variation in these basic water balance elements for various regions has been shown in percentage in Figures 8.2, 8.3, 8.4 and 8.5. A positive change indicates a decrease from the baseline and a negative change indicates an increase from the baseline. Generic inferences have been drawn for each region and presented in the following sections.

8.5.3.1 Himalayan Region

The Himalayan region is mainly fed by the Indus river system. The whole area is exhibiting an increase in the precipitation in the 2030s scenario (Figure 8.2). The increase varies between 5% and 20% in most areas, with some areas of Jammu and Kashmir and Uttarakhand showing an increase of up to 50%.

The impact of the increase in precipitation in this region is reflected in an almost similar pattern of increase in the evapotranspiration (ET) (Figure 8.3). This is expected to happen presumably on account of

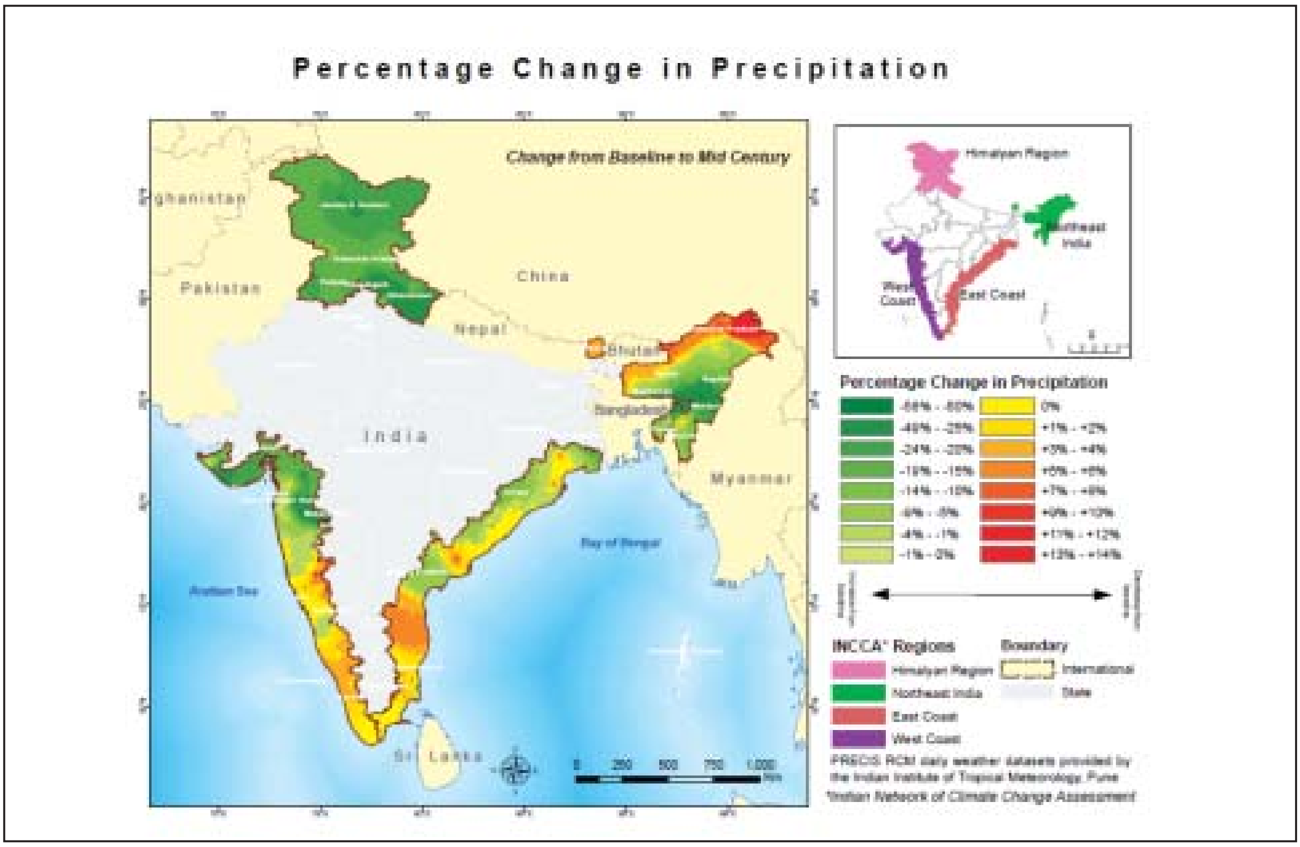


Figure 8.2 Change in precipitation towards 2030s with respect to 1970s.

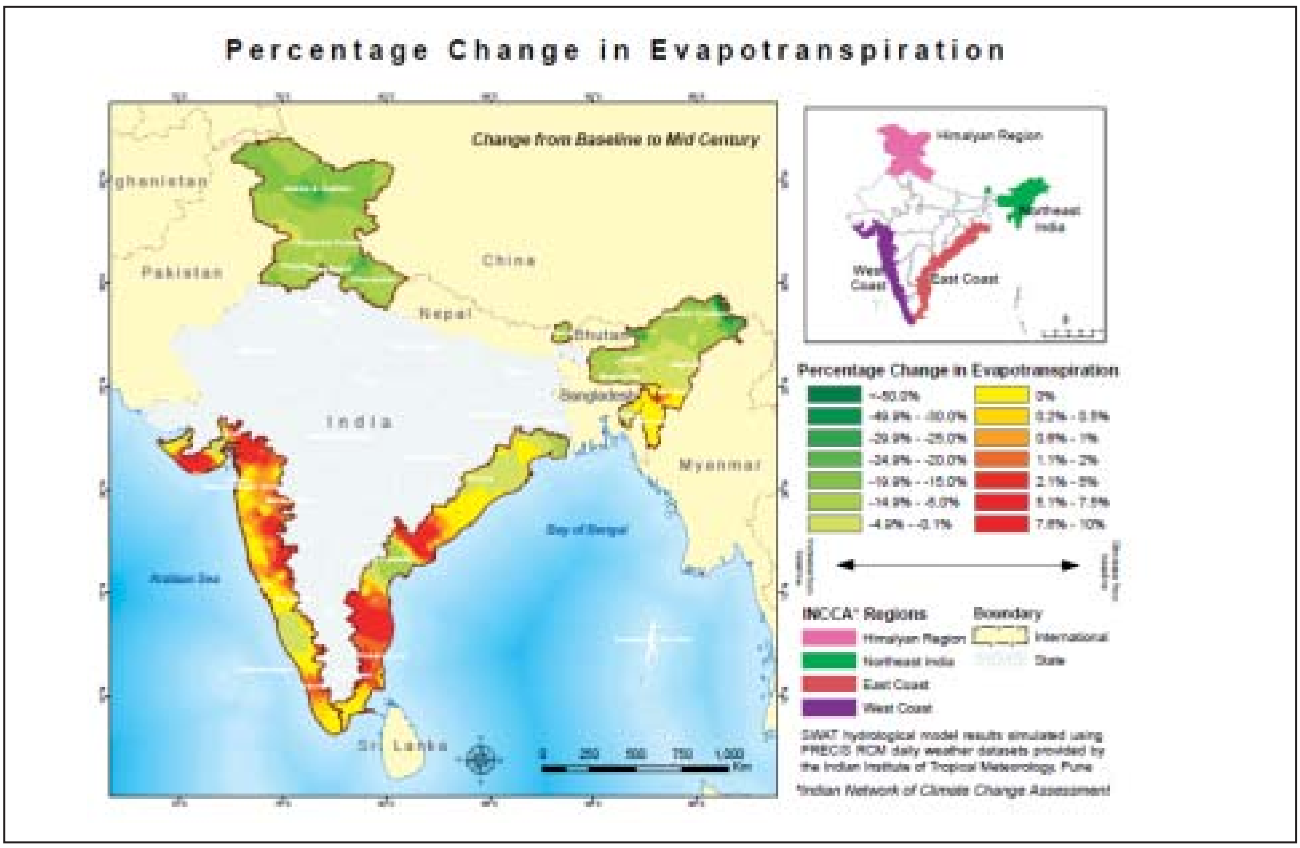


Figure 8.3 Change in Evapo-transpiration (crop water demand) towards 2030s with respect to 1970s.

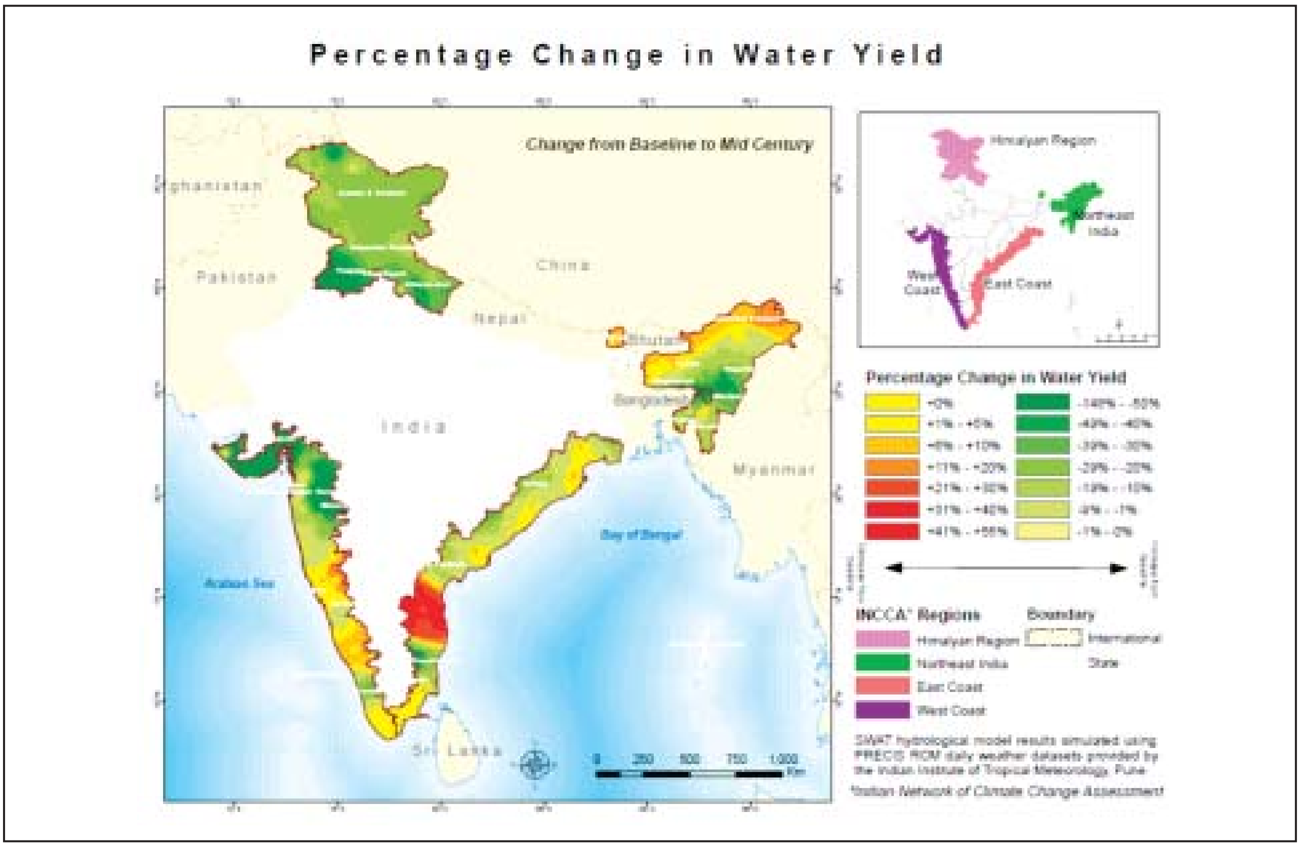


Figure 8.4 Change in Water Yield towards 2030s with respect to 1970s.

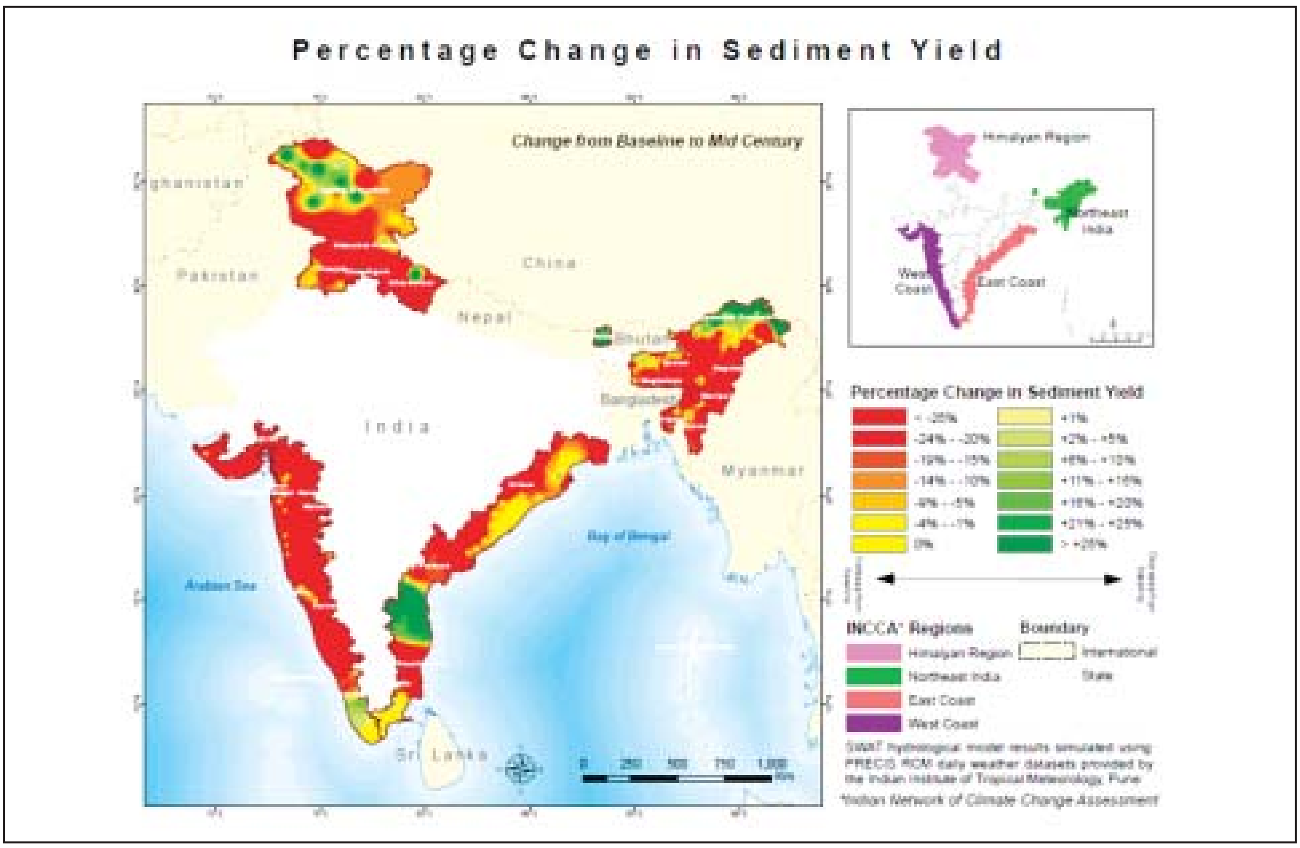


Figure 8.5 Change in Sediment Yield towards 2030s with respect to 1970s.

(a) the increase in the amount of moisture in the soil and land surface and (b) the increase in temperature. Both these factors enhance the opportunity for ET.

The water yield, which is the total surface runoff, is usually a function of precipitation and its distribution. The other factors that influence water yield are the soil profile and land use in the area. It may be noted that for the Himalayan region there has been a general increase in the water yield for the 2030s scenario (Figure 8.4). However, it may be noticed that the increase in the water yield is more for those areas where the increase in ET is less. The increase in water yield has been up to about 50% for some areas of Indus River for the 2030s.

The general impact of increase in the precipitation is reflected in the increase in sediment yield. This is quite evident in the Himalayan region as well (Figure 8.5). The other major factors that dictate sediment yield are the intensity of rainfall, land use and the soil type of the area. The increase in the sediment yield in the Himalayan region is up to 25%, which can be detrimental for the existing water resources projects and has the potential to cause considerable damage to the environment.

8.5.3.2 North-Eastern Region

The trend in precipitation in the North-Eastern region exhibits considerable spatial variability with respect to the predictions for the 2030s. The northern part shows a reduction in precipitation varying from 3% in the north-western portion to about 12% in the north-eastern portion (Figure 8.2). In the remaining part of the North-East, there is increase in precipitation varying from 0% to as much as 25% for the central portion of the North-East.

The majority of the North-Eastern region, but for some parts of Mizoram, Tripura, Manipur and Assam, shows an increase in ET during the 2030s scenario. It is interesting to note that even those parts of Arunachal Pradesh that were showing a decrease in precipitation, show an increase in ET (Figure 8.3). This can only be explained by the occurrence of higher temperatures that enhance the evaporative force. However, the increase in ET ranges from a small fraction to about 20%. The reduction in ET in the southern portion is only marginal.

The trend in water yield in the North-Eastern region is similar to the precipitation trend. The areas that have shown less increase in precipitation show a correspondingly low water yield (Figure 8.4). The reduction in water yield in Arunachal Pradesh is up to about 20%. An increase in water yield is seen in Assam and Manipur and the magnitude is up to about 40%.

The North-Eastern region also shows a considerable increase in sediment yield for the majority of the areas which are expected to see increase in precipitation (Figure 8.5). The increase in the sediment yield in the region is up to 25%. There are a few areas of Arunachal Pradesh that are expected to receive less rainfall and show a reduction in sediment yield of up to 25% under the 2030s scenario.

8.5.3.3 West Coast Region

The west coast region exhibits a wide variability in the change in precipitation under the 2030s scenario. The northern portion of the west coast, consisting of areas of Gujarat and Maharashtra, shows an increase in precipitation for the 2030s scenario, and the increase varies from 4% to over 25% (Figure 8.2). However, areas of Karnataka and Kerala show a decrease in precipitation, although the decrease is marginal and varies from a small fraction to about 4%.

The west coast region shows a general reduction in ET, which varies from a very nominal value to about 5% for the 2030s scenario (Figure 8.3). It may be noted that even the areas of Gujarat and Maharashtra, which had shown an increase in precipitation, show a reduction in ET. The possible explanation is that the high-intensity rainfall that runs off the surface with much increase in the soil moisture storage lowers the opportunity for ET. The enhanced reduction in ET for areas such as Karnataka and Kerala, which have received less precipitation, is understandable on account of non-availability of moisture for ET.

The trend in water yield in the west coast region is also similar to the precipitation change in this region. The areas that have shown less increase in precipitation show a correspondingly low water yield (Figure 8.4). The reduction in water yield for Karnataka and Kerala is up to about 10%. Gujarat and Maharashtra areas see an increase in water yield, and the magnitude is up to about 50%.

The west coast region also shows a considerable increase in the sediment yield for majority of the areas (Figure 8.5). In this region, even those areas that are expected to receive less precipitation show an increase in sediment yield of up to 25%. The increase in sediment yield in these areas can possibly be explained due to an increase in the intensity of precipitation.

8.5.3.4 East Coast Region

The east coast region also exhibits wide variability in the change in precipitation under the 2030s scenario. The northern portion of the east coast consisting of areas of West Bengal, Orissa and Andra Pradesh show an increase in precipitation for the 2030s scenario in some parts, and the increase varies from a small fraction to about 10% (Figure 8.2). However, some parts show a marginal reduction of up to about 3%. The southern portion of the east coast, which comprises mainly the Tamil Nadu area, shows a trend similar to that observed in the southern part of the west coast. This area shows a decrease in precipitation of up to 5%.

The east coast region shows an increase in ET for some areas of West Bengal and Orissa, which are expected to receive enhanced precipitation. For other areas, there is a general reduction in the ET, which varies from a very nominal value to about 5% for the 2030s scenario (Figure 8.3). The enhanced reduction in ET for those areas such as Andhra Pradesh and Tamil Nadu which have received less precipitation is understandable on account of non-availability of moisture for ET.

The trend in water yield in the east coast region is also reflects the precipitation change in this region. The areas that have shown less increase in precipitation show correspondingly a low water yield (Figure 8.4). The reduction in water yield in the region is up to about 20%, while in other parts of the region, the increase in the water yield is up to about 20%.

The east coast region also shows a considerable increase in the sediment yield for the majority of the area (Figure 8.5). In this region, sediment yield of up to 25% is predicted. There are a few areas that have exhibited some reduction in the sediment yield, mainly on account of the reduction in precipitation.

8.6 Impact Assessment

The outputs from the hydrological model have been used to assess the impact of climate change on the river basins in the regions, in terms of occurrence of droughts and floods.

8.6.1 Drought Analysis

Drought indices are widely used for the assessment of drought severity by indicating relative dryness or wetness affecting water sensitive economies. The Palmer Drought Severity Index (PDSI) is one such widely used index that incorporates information on rainfall, land use, and soil properties in a lumped manner (Palmer 1965). The Palmer index categorizes drought into different classes. A PDSI value below 0.0 indicates the beginning of a drought situation and a value below -3.0, a severe drought condition.

The soil moisture index developed (Narasimhan and Srinivasan, 2005) to monitor drought severity using SWAT output to incorporate the spatial variability has been used in the present study to focus on agricultural drought, where severity refers to the cumulative water deficiency. Weekly information has been derived using daily SWAT outputs, which in turn, have been used for subsequent analysis of drought severity.

The severity of drought is proportional to the relative change in climate. For example, if a climate usually has very nominal deviations from the normal, even a moderate dry period might have quite dramatic effects. On the other hand, a very dry period would be needed in a climate that is used to large variations to produce equally dramatic effects. In the current context, scale 1 (Index between 0 and -1) represents the drought-developing stage and scale 2 (Index between -1 and -4) represents mild to moderate and extreme drought conditions.

For the present study, the Soil Moisture Deficit Index (SMDI) was calculated for 30 years of simulated soil moisture data from the baseline (1961–1990) and the MC (2021–2050) climate change scenario. The spatial distribution of percentage change (baseline to mid century) in drought weeks are shown using the SWAT output for smaller drainage basins in the GIS format. Weeks when the soil moisture deficit may start drought development (drought index value between 0 and -1) as well as the areas, which may fall under moderate to extreme drought conditions (drought index value between -1 and -4), have been assessed and are shown in Figure 8.6.

It may be seen that there is an increase in the drought development for those areas of various regions that have either predicted decrease in precipitation or have enhanced level of evapotranspiration for the near-term scenario. Similarly, the weeks belonging to moderate soil moisture stress (depicted in Figure 8.6) show an increase in severity of drought from the baseline to the mid-century scenario, which is self evident. Moderate to extreme drought severity has been pronounced for the Himalayan region, where the increase is more than 20% for many areas despite the overall increase in precipitation.

8.6.2 Flood Analysis

The vulnerability assessment with respect to the possible future floods has been carried out using the daily outflow discharge taken for each sub-basin from the SWAT output. These discharges have been analysed with respect to the maximum annual peaks. Maximum daily peak discharge has been identified for each year and for each sub-basin. Analysis has been performed to earmark which are the basins where flooding conditions may deteriorate under the GHG scenario. The analysis has been performed ascertain the change in magnitude of flood peaks above 99th percentile flow under baseline (1961-1990) and mid century scenario (2021-2050) (Fig. 8.7).

The Figure shows change in peak discharge equal to or exceeding at 1% frequency from baseline to MC scenario for various regions. It may be observed that all the regions show an increase in the flooding varying between 10 to over 30% of the existing magnitudes. This has a very severe implication for the existing infrastructure such as dams, bridges, roads, etc., for the areas and shall require appropriate adaptation measures to be taken up.

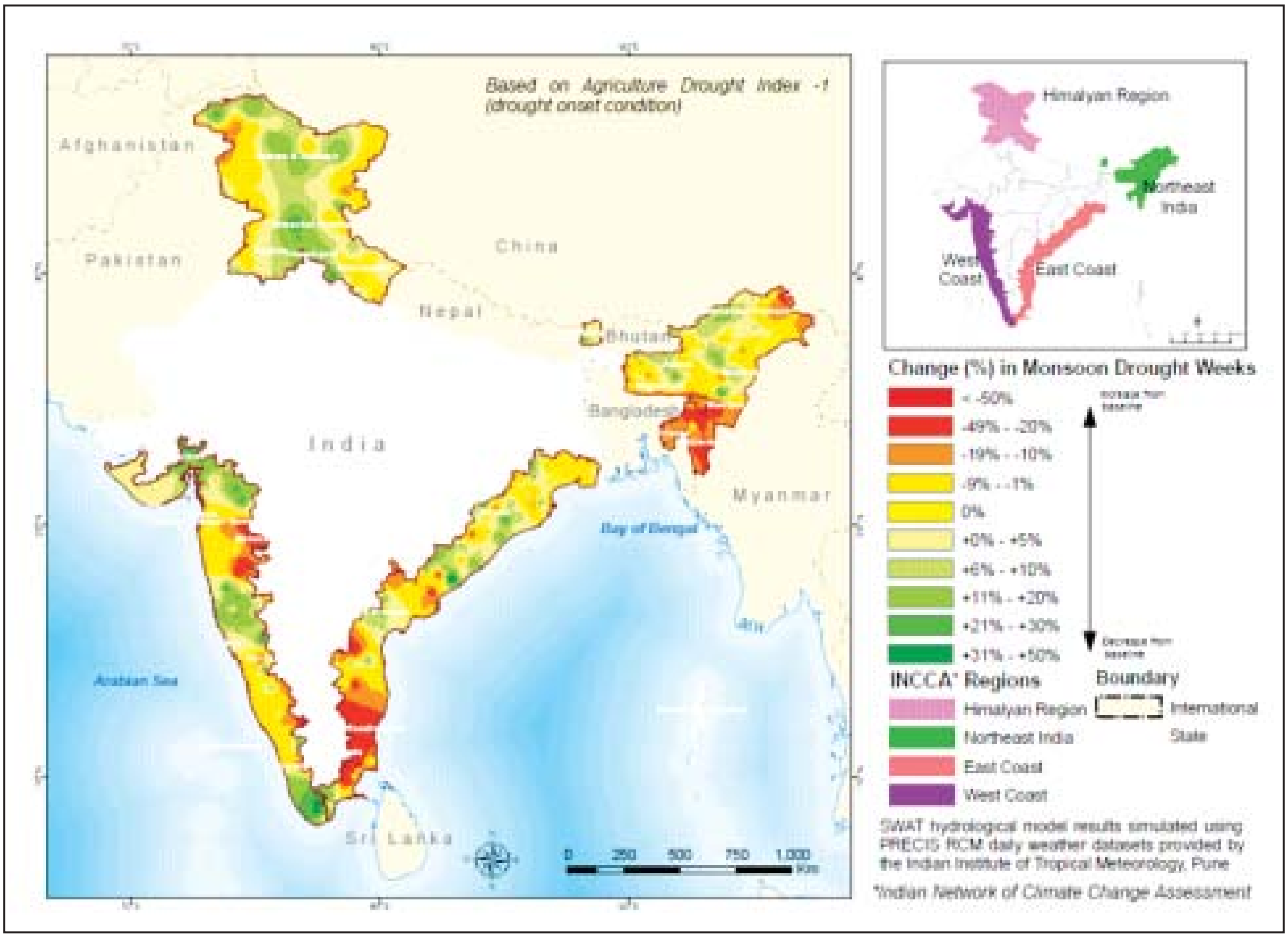


Figure 8.6 Change in monsoon drought weeks towards 2030s with respect to 1970s

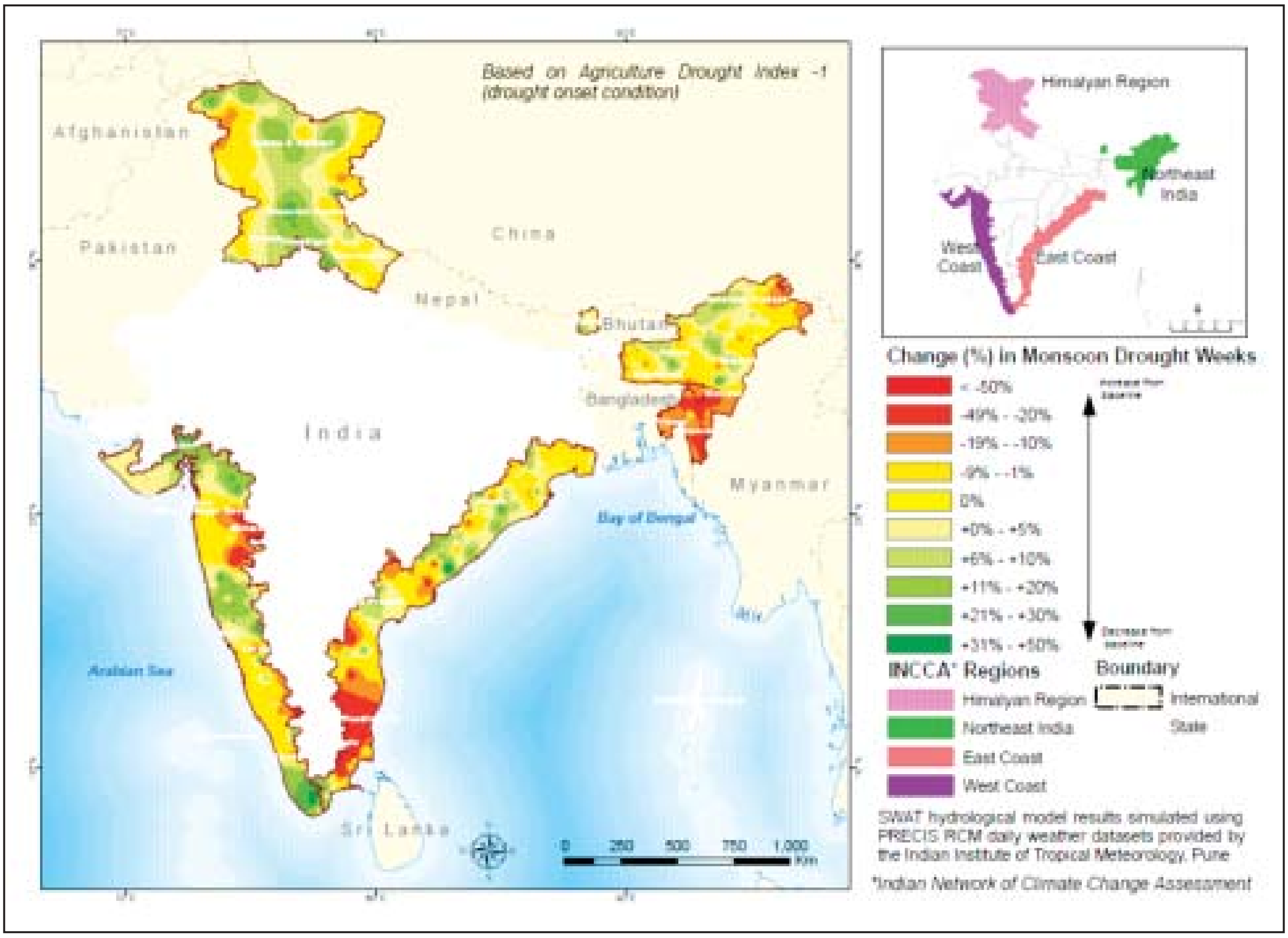


Figure 8.7 Change in magnitude of flood (stream discharge at 99th percentile) towards 2030s with respect to 1970s

9

Salient findings, Challenges and the Way forward

This chapter synthesises the salient findings on the sectoral concerns about climate change impacts and presents them in a question–answer format. The impact assessments have been made using biophysical models with inputs on climate change obtained from a regional climate change model (PRECIS, a version of HadRM3) with a resolution of 50km x 50km run on A1B IPCC SRES (Special Report on Emission Scenario; IPCC, 2000). The A1B scenario assumes significant innovations in energy technologies, which improve energy efficiency and reduce the cost of energy supply. The 2030s is the average of the period 2021– 2050. All the changes in the 2030s are measured with respect to the period 1961–1990s, also referred to as "1970s" or "baseline".

9.1 Salient findings

Question 1: What are the projected changes in regional temperatures and precipitation in the 2030s?

Climatologically, the entire Indian region is divided into the western Himalayas, north-west, north-east; northern-central region, eastern coast, western coast, and the interior plateau. The projected climate change information obtained from PRECIS for these regional entities have been adapted for the present assessment as per the regions in focus. For example, the projections for the Western Ghats refer to projections for the western coast. Projections for the coastal region represent the climate projections for the western coast and the eastern coast together. Projections for the Himalayan region represent the climate of the western Himalayas and the projections for the North-Eastern region represent the climatological entity of the North-East.

1. Temperature: PRECIS simulations for the 2030s indicate an all-round warming, associated with increasing greenhouse gas concentrations, over the Indian subcontinent. The rise in annual mean surface air temperature by the 2030s ranges from 1.7°C to 2.0°C. The variability of seasonal mean temperature may be more in winter months. On a regional scale, the variations in temperatures are likely to be as follows (also see Figure 9.1):

Himalayan region: The annual temperature is projected to increase from 0.9±0.6°C to 2.6±0.7°C

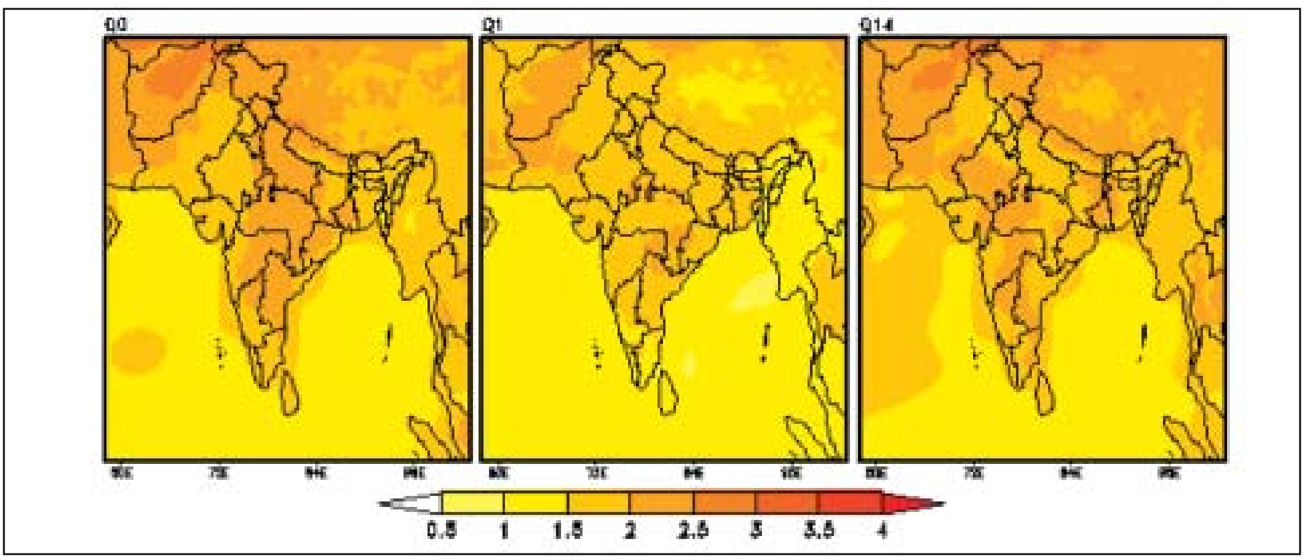


Figure 9.1: Projected changes in the annual surface air temperature in 2030s with respect 1970s.

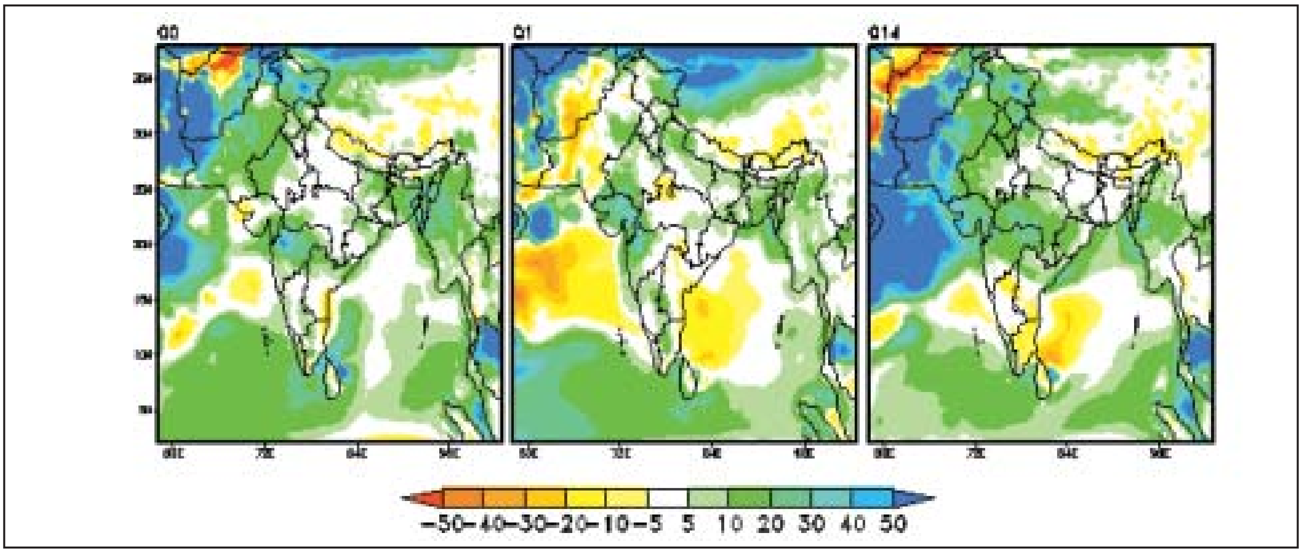


Figure 9.2: Projected changes in summer monsoon precipitation on 230s with respect to 1970s.

in the 2030s. The net increase in temperature ranges from 1.7°C to 2.2°C with respect to the 1970s. Seasonal air temperatures also show a rise in all seasons.

North-Eastern region: The surface air temperature in this region is projected to rise by 25.8°C to 26.8°C in the 2030s, with a standard deviation ranging from 0.8°C to 0.9°C. The rise in temperature with respect to the 1970s ranges from 1.8°C to 2.1°C.

Western Ghats: In the Western Ghats, annual temperatures are likely to increase to 26.8°C–27.5°C in the 2030s. The rise in temperature with respect to the 1970s will be between 1.7°C and 1.8°C.

Coastal region: In the eastern coastal region, the annual air temperature is likely to rise from 28.7±0.6°C to 29.3±0.7°C. The rise in temperature with respect to the 1970s is around 1.6°C to 2.1°C. In the western coastal region, annual temperatures are likely to increase to 26.8°C–27.5°C in the 2030s. The rise in temperature with respect to the 1970s will be between 1.7°C and 1.8°C

2. Precipitation: All the regions under consideration show a small increase in annual precipitation in the 2030s, with respect to the baseline, that is, 1961–1990s (or 1970s). The projected precipitation in the 2030s for each region is as follows (also see Figure 9.2):

Himalayan region: The annual rainfall in the Himalayan region is likely to vary between 1268±225.2 and 1604±175.2 mm in 2030s. The projected precipitation is likely to increase by 5% to 13% in 2030s with respect to 1970s.

North-Eastern region: The mean annual rainfall is projected to vary from a minimum of 940±149 mm to a maximum of 1330±174.5mm. The increase in the 2030s, with respect to the 1970s, is of the order of 0.3% to 3% .

Western Ghats: In the Western Ghats in the 2030s, the mean annual rainfall is likely to vary from 935± 185.33mm to 1794±247mm, which is an increase of 6%–8% with respect to the 1970s.

Coastal region: In the eastern coast, the rainfall is likely to range between 858±85.8mm to 1280± 204.8mm in the 2030s. The increase in the 2030s with respect to the 1970s is estimated to range between 0.2% to 4.4%. Projections for the western coast indicate a variation from 935±185.33mm to 1794± 247mm, which is an increase 6%–8% with respect to the1970s.

Question 2: What are the projected changes in extreme events?

1. Extreme temperatures: The analysis of the three simulations (namely, Q0, Q1 and Q14) indicate that both the daily extremes in surface air temperature, i.e. daily maximum and daily minimum, may intensify in the 2030s. The spatial pattern of the change in the lowest daily minimum and highest maximum temperature suggests a warming of 1°C to 4°C towards the 2030s. Night temperatures are likely to rise more over the south peninsula and central and northern India,. Central and northern India may experience an increase in daytime warming also (see Figure 9.3a).

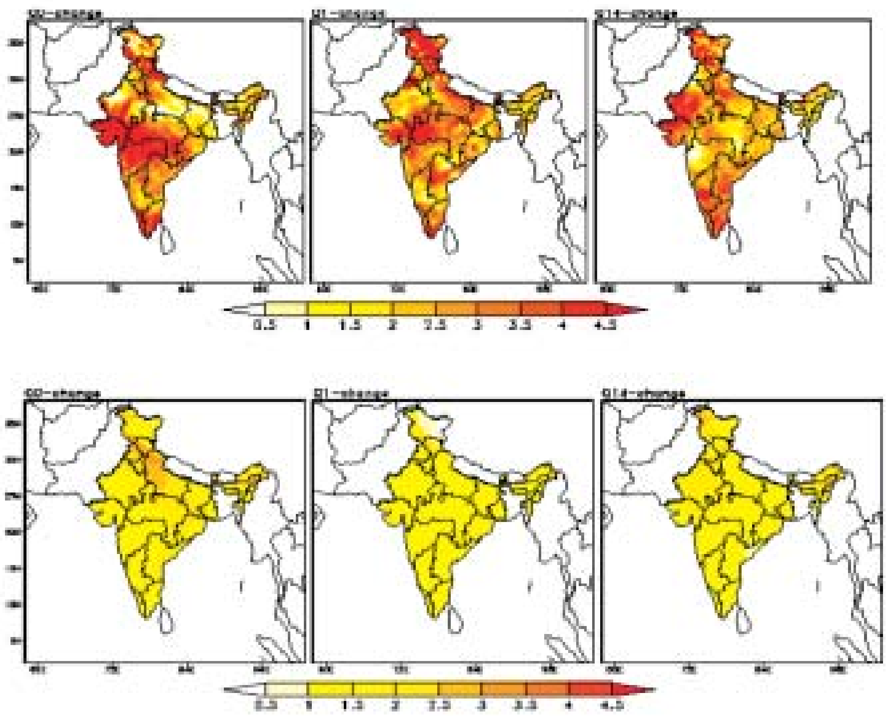


Figure 9.3a: Changes in extreme temperatures in the 2030s with respect to the 1970s. Change in minimum temperature (upper panel); Change in maximum temperature (lower panel).

Himalayan region: In this region, minimum temperatures are projected to rise by 1°C to 4.5°C, and the maximum temperatures may rise by 0.5°C to 2.5°C.

North-Eastern region: Minimum temperatures are likely to rise from 1°C to 2.5°C and maximum temperatures may rise by 1oC to 3.5°C.

Western Ghats: In the Western ghats region, minimum temperatures may rise by 2.0°C to 4.5°C, with minimum increase in those parts of Karnataka that lie in the Western Ghats. Within the region bordering the state of Kerala, the maximum temperature is likely to rise by 1°C–3°C.

Coastal region: The rise in minimum temperatures along the eastern coastal regions is likely to be lower than in the western coastal region. The change in minimum temperatures along the eastern costal region is projected to range from 2.0°C to 4.5°C, the higher end of the change being limited to Tamilnadu. The change in maximum temperature in the 2030s with respect to 1970s ranges between 1°C and 3.5°C. The western coast experiences similar extremes in temperature as the Western Ghats.

2. Extreme precipitation: Extreme precipitation can be defined in terms of number of rainy days if it exceeds the currently observed average number of rainy days in a year (exceeding 2.5 mm) as well as the volume of rain fall in a day if it exceeds particular threshold. Currently, the frequency of rainy days is more in east and North East India and less over western India. Projections for 2030s however indicate that the frequency of the rainy days is likely to decrease in most parts of the country. Presently, intensity of a rainy day is more along the Western coast, especially in the Western Ghats and North east India. The intensity of the rainy days increases in a more warming scenario suggesting both decrease and increase in intensity across India. Specifically, at a regional level in 2030s the extreme precipitation events are likely to be (also see figure 9.3b):

Himalayan region: The number of rainy days in the Himalayan region in 2030s may increase by 5-10 days on an average, with an increase by more than 15 days in the eastern part of the Jammu and Kashmir region. The intensity of rain fall is likely to increase by 1-2mm/ day.

Western Ghats: The number of rainy days are likely decrease along the entire Western coast, including in the Western Ghats, however, 2 runs, namely Q0 and Q1 indicate an increase in rain fall in the range of 1-5 days in the Karnataka region which is contrary to the projections in the Q14 run, which indicates a

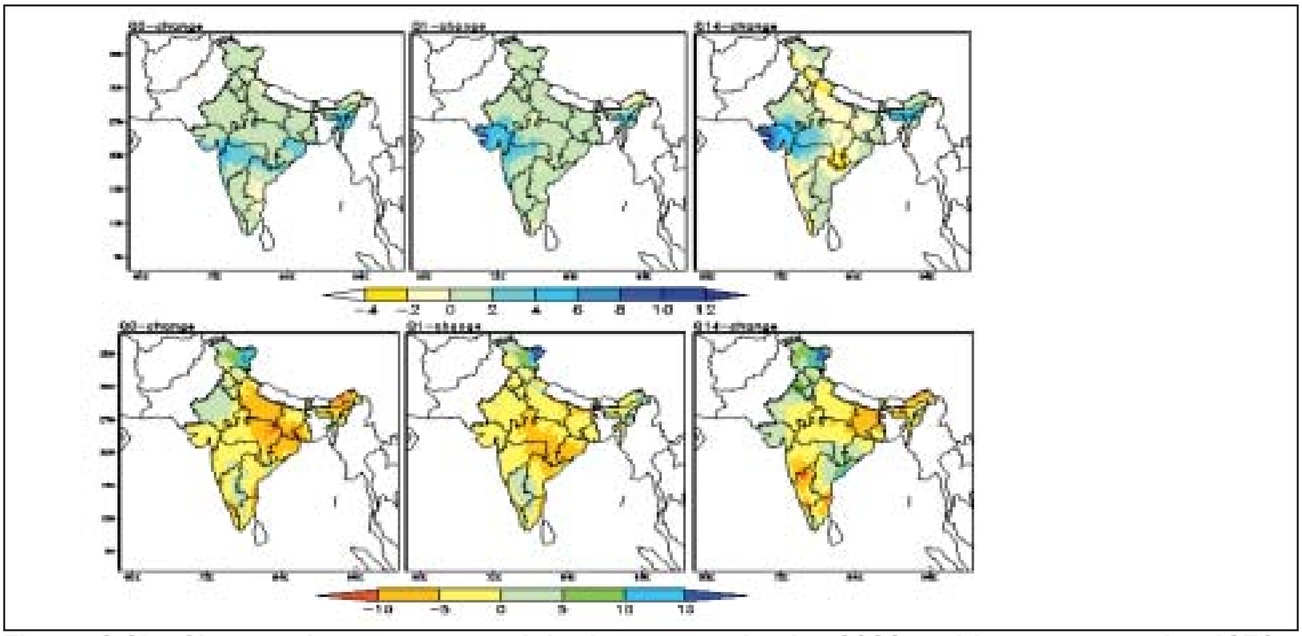


Figure 9.3b: Changes in extreme precipitation events in the 2030s with respect to the 1970s. Change in precipitation intensity (upper panel); Change in the number of rainy days (lower panel).

decrease in the number of rainy days by 5 to 10 days with respect to 1970s. The intensity of rainfall is likely to increase by 1-2 mm/day.

Coastal region: In the eastern coast, the number of rainy days are likely to decrease by 1–5 days, with a slight increase along the Orissa coast. The intensity of rainfall is likely to increase between 1mm/day and 4mm/day, with the maximum increase in the Gujarat region. The projections of extreme precipitation events for the western coast are same as projected for Western Ghats.

North east: In the North-Eastern region, the number of rainy days is likely to decrease by 1–10 days. The intensity of rainfall in the region is likely to increase by 1–6mm/day.

3. Cyclones: Observations since 1986 indicate a decreasing frequency in cyclones along the eastern coast surrounded by the Bay of Bengal and the Northern Indian ocean. Also. no trend is seen in the western coast – along the Arabian sea – for the same period. The projected number of cyclonic disturbances along both the coasts in the 2030s is likely to decrease with respect to the 1970s. However, cyclonic systems might be more intense in the future.

4. Storm surges[1]: Storm surge return periods could only be estimated on a 100-year time scale. All locations along the eastern coast of India that are north of Vishakhapatnam, except at Sagar and Kolkata, show an increase in storm surge levels in the 100-year return period by about 15% to 20% with respect to the 1970s. For Sagar and Kolkata, the two stations considered in the head Bay, the increase in the 100-year return levels was found to be less than 5% for the future senario.

Question 3: What is the magnitude of sea-level rise expected in the 2030s and at longer time periods?

Global sea-level change results from mainly two processes, mostly related to recent climate change, which alter the volume of water in the global ocean through i) thermal expansion and ii) through exchange of water between oceans and other reservoirs (glaciers and ice caps, ice sheets, other land water reservoirs), including through anthropogenic change in land hydrology and the atmosphere. Some oceanographic factors such as changes in ocean circulation or atmospheric pressure also cause changes in regional sea level, while contributing negligibly to changes in the global mean. All these processes cause geographically non-uniform sea-level variations. Vertical land movements, such as resulting from Glacial Isostatic Adjustment (GIA), tectonics, subsidence and sedimentation, influence local sea-level measurements.

Observations based on tide gauge measurements along the Indian coast for a period of 20 years and more, for which significantly consistent data is

[1] The storm surge projections have been made using IPCC SRES A2 scenario. The A2 storyline and scenario family describes a very heterogeneous world underlying self-reliance and preservation of local identities with economic development primarily regionally oriented.

available, indicate that the sea level along the Indian coast has been rising at the rate of about 1.3mm/year on an average.

Globally, the sea level is expected to continue to rise over the next several decades. During 2000–2020 under the SRES A1B scenario in the ensemble of atmosphere–ocean general circulation models (AOGCM), the rate of thermal expansion is projected to be 1.3±0.7 mm/year, and is not significantly different when using the A2 or B1 SRES scenarios. The sea-level rise at such short-term timelines is mainly due to committed thermal expansion, caused by the constant atmospheric composition taken at year 2000 value. In the absence of the availability of regional projections, for the 2030s, global projections can be used as a first approximation of sea-level rise along the Indian coasts in the next few decades

Question 4: What is the projected productivity of important crops in the four key regions?

The impact of climate change is assessed for four major crops of these regions, such as rice, maize and sorghum, apple and coconut plantations. The assessment has been made using a simulation model called InfoCrop (see Chapter 6 for details). The analyses were done for every 1°x1° grid in the entire zone of the four ecosystems with inputs of (a) weather data obtained from India Meteorological Department (IMD) at 1°x1° grids for the baseline period 1961–1990; (b) soil data rescaled to the same grid size, values taken from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) and the ISRIC soil database; (c) crop management data that pertains to normal crop practices as followed by the farmers; (d) genetic coefficients of varieties best suitable for different regions; and (e) climate change scenarios of PRECIS A1B for the 2030 periods.

Due to the non-availability of relevant climate data that could have been used to assess the projected impacts on crops in the Himalayan region, modelling activities could not be carried out per se. However, the trends of production have been analysed *vis-à-vis* trends in climate parameters that help us deduce the likely scenario of apple production in this region in the future. Also, this section deals with the likely impacts of climate change on coastal fisheries based on observation of trends of current fish productivity, climate and sea parameters.

Western ghats

Rice: The productivity of irrigated rice is likely to change +5 to –11%, depending upon the location, in PRECIS A1B 2030 scenario. A majority of the region is projected to lose the yield by about 4%. However, irrigated rice in parts of southern Karnataka and the northern-most districts of Kerala are likely to gain. In the case of rain-fed rice, the change in yield will range between –35 and +35%. A large portion of the region is likely to lose rice yields by up to 10%. The results thus indicate that irrigated rice is able to benefit due to the CO_2 fertilization effect as compared to rain-fed rice, which is supplied with less amount of fertilizers.

Maize and sorghum: Climate change is likely to reduce yields of maize and sorghum by up to 50%, depending upon the region. These crops have a C4 photosynthetic system and hence do not have a relative advantage at higher CO_2 concentrations

Coconut: Coconut yields are projected to increase by up to 30% in the majority of the region by the 2030s. Increase in coconut yield may be mainly attributed to the projected increase in rainfall (~10%) and relatively less increase in temperatures, apart from the CO_2 fertilization benefits. However, some areas like south-west Karnataka, parts of Tamil Nadu and parts of Maharashtra may show reduction in yields by up to 24%.

Coastal region

Rice: Climate change is projected to reduce the yields of irrigated rice by about 10% to 20% in this region. However, in some coastal districts of Maharashtra, northern Andhra Pradesh and Orissa, irrigated rice yields are projected to marginally increase by 5% with respect to the 1970s. On the other hand, rain-fed rice yields are projected to increase up to 15% in many of districts in the east coast, but reduce by up to 20% in the west coast.

Maize and sorghum: Impacts of climate change on irrigated maize in the coastal districts are projected to be high with yield loss between 15% and 50%, whereas in the case of rain-fed maize, the projected yield loss is up to 35%. In some districts of coastal Andhra Pradesh, rain-fed maize yields are likely to increase by 10%. The projected increase in seasonal maximum temperature in these areas is less than 1°C in the 2030 scenario.

Coconut: Yields of coconut are projected to increase in the west coast of India by up to 30% (provided the current level of water is made available in the future scenario as well), while in the east coast specifically in the north coastal districts of Andhra Pradesh, yields may increase by about 10%. All other coastal districts in eastern coast and those in the Gujarat coast are projected to lose coconut yields by up to 40%.

Fisheries:

(a) Oil Sardines: An increase in recruitment and catches of oil sardine during the post-southwest monsoon season along the coastal region, especially along the Kerala coast, is expected in the future due to warming, elevated sea surface temperature (SST), favourable wind (and perhaps current) and increasing coastal upwelling index (CUI) inducing higher chlorophyll concentration during the southwest monsoon.

(b) Indian mackerel: The Indian mackerel is predominant in the south-west coast. However, the mackerel catch along this coast that contributed about 81.3% to the all-India mackerel catch during 1961–76, has decreased to 56.1% during 1997–2006. The catch in north-west coast and north-east coast has increased from 7.5% of the total mackerel catch in 1961–76 to 18% during 1997–2006. The Indian mackerel is able to take advantage of the increase in temperatures of subsurface seawater. Therefore, with increase in global temperatures and sea surface temperatures, it is likely to move northwards and deeper into the seas surrounding it.

(c) Threadfin breams: Threadfin breams (*Nemipterus Japonicus* and *Nemipterus Mesoprion*) are distributed along the entire Indian coast at depths ranging from 10m to 100m. They are short-lived (longevity: about three years), fast growing, highly fecund and medium-sized fish (maximum length: 30–35cm). The threadfin bream spawns optimally in SST between 27.5°C and 28.0°C and when the SST exceeds 28.0°C, the fish shift the spawning activity to seasons when the temperature is around the preferred optimum. Therefore in the climate change context, in the 2030s if the SST exceeds 28°C during April to September, an increase in catch might take place in the comparatively cooler months of October to March.

North-Eastern region

Rice: Irrigated rice yields in this region may range between about –10% to 5% with respect to the 1970s, while the impact on rain-fed rice is likely to be in the range of –35% to 5% in A1B 2030 climate scenarios in North-Eastern regions.

Maize: Maize crop yields are projected to reduce by about 40% in North-Eastern region.

Himalayan region

Apples: Apple production in the Himachal region has decreased between 1982 and 2005 as the increase in maximum temperature has led to a reduction in total chilling hours in the region—a decline of more than 9.1 units per year in last 23 years has taken place. This reduction was more during the months of November and February. With increasing temperatures, it is anticipated that there may be an all-round decrease in apple production in the Himalayan region, and the line of production may shift to higher altitudes.

Question 5: What is the likely impact of climate change on the forests of the four regions in focus?

Using the inputs of the regional climate model, the dynamic vegetation IBIS model has been used to derive the changes in vegetation types across 50km x 50km grids in the four regions in the 2030s. The main climatological parameters required by IBIS are: monthly minimum, maximum and mean temperatures (C), monthly mean precipitation rate (mm/day), monthly mean relative humidity (%), wind speed (m/s) and monthly mean cloudiness (%). The main soil parameter required is the texture of soil (that is, percentage of sand, silt and clay). The model also requires topography information. Observed climatology is obtained from Climate Research Unit (CRU) and the projected climate, is obtained from the runs of regional model PRECIS.

It has been concluded that the forest vegetation types in the four eco-sensitive regions are vulnerable to projected climate change in the short term, that is, in the 2030s, even under a moderate climate change scenario (A1B). The impacts vary from region to region (see description below and Figure 9.5).

Himalayan region: The Himalayan region considered in the study includes the states of Jammu and Kashmir, Uttarakhand and Himachal Pradesh. Of the 98 IBIS grids covering this region, 56% of the grids are projected to undergo change in the 2030s. The net primary productivity (NPP) is projected to increase in the region by about 57% on an average by the 2030s.

North-Eastern region: Much of the dense forests

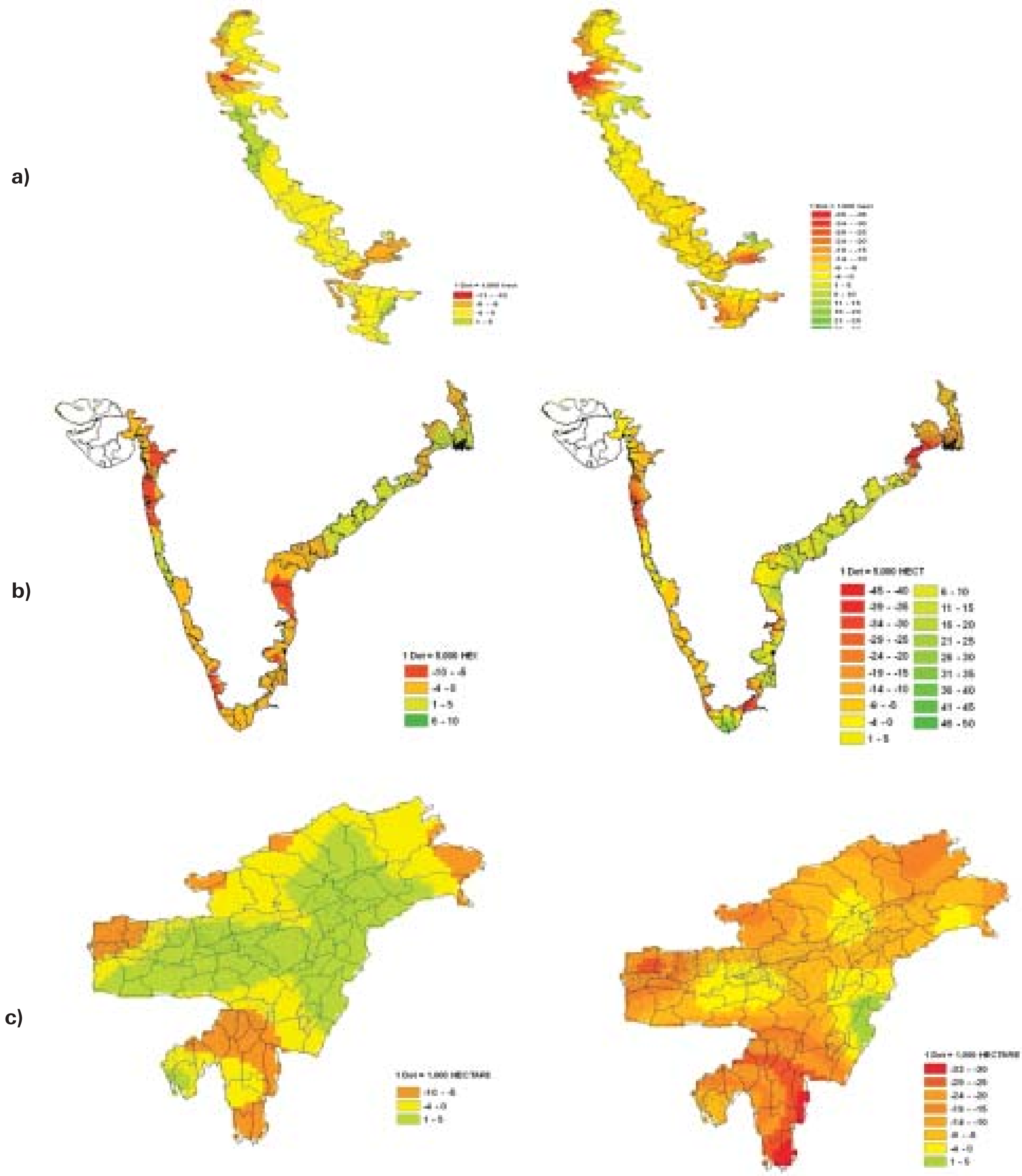
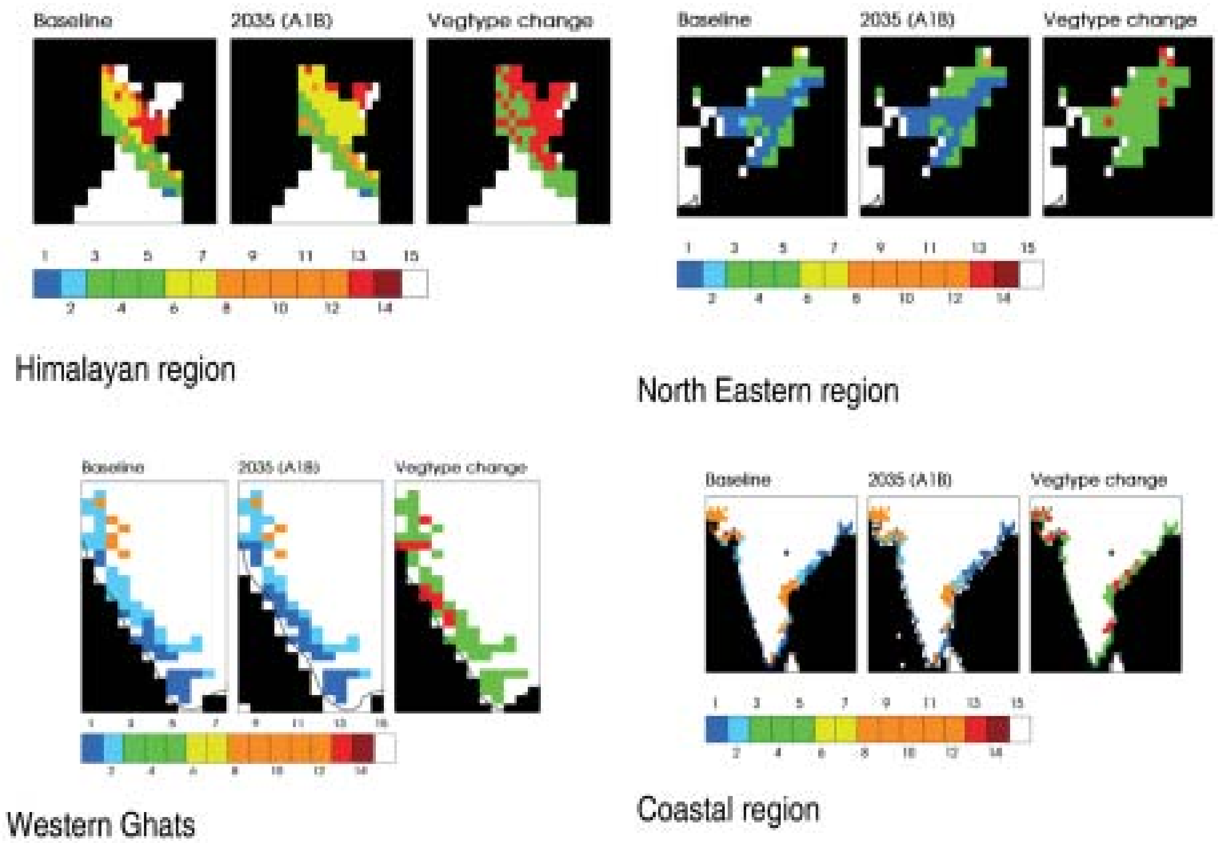


Figure 9.4: Changes in yields of irrigated rice (left panel) and rain-fed rice (right panel) in the 2030s with respect to the 1970s- (a) Western Ghats, (b) Coastal Regions and (c) North-Eastern Region.



Base line and 2035

Key: 1.Tropical wet evergreen forests, 2.Tropical semi evergreen forests, 3.Tropical moist deciduous forest, 4.Tropical dry decidious forest, 5.Tropical thorny/scrub forests, 6.Tropical dry evergreen forest, 7.Littoral and swampy forest, 8.Subtropical broad -leaved hill forests, 9.Subtropical pine forests, 10.Sub-tropical dry evergreen forests, 11.Montane wet temperate forests, 12.Himalayan wet/ moist temperate forests, 13.Himalayan dry temperate forests, 14.Sub-alpine forests, 15.Moist alpine, 16.Dry alpine Forests

Change in 2035 wrt Base line

Key: 1: tropical evergreen forest / woodland, 2: tropical deciduous forest / woodland, 3. temperate evergreen broadleaf forest / woodland, 4: temperate evergreen conifer forest / woodland, 5: temperate deciduous forest / woodland, 6: boreal evergreen forest / woodland, 7: boreal deciduous forest / woodland, 8: mixed forest / woodland, 9: savanna, 10: grassland / steppe, 11: dense shrubland, 12: open shrubland, 13: tundra, 14: desert, 15. polar desert / rock / ice

Figure 9.5: Projected changes in forest productivity in 2030s.

of Assam, Nagaland and Arunachal Pradesh are part of the Himalayan biodiversity hotspot. In the North-Eastern region only about 8% of the 73 forested grids are projected to undergo change in the 2030s. The region is projected to see an increase of 23% in NPP on an average.

Western Ghats: The entire Western Ghats region is covered by 54 forest grids, out of which 18% are projected to undergo change in the 2030s. The NPP of the region is projected to increase by 20% on an average.

Coastal region: The coastal region is defined by all districts that lie on the Indian coast. The entire coastal region is covered by 96 grids, excluding the grids in the Western Ghats. Of these, 30% are projected to undergo change. The NPP in this region is predicted to rise by 31% on an average.

Question 6: What are the likely impacts of climate change on human health in the four regions in the 2030s?

The impacts of climate change on health have been deduced in quantitative as well as qualitative terms. The quantitative aspects that have been studied are only for the transmission of malaria in the 2030s. The transmission windows have been determined in terms of (a) temperature only and (b) temperature plus the relative humidity requirements for transmission. It has been concluded that the projections based on

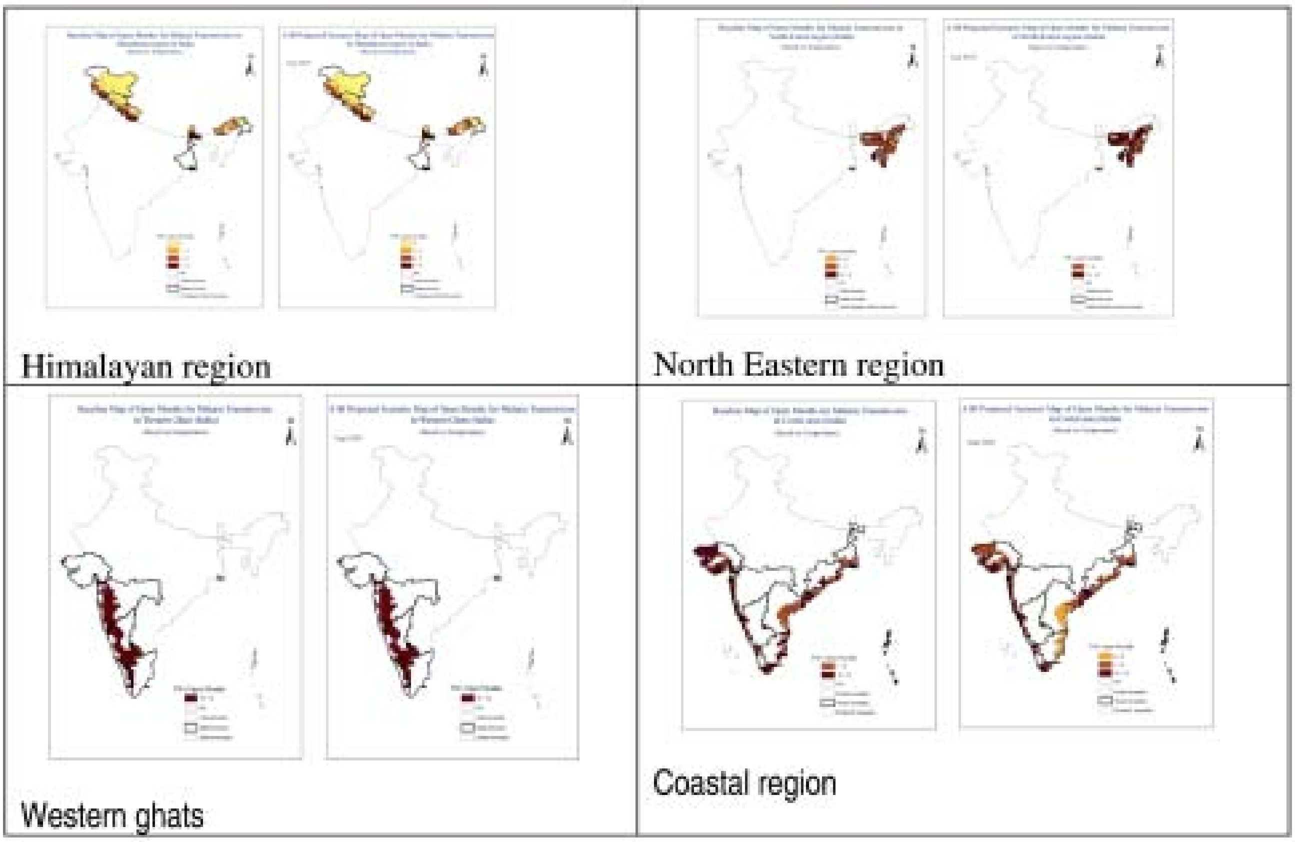


Figure 9.6: projections of malaria transmission windows in the 2030s with respect to the baseline. The right hand panel in each represents the baseline and left hand panel represents the projected changes in the 2030s.

temperature (T) and relative humidity (RH) do not corroborate the observations made in the Himalayan region, Western Ghats and the coastal areas. It indicates that there is dissimilarity in the outside climatic conditions and the resting habitats of mosquito vectors, and they seek micro-niches to rest so that they may get the required RH for survival. The reason of almost similar projections in North-Eastern states may be due prevalent high RH. The specific regional projections are as follows (also see Figure 9.6):

Himalayan region: In this assessment, the study area in the Himalayan region includes the northern states in the North-Eastern region as well as the states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand in the north-western Himalayas. The increase in temperatures may lead to increasing morbidity due to heat stress. Flash floods due to glacial lake outburst floods (GLOF) may lead to large scale landslides and affect food security and hence nutritional health. Projections of malaria transmission windows for the 2030s, based on temperature, reveal the introduction of new foci in Jammu and Kashmir and an increase in the opening of more transmission months in districts of the Himalayan region and north-eastern states. The transmission windows in Jammu and Kashmir, however, still remain open only for 0–2 months in the 2030s.

Western Ghats: Increase in extreme rainfall may lead to flooding, and hence increase in morbidity and mortality due to flood-related diseases such as cholera. Reduction in productivity of cash crops may lead to decrease in employment days and hence an overall decrease in health and life expectancy. Malaria transmission in the Western Ghats is projected to experience no change with respect to current scenario and likely to remain open for 10–12 months in a year.

Coastal regions: The increase in the salinity of water due to sea-level rise and the increase in the intensity of cyclones and storm surges, leading to a rise in water-borne diseases and the scarcity of potable water may be the cause of morbidity in this region in the 2030s. Malaria transmission in coastal areas, particularly the east coast, is projected to experience reduction in the number of months open for transmission. The number of times it is open for in 10–12 months may reduce by 34%.

North-Eastern region: Projected increase of night-time temperature may lead to decrease

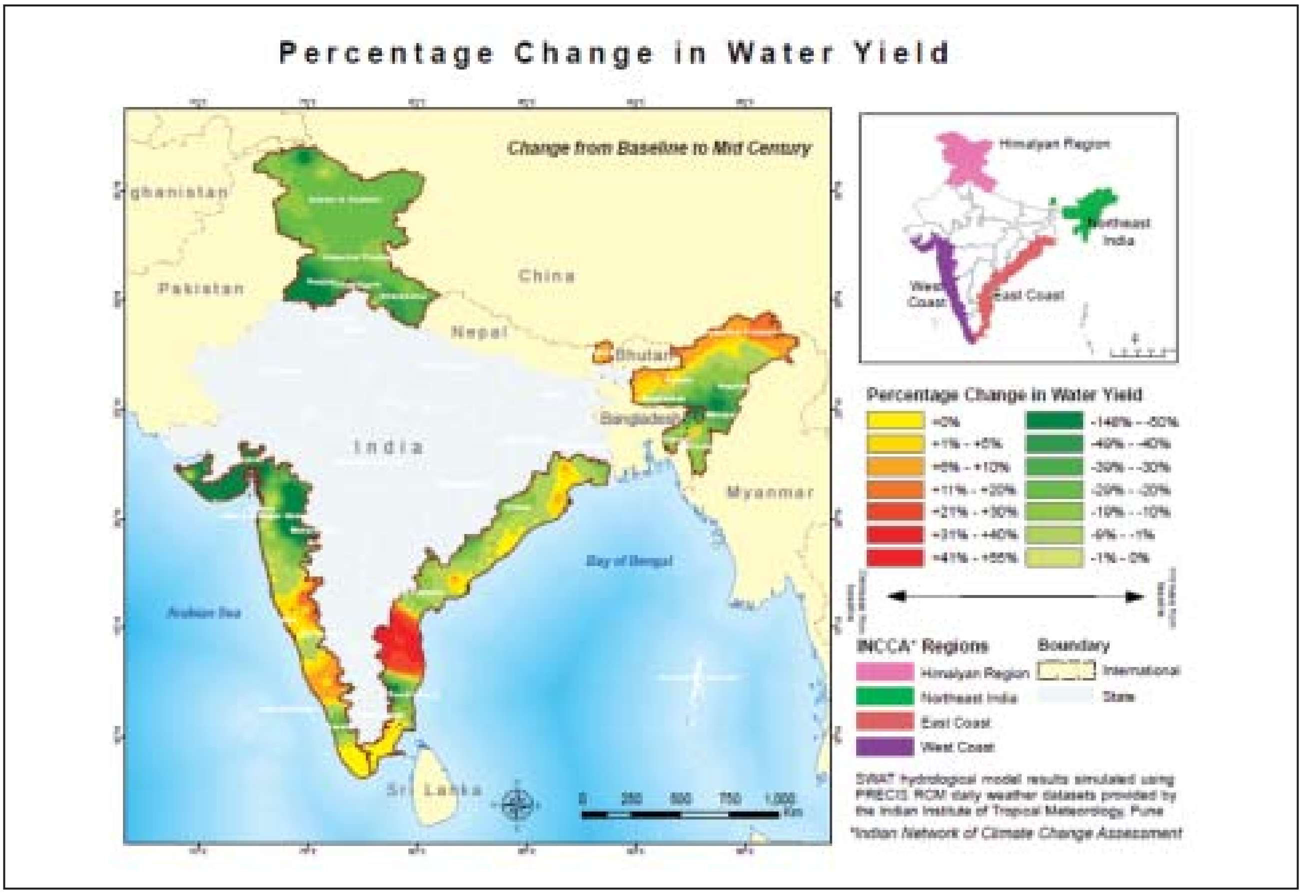


Figure 9.7: Projected changes in water yields (in percentages) in the Himalayan region, North-Eastern region and the coastal regions of India in the 2030s with respect to the 1970s.

in the production of rice and hence affect the nutritional health of the population. Soil erosion due to an increase in the intensity of precipitation events may lead to an increase in occurrence of landslides, affecting agriculture activities, including tea plantations. This might lead to morbidity among the workforce dependent on this. Also there is a likelihood that the windows of transmission of malaria may increasingly remain open for at least for 7–9 and may even remain open for a larger number of months (10–12 months) in a year.

Question 7: What is the impact of climate change on water resources in the four regions in India in the 2030s?

In this study, water resources have been assessed in terms of water yield in the various river basins in the four regions. Water yield is the total surface runoff, which is usually a function of the precipitation, its distribution, evapotranspiration (ET) and soil characteristics. The region-specific projections are given below (also see Figure 9.7).

Himalayan region: The water yield in the Himalayan region, mainly covered by the river Indus, is likely to increase by 5%–20% in most of the areas, with some areas of Jammu and Kashmir and Uttarakhand showing an increase of up to 50% with respect to the 1970s. The impact of increase in precipitation in this region has been reflected in an almost similar pattern of increase in the ET. Increase in the water yield is more for those areas that have experienced a low increase in ET.

North-Eastern region: The trend in precipitation in the North-Eastern region exhibits considerable spatial variability in water yield in the 2030s but is in line with the projected patterns of precipitation and evapotranspiration. As compared to the 1970s, in the 2030s the northern parts of the region show a reduction in precipitation that varies from 3% in the north-western part of the North-East to about 12% in the north-eastern part. The central portion of the North-East shows an increase in precipitation varying from 0% to as much as 25%. However, the majority of the North-Eastern region, except for Mizoram,

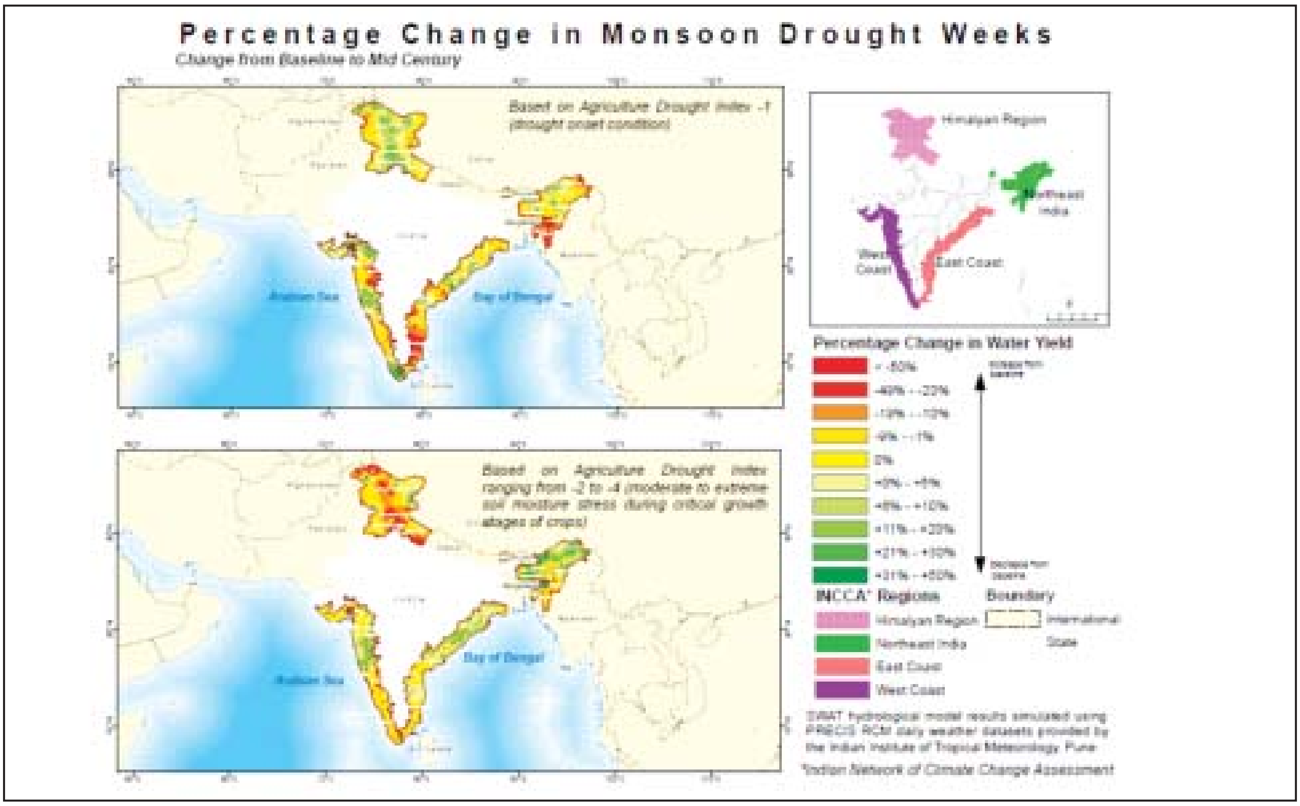


Figure 9.8a: Change in monsoon drought weeks towards the 2030s with respect to the 1970s

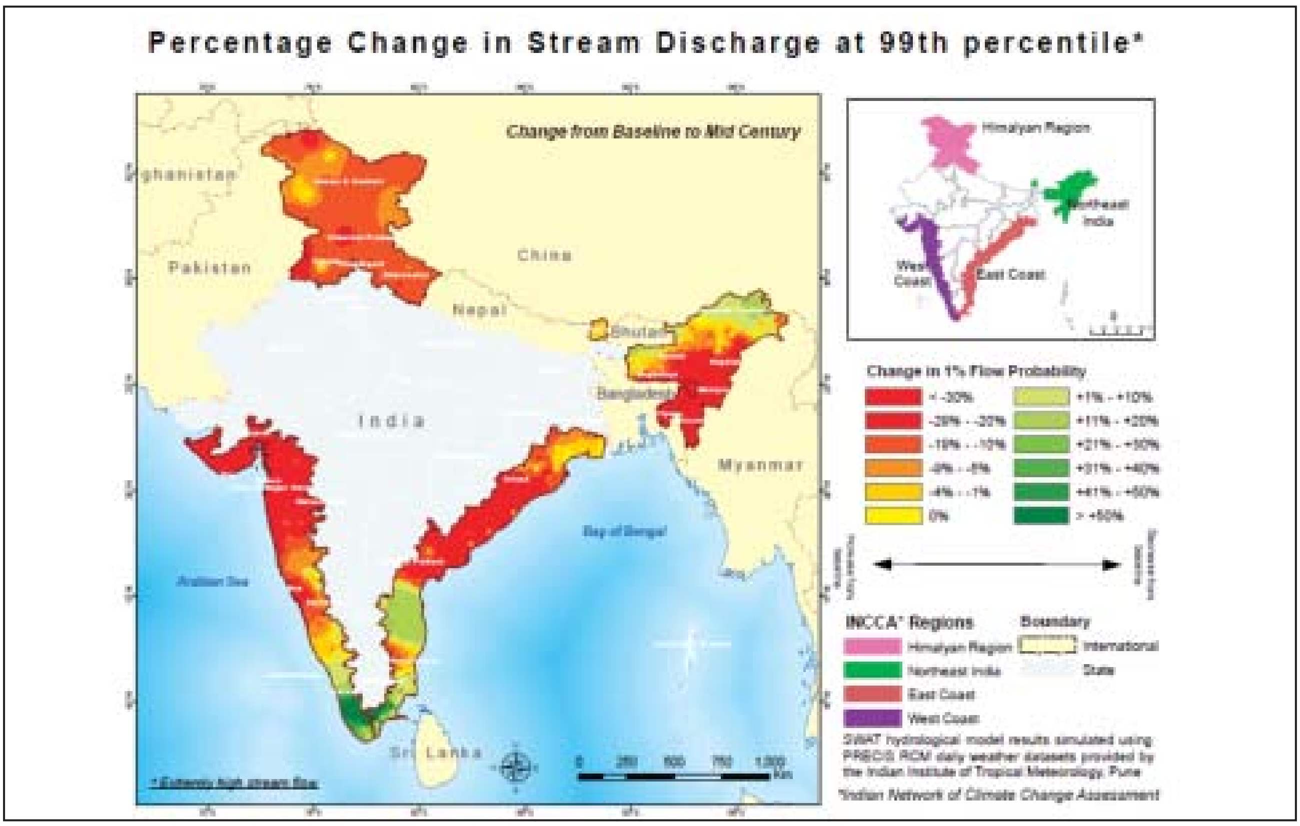


Figure 9.8b: Change in the magnitude of flood (stream discharge at 99th percentile) towards the 2030s with respect to 1970s

Tripura, Manipur and Assam, shows an increase in ET in the 2030s. As a result, the reduction in water yield for the Arunachal Pradesh is up to about 20%. There is an increase in the water yield to up to about 40% in Assam and Manipur.

Western Ghats: The Western Ghats region exhibits wide variability in water yield in the 2030s. The northern portion of the Western Ghats shows a decrease in the water yield ranging from 10%–50% in the 2030s with respect to the 1970s. The central portion, however, indicates an increase in water yield between 5%–20%. The southern portions of Karnataka and Kerala show a decrease of up to 10% in the yields.

Coastal region: There is a general reduction in water yield in the eastern coastal region of West Bengal, Orissa and the northern coastal regions of Andhra Pradesh. The reduction in water yield in the 2030s in this region is as less as 40%. However, in the southern parts of Andhra Pradesh and northern parts of Tamil Nadu, water yield is projected to rise by 10%–40%. The western coastal region, also shows an overall reduction in water yield (ranging from 1% to 50%), except, in the coast along Karantaka, where it shows an increase of 10%–20% in the water yield in the 2030s with respect to the 1970s. No change in water yield is projected for the 2030s in the southern tip of the coastal region.

Question 8: What are the projected changes in droughts and floods in the four regions in focus?

1. Droughts: The percentage change in the spatial distribution of Soil Moisture Deficit Index (SMDI) between 1970s and 2030s has been used for defining the drought index. The weeks when the soil moisture deficit may start drought development (drought index value between 0 and -1) as well as the areas that may fall under moderate to extreme drought conditions (drought index value between -1 and -4) have been assessed. There is an increase in the drought development in those areas of various regions that have either a projected decrease in precipitation or an enhanced level of evapotranspiration in the 2030s. Similarly, the weeks belonging to moderate soil moisture stress show an increase in severity of drought from the baseline to the mid-century scenario, which is self-evident. It is very evident from the depiction that moderate to extreme drought severity is pronounced for the Himalayan region where the increase is more than 20% for many areas despite the overall increase in precipitation (see Figure 9.8a).

2. Floods: Possible floods have been projected using the daily outflow discharge in each sub-basin (generated by the SWAT model). The changes in magnitude of flood peaks above the 99th percentile flow have been ascertained under the baseline (1961–1990) and the mid-century scenario (2021–2050). Change in peak discharge equal to or exceeding at 1% frequency in the 1970s and the 2030s for various regions indicates that flooding in the 2030s varies between 10% and over 30% of the magnitudes in the 1970s in most of the regions. This has a very severe implication for existing infrastructure such as dams, bridges, roads, etc., and shall require appropriate adaptation measures to be taken up (Figure 9.8b).

9.2 Challenges, gaps and uncertainties

Impact assessment research is a complex challenge because it includes physical, biological and socio-economic aspects. Tools and data used for these assessments need to continuously evolve to be in sync with the latest advances in science and maintain the scientific rigour of the findings. The results obtained from this assessment of the four regions in India are though the best methods that are available so far. However, research gaps in terms of data gaps and uncertainties persist. Further, the impact assessments documented here are mostly sectoral,and have not explicitly looked at inter-sectoral linkages or at the human dimension. Identifying and using appropriate sectoral tools and an integrated assessment approach with adequate data inputs can lead to improved assessments with reduced uncertainties. The following sections identify some of the challenges and gaps of this assessment.

It is essential to have more scientifically rigorous and policy relevant assessments. This chapter articulates some of the challenges and their solutions, which can be implemented in the future to remedy the limitations of this study.

9.2.1. Demarcating the regions

India is a climatologically diverse country. Its climate is characteristic of the subregional physical features, which also typifies its very diverse biological reserves and natural resources. The climate of each region, though very distinctive, merges seamlessly. Therefore, demarcating these four regions has been difficult as they do not conform to the standard agroclimatic zones or the climatic zones[2].

The description of the extent and location of Western Ghats is taken from literature. They were then used to extract grids for deciphering the observed climate and climate projections. Demarcating the coastal region has been a challenge. The coastal zone includes 5,500km along the mainland and 20,000kms along its various islands. Demarcating the coastal zone, as defined in the CRZ notification 2010 of MoEF[3], would have been a separate task in itself. For convenience, only the coastal areas along the mainland have been included in the assessment and the impacts have been estimated for the region that encompasses the coastal districts.

9.2.2. Data gaps and Uncertainty in modeling

Climate: Presently the climate projections are based on one regional model HadRM3, using a single socio-economic scenario (A1B SRES scenario) that drives the trends of the greenhouse gases in the model. Further, there are inherent uncertainties in the key assumptions about and relationships between future population, socio-economic development and technical changes that constitute the basis of the IPCC SRES Scenarios. The uncertainty in emissions can be allowed for by making climate projections for a range of these SRES emissions scenarios. Also, an imperfect understanding of some of the processes and physics in the carbon cycle and chemical reactions in the atmosphere generates uncertainties in the conversion of emissions to concentration. Uncertainties also arise due to the incomplete description of key processes and feedbacks in the model. This can be reduced by running ensembles of future climate projections using the same model and the same emission or concentration scenarios. Further, regionalization techniques carry with them errors in the driving general circulation model (GCM) fields.

The resolution of the regional climate model (RCM) should be high enough to resolve the fine-scale details that characterize regional forcings. The PRECIS at 50km resolution can provide good simulations of daily precipitation over the broad plateau region in India. However, detailed projections for inner Himalayan valleys, the hills in the North-East and the Western Ghats require a much higher resolution. Therefore, it is perceived that a higher resolution model (at least 25km x 25km or less) will be more appropriate for capturing the orography of the Indian region.

Sea-level rise: Since the beginning of satellite measurements, the sea level has risen about 80% faster, at 3.4 millimetres per year, than the average IPCC model projection of 1.9 millimetres per year (Nature, http://www.nature.com/climate/2010/1004/full/climate.2010.29.html, accessed on 18th October, 2010). The difference between the semi-empirical estimates and the model-based estimates of the IPCC can be attributed largely to the response of continental ice to greenhouse warming. The IPCC range assumes a near-zero net contribution of the Greenland and Antarctic ice sheets to future sea-level rise, on the basis that Antarctica is expected to gain mass from an increase in snowfall. Observations show, however, that both ice sheets have been losing mass at an accelerating rate over the past two decades. A number of recent studies, taking the semi-empirical approach, have predicted a sea-level rise exceeding one metre in the twenty-first century if GHG emissions continue to escalate—a figure much higher than that projected by the IPCC. Because of the limitations of the physical climate models used by the IPCC, alternative approaches to estimating sea-level rise may be explored which are semi-empirical in nature and based on the idea that the rate of sea-level rise is proportional to the amount of global warming—the warmer it gets, the faster ice melts. Past sea level and temperature data is used to quantify this effect. Also, increase in the meltwater from the Himalayan glaciers may contribute to the rise in the local sea level along the Indian coastline.

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[2] Climatologically, the entire Indian region is divided as western Himalayas, north-west, north-east, northern-central region, eastern coast, western coast and the interior plateau.

[3] According to the draft CRZ Notification, 2010 (MoEF, 2010), the coastal zone includes area up to 500mts from the high tide line on the landward side, including the intertidal area on the seafront; 100mts or the width of the creek, whichever is less, from the high tide line on the landward side along tidal-influenced waterbodies and the land area falling in the hazard zone beyond 500mts plus the aquatic area up to 12 nautical miles in the territorial waters and tidal-influenced waterbodies.

Agriculture: The InfoCrop model does not take into account the socio-economic trends, and hence does not account for technological improvements in the future, farmers' economic status, market demand, and future land use for agriculture, etc., which drive the changes in yields and production to a large extent. The major limitation of this study is the assumption that future rainfall distribution will remain the same as in the baseline period. Further, even though the model has the provision, pests and disease scenarios are not integrated in this assessment due to the lack of proper scientific data.

Apart from the above, the primary database on farm inputs applied by the farmers needs to be developed on a fine gridded level. In this simulation analysis, the yields are calibrated to current district-level yields to overcome such limitation. For working out the comprehensive impacts, there is a need to link other influential biophysical and socio-economic driving forces—those which are indirectly impacted by climate change but influence agriculture. Suitable agronomic management options can act as one of the important adaptation strategies to face climate change. We also need to construct climate change scenarios on better spatial and temporal scales. Moreover, there exists a lot of uncertainty in the projections of future climate, particularly with reference to rainfall.

Natural ecosystems and biodiversity: The IBIS model used for assessing changes in vegetation and net primary productivity in forests in 2030s requires an extensive finely gridded database on soil, water, and climate parameters, in addition to types of biome. As the full set of input parameters could not be assembled satisfactorily at even one of the locations, exploratory runs were made based on the database using a range of default/approximate values. These could reproduce the current vegetation patterns only to a low level of accuracy. For example, tropical forests such as those in the Western Ghats are highly diverse with vegetation, changing every few kilometres. It is necessary that a long-term observational plan be set in place that identifies the vegetation type at least within 1km x 1km.

Water: The SWAT model used for assessing water yields in the various regions requires information on terrain, soil profile and land use of the area as input. These have been obtained from global sources in the absence of accessibility to nationally generated data. Further, the study determines the present water availability in space and time without incorporating any man-made changes like dams, diversions, etc These entities are assumed to be static in future as well, which might not be the case. Therefore, a scenario projection is required that can realistically capture the trends of these parameters.

9.3 Way forward

9.3.1 Addressing data gaps

Climate change is an inter-disciplinary subject that cuts across physics, chemistry, biology, earth sciences, economics, technology development, etc. Therefore, multiple data sets are required even to simulate the current situations by different models. So, current data on observations on climate, natural ecosystems, soils, water from different sources, agricultural productivity and inputs and socio-economic parameters amongst others are continuously required. In this context, it is essential to have accessibility to databases that reflect national and regional concerns. Various agencies in India are presently collecting such data on a regular basis. However, efforts need to be made to establish an effective mechanism for sharing and accessing this data in formats that can be easily deciphered.

9.3.2 Systematic observations

New systematic observations that are long term in nature must be taken up on a continuous basis in India to add to the South–South database on physical and biological systems (for example, data on forest vegetation types). In India, forest observation plots were established in the early nineteenth century to observe the changes in nature of forest vegetation in different regions. However, most of these plots have not been continuously observed, and as a result we have failed to gather data on the vegetation types, forest soil characteristics etc. that could have been effectively used for modelling. The Forest Survey of India (FSI) is now making efforts to revive these plots. Even so, these have to be observed for a long period of time to attribute the effects of climate on the systems.

9.3.3 Accessing multiple regional climate models with higher resolution

So far, all the impact assessments have been made using one regional climate model developed by the Hadley Centre, UK. Other regional models may be used but they have to be validated by simulating observed climate. This is important because multiple climate model outputs obtained using a large number of perceivable socio-economic scenarios can capture the probable path of growth. This gives a clearer picture of GHG emission trends, the behaviour of the future climate and impacts on various biophysical systems and the economic sectors dependent on such systems. Thus, it can reduce the uncertainty of our estimates to an extent. estimates to an extent.

9.3.4 Building capacity

A rapid building up of capacity is essential to enhance the level of climate change research in India. In this context, scientific cooperation and collaboration is essential, be it in the area of climate modelling, impact assessment, integrated impact assessments, research on mitigation of climate change concerns and adaptation to impacts of climate change. Extensive networking of researchers within India, through platforms such as the Indian Network for Climate Change Assessment, can be used to create a critical mass of researchers who can carry forward the work on science, impacts and mitigation of climate change in India.

9.3.5 Making a pan-Indian regional assessment for informed policymaking at all levels

(a) Other regions in India are equally important and it would be worthwhile to make future assessments keeping in view the division of the Indian region according to its climate. A study of the impacts on all economic activities, which are sensitive to climate, needs to be made in regions such as the western Himalayas, north-west, north-east, northern-central region, eastern coast, western coast, and the interior plateau. (b) The Government of India, has initiated the process of developing climate change action plans for the states. Therefore, it might be interesting to have a state-level assessment of the impacts of climate change for sectors that are important for the state. This will, in turn, help develop state-specific action plans for adapting to climate change. These can be made for the short-, medium- and long-term periods, taking into account the requirements of planning for a perceptible future in the short term and the very nature of climate change issues, which are long term.

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Glossary of Key Terms

A1B: The A1B scenario assumes significant innovations in energy technologies, which improve energy efficiency and reduce the cost of energy supply. Such improvements occur across the board and neither favour, nor penalize, particular groups of technologies. A1B assumes, in particular, drastic reductions in power-generation costs, through the use of solar, wind, and other modern renewable energies, and significant progress in gas exploration, production, and transport. This results in a balanced mix of technologies and supply sources with technology improvements and resource assumptions such that no single source of energy is overly dominant.

A2: The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per-capita economic growth and technological change more fragmented and slower than other storylines.

Alpine: The bio-geographic zone made up of slopes above the treeline, characterised by the presence of rosette-forming herbaceous plants and low, shrubby, slow-growing woody plants.

B2: The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

Biodiversity: The total diversity of all organisms and ecosystems at various spatial scales (from genes to entire biomes).

C3 plants: Plants that produce a three-carbon compound during photosynthesis, including most trees and agricultural crops such as rice, wheat, soybeans, potatoes and vegetables.

C4 plants: Plants, mainly of tropical origin, that produce a four-carbon compound during photosynthesis, including many grasses and the agriculturally important crops maize, sugar cane, millet and sorghum.

Climate: Climate in a narrow sense is usually defined as the 'average weather', or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. The classical period of time is 30 years, as defined by the World Meteorological Organization (WMO).

Climate change: Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), which defines 'climate change' as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. See also climate variability.

Committed climate change: Due to the thermal inertia of the ocean and slow processes in the biosphere, the cryosphere and land surfaces, the climate would continue to change even if the atmospheric composition was held fixed at today's values. Past change in atmospheric composition leads to a 'committed' climate change, which continues for as long as a radiative imbalance persists and until all components of the climate system have adjusted to a new state. The further change in temperature after the composition of the atmosphere is held constant is referred to as the committed warming or warming commitment. Climate change commitment includes other future changes, for example in the hydrological cycle, in extreme weather events, and in sea-level rise.

Chlorophyll -*a*: Is member of the most important class of pigments that absorbs energy from lightand converts carbon dioxide to carbohydrates. Chlorophyll occurs in several distinct forms: chlorophylls *a* and *b* are the major types found in higher plants and green algae; chlorophylls *c* and *d* are found, often with a, in different algae.

Climate model: A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity (i.e., for any one component or combination of components a hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterisations are involved. Coupled atmosphere/ocean/sea-ice General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system. More complex models include active chemistry and biology. Climate models are applied, as a research tool, to study and simulate the climate, but also for operational purposes, including monthly, seasonal, and inter-annual climate predictions.

Climate prediction: A climate prediction or climate forecast is the result of an attempt to produce an estimate of the actual evolution of the climate in the future, e.g., at seasonal, inter-annual or long-term time scales. See also climate projection and climate (change) scenario.

Climate projection: The calculated response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based on simulations by climate models. Climate projections are distinguished from climate predictions, in that the former critically depend on the emissions/concentration/radiative forcing scenario used, and therefore on highly uncertain assumptions of future socio-economic and technological development.

Climate (change) scenario: A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships and assumptions of radiative forcing, typically constructed for explicit use as input to climate change impact models. A 'climate change scenario' is the difference between a climate scenario and the current climate.

Climate system: The climate system is defined by the dynamics and interactions of five major components: atmosphere, hydrosphere, cryosphere, land surface, and biosphere. Climate system dynamics are driven by both internal and external forcing, such as volcanic eruptions, solar variations, or human-induced modifications to the planetary radiative balance, for instance via anthropogenic emissions of greenhouse gases and/or land-use changes.

Climate threshold: The point at which external forcing of the climate system, such as the increasing atmospheric concentration of greenhouse gases, triggers a significant climatic or environmental event which is considered unalterable, or recoverable only on very long time scales, such as widespread bleaching of corals or a collapse of oceanic circulation systems.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also climate change.

Coastal region: In this assessment, for the purposes of the climatogical assessments, the coastal region covers the eastern coast and the western coast, including the western ghats.

Communicable disease: An infectious disease caused by transmission of an infective biological agent (virus, bacterium, protozoan, or multicellular macroparasite).

Control run: A model run carried out to provide a 'baseline' for comparison with climate-change experiments. The control run uses constant values for the radiative forcing due to greenhouse gases and anthropogenic aerosols appropriate to pre-industrial conditions.

Coastal Upwelling Index (CUI): is a measure of the volume of water that upwells along the coast; it identifies the amount of offshore transport of surface waters due to geostrophic wind fields. Indices are in units of cubic meters per second along each 100 meters of coastline. Positive numbers indicate offshore transport for the upwelling index product.

Drought: The phenomenon that exists when precipitation is significantly below normal recorded levels, causing serious hydrological imbalances that often adversely affect land resources and production systems.

Dynamic Global Vegetation Model (DGVM): Models that simulate vegetation development and dynamics through space and time, as driven by climate and other environmental changes.

East coast: East cost covers the coastal areas in the eastern side of the peninsula adjoining the Bay of Bengal.

Ecosystem: The interactive system formed from all living organisms and their abiotic (physical and chemical) environment within a given area. Ecosystems cover a hierarchy of spatial scales and can comprise the entire globe, biomes at the continental scale or small, well-circumscribed systems such as a small pond.

Ecosystem services: Ecological processes or functions having monetary or non-monetary value to individuals or society at large. There are (i) supporting services such as productivity or biodiversity maintenance, (ii) provisioning services such as food, fibre, or fish, (iii) regulating services such as climate regulation or carbon sequestration, and (iv) cultural services such as tourism or spiritual and aesthetic appreciation.

Emissions scenario: A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships. In 1992, the IPCC presented a set of emissions scenarios that were used as a basis for the climate projections in the Second Assessment Report. These emissions scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović *et al*., 2000), new emissions scenarios – the so-called SRES scenarios – were published.

Evapotranspiration: The combined process of water evaporation from the Earth's surface and transpiration from vegetation.

Extreme weather event: An event that is rare within its statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called 'extreme weather' may vary from place to place. Extreme weather events may typically include floods and droughts.

Greenhouse effect: The process in which the absorption of infrared radiation by the atmosphere warms the Earth. In common parlance, the term 'greenhouse effect' may be used to refer either to the natural greenhouse effect, due to naturally occurring greenhouse gases, or to the enhanced (anthropogenic) greenhouse effect, which results from gases emitted as a result of human activities.

Greenhouse gas: Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere. As well as CO2, N2O, and CH4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

(climate change) Impacts: The effects of climate change on natural and human systems.

Himalayan region: Comprises of the mountainous region stretching over 2500 km from north-west to north-east of India and covering 12 Indian states.

HadRM3: HadRM3 is the Met Office Hadley Centre's regional climate model used to produce regional projections of the future climate.

IBIS (Integrated Biosphere Simulator): IBIS is a dynamic vegetation model designed to explicitly link land surface and hydrological processes, terrestrial biogeochemical cycles, and vegetation dynamics within a single physically consistent framework.

INCCA: Indian Network for Climate Change Assessment. An initiative of the Ministry of Environment and Forests, Government of India.

Info Crop: InfoCrop is a generic crop growth model that can simulate the effects of weather, soil, agronomic managements (including planting, nitrogen, residue and irrigation) and major pests on crop growth and yield. It has been developed by the scientists of Indian Agriculture Research Institute.

Integrated assessment: An interdisciplinary process of combining, interpreting and communicating knowledge from diverse scientific disciplines so that all relevant aspects of a complex societal issue can be evaluated and considered for the benefit of decision-making.

Intergovernmental Panel on Climate Change (IPCC): Established jointly by United Nations Environment Programme and WMO in 1988, it is mandated to produce scientific assessments on various aspects of climate change.

Likelihood: The likelihood of an occurrence, an outcome or a result, where this can be estimated probabilistically, is expressed in this Report using a standard terminology, defined in the Introduction.

Malaria: Endemic or epidemic parasitic disease caused by species of the genus Plasmodium (Protozoa) and transmitted by mosquitoes of the genus Anopheles; produces bouts of high fever and systemic disorders, affects about 300 million and kills approximately 2 million people worldwide every year.

Monsoon: A monsoon is a tropical and sub-tropical seasonal reversal in both the surface winds and associated precipitation.

Montane: The biogeographic zone made up of relatively moist, cool upland slopes below the sub-alpine zone that is characterised by the presence of mixed deciduous at lower and coniferous evergreen forests at higher elevations.

Morbidity: Rate of occurrence of disease or other health disorders within a population, taking account of the age-specific morbidity rates. Morbidity indicators include chronic disease incidence/prevalence, rates of hospitalisation, primary care consultations, disability-days (i.e., days of absence from work), and prevalence of symptoms.

Mortality: Rate of occurrence of death within a population. Calculation of mortality takes account of age-specific death rates, and can thus yield measures of life expectancy and the extent of premature death.

Net Primary Production (NPP): Net Primary Production is the gross primary production minus autotrophic respiration, i.e., the sum of metabolic processes for plant growth and maintenance, over the same area.

North-Eastern region: Refers to the easternmost part of India consisting of seven states, which also includes a part of the Himalayan region.

Phenology: The study of natural phenomena that recur periodically (e.g., development stages, migration) and their relation to climate and seasonal changes.

PRECIS: is essentially a regional climate modelling system. It is based on the third generation of the Hadley Centre's Regional Climate Model (HadRM3), together with user-friendly data processing and visualization interface.

Projection: The potential evolution of a quality or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasise that projections involve assumptions – concerning, for example, future socio-economic and technological developments, that may or may not be realised – and are therefore subject to substantial uncertainty. See also climate projection and climate prediction.

Runoff : That part of precipitation that does not evaporate and is not transpired.

Sea-level rise: An increase in the mean level of the ocean. Eustatic sea-level rise is a change in global average sea level brought about by an increase in the volume of the world ocean. Relative sea-level rise occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land-level uplift, relative sea level can fall.

Sea Surface Temperature (SST): Is the water temperature at 1 meter below the sea surface.

Socio-economic scenarios: Scenarios concerning future conditions in terms of population, Gross Domestic Product and other socio-economic factors relevant to understanding the implications of climate change.

SRES: The storylines and associated population, GDP and emissions scenarios associated with the Special Report on Emissions Scenarios (SRES) (Nakićenović *et al*., 2000), and the resulting climate change and sea-level rise scenarios. Four families of socio-economic scenario (A1, A2, B1 and B2) represent different world futures in two distinct dimensions: a focus on economic versus environmental concerns, and global versus regional development patterns.

Sub-alpine: The biogeographic zone below the tree line and above the montane zone that is characterised by the presence of coniferous forest and trees.

Surface runoff: The water that travels over the land surface to the nearest surface stream; runoff of a drainage basin that has not passed beneath the surface since precipitation.

SWAT: is a distributed parameter and continuous time simulation model. The SWAT model has been developed to predict the response to natural inputs as well as the manmade interventions on water and sediment yields in un-gauged catchments. The model (a) is physically based; (b) uses readily available inputs; (c) is computationally efficient to operate and (d) is continuous time and capable of simulating long periods for computing the effects of management changes.

Temperature Humidity Index (THI): It is used to represent thermal stress due to the combined effects of air temperature and humidity. THI is used as a weather safety index to monitor and reduce heat-stress-related losses.

Thermal expansion: In connection with sea-level rise, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level.

Uncertainty: An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values calculated by various models) or by qualitative statements (e.g., reflecting the judgement of a team of experts).

United Nations Framework Convention on Climate Change (UNFCCC): The Convention was adopted on 9 May 1992, in New York, and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It contains commitments for all Parties. Under the Convention, Parties included in Annex I aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered into force in March 1994.

Vector: A blood-sucking organism, such as an insect, that transmits a pathogen from one host to another. See also vector-borne diseases.

Vector-borne diseases: Diseases that are transmitted between hosts by a vector organism (such as a mosquito or tick); e.g., malaria, dengue fever and leishmaniasis.

Vulnerability: is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

West coast: For the purposes of this assessment, the west coast represents the coastal areas on the west coast. This also includes the Western ghats. The west coast is also one of the meteorological divisions for climatological assessments.

Western Ghats: is a narrow strip of mountain range along the west coast of India. See west coast.

INCCA Reports:

1. **India: Greenhouse Gas Emissions 2007**, *May 2010*
2. **Climate Change and India: A 4x4 Assessment** - A Sectoral and Regional Analysis for 2030s, *November 2010*

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