CLIMATE CHANGE AND INDIA:
A 4x4 Assessment
A sectoral and regional analysis for 2030
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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 70 million 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 scenarios 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.
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 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:

1. Assess the drivers and implications of climate change.
2. Prepare climate change assessments once every two years (GHG estimations and impacts of climate change, associated vulnerabilities and adaptation).
3. Develop decision support systems.
4. Build disaster risk management and climate change management.

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 other socio-economic 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
- Undertaking an assessment of black carbon and its impact on ecosystems.
- Undertaking a long-term ecological, social, and economic monitoring of ecosystems to identify patterns and drivers of change that influence the sustainability of livelihoods dependent on these systems across India.
- Building capacity through thematic workshops and training programmes.
- Synthesizing 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 threats because of the projected changes in climate (NAPCC, 2007). The 4x4 assessment

Climate change has enormous implications for the natural resources and livelihoods of the people. The available knowledge suggests adverse implications for key sectors of the economy. Accordingly, a 4x4 assessment has been devised to ascertain the impacts in 2030s. 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 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) Developing Scenarios; (4) Impact Assessments; (5) Ecoysystem Monitoring; (6) Integrated V&A Assessments; (7) Greenhouse Gas Inventory Programme; (8) Developing Scenarios; and (9) Impact Assessments.
Chapter 4: Key sectors and regions: This chapter examines the effects of climate change on different sectors and regions of India. It includes the analysis of key sectors such as agriculture, energy, water, and coastal areas. The chapter describes the changes in frequency and intensity of extreme events such as cyclones and storm surges.

Chapter 5: Agriculture: This chapter focuses on the impacts of climate change on agriculture. It discusses the changes in temperature, precipitation, and pattern of extreme events and their implications for agricultural productivity. The chapter also highlights the potential threats to crop productivity and identifies the impacts of climate change on different crops such as rice, wheat, and cotton.

Chapter 6: Natural Ecosystems and Forests: This chapter addresses the impacts of climate change on natural ecosystems and forests. It examines the changes in temperature and precipitation and their effects on forest cover, biodiversity, and associated services.

Chapter 7: Human Health: This chapter discusses the impacts of climate change on human health. It identifies the challenges posed by climate change on various health conditions such as vector-borne diseases, heat-related illnesses, and malnutrition.

Chapter 8: Water: This chapter analyzes the impacts of climate change on water resources. It examines the changes in temperature, precipitation, and river flows and their implications for water availability and quality.

Chapter 9: Coastal areas: This chapter focuses on the impacts of climate change on coastal areas. It discusses the changing trend of sea-level rise, storm surges, and hurricanes and their effects on coastal infrastructure and communities.
Climate is one of the most important determinants of global vegetation patterns and has significant influence on the distribution, structure and ecology of natural ecosystems including forests. Changes in climate alter the configuration of forest ecosystems. 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.

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.

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 evapotranspiration 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.

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.
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 scales are not very comprehensive. There is a need for more comprehensive studies at the regional and sub-regional levels.

The present assessment provides a review of the observed climate and climate change projections for the year 2030 for the key sectors of the economy, namely, 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.

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 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 and frequency 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 the oceanic variability, and are used to project the future sea-level rise. The results are then used to project the projected changes in the occurrence and frequency of storm surges.
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 east. The region is characterized by high altitude, steep topography and diverse ecosystems. The Himalayas are formed by the collision of the Indian plate with the Eurasian plate, resulting in the tectonic uplift and the formation of the world's highest mountains. The region is home to a rich biodiversity, with a variety of plant and animal species found nowhere else in the world.
are high altitude lakes form a unique reservoir storing downstream people. Over 9,000 Himalayan glaciers 'eco-system' services to millions of local as well as supporting, provisioning, regulating, and cultural the country. The forests of the region provide life nearly half (46%) of the very good forest cover of representing one-third of the total forest cover and than 65% of its geographical area is under forests, i.e. the hill districts of Assam and West Bengal. More Mizoram, Tripura, Meghalaya and two states partially Sikkim, Arunachal Pradesh, Nagaland, Manipur, Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Administratively it covers 10 states entirely i.e., birch. Natural vegetation too is infl uenced by the climate on elevation and location. India. Within the Himalayas, climate varies depending timely and heavy precipitation in the entire Northern from travelling further northwards and thus facilitating the moisture-laden monsoon winds, preventing them latitudes throughout the globe. They are a barrier for compared to regions located between corresponding subcontinent keeping South Asia much warmer when and dry arctic winds from blowing south into the Central Asia. The range also exerts a major infl uence continent by sheltering it from the cold air mass of Himalayas infl uence the climate of the Indian sub-region is naturally unstable and fragile. elevation) of the world and still rising, the Himalayan chain (more than 30 peaks exceeding 7,600 m in erosion. Being the youngest and loftiest mountain lies below the snow-line and is dissected by fl uvial valley glaciers, but the greater part of the Himalayas are covered with perpetual snow, which feeds the heights rise rapidly northwards to over 8,000 m within a short at different places. From the foothills, the Himalayas (Fig. 2.1), but its width varies from 150 km to 600 km east, covering partially/ fully twelve states of India 3. Siwalik (Outer Himalayas) – It is the southernmost features:

1. Himadri

Himalayas. A characteristic feature of this region is the large number of long, fl at-bottomed valleys known as duns, which are usually spindle-shaped and fl lled with gravelly alluvium. South and hill towns such as Shimla, Mussoorie and settlements. Musk deer, wild goats, sheep, wolves are some high valleys are occupied by small clustered centers such as Srinagar, Kangra and Kathmandu and fertile valleys. Except for the major valley and elevation. Tropical, moist deciduous forest at one point housed many species of and many varieties of deer once inhabited the region, which at one time covered all of the Sub-Himalayan area. With few exceptions, most of this forest has been cut for time. MAIZE, WHEAT, MILLET and MUSTARD. Major crops grown include deforestation of their habitats, most of the wildlife remains only in a few inaccessible areas and on steep forested areas of this region, but as a result of numerous gorges and rugged mountains make to separate the densely populated valleys. The Himalayas are divided into three parallel or longitudinal zones, each with defi nite orographical characteristics:

1. Himadri – It is the highest and loftiest part of the Himalayas. The width of this zone, composed largely but not entirely of gneiss and granite, is about 24 km. It

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. The Himachal, the intervening ranges tend

3. Siwalik – It is the southernmost part of the Himalayas. The Siwalik is a complex mosaic of forest-covered ranges and hills, varying in altitude and location. The Siwalik ranges contain the most extensive forests and are home to a diverse range of wildlife, including tigers, leopards, and wild boar. The Siwalik is also known for its rich biodiversity, with a wide variety of plant and animal species found in the region.
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, also known as Sahyadri, 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 km² 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°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...
Principal crops include rice, ragi (finger millet), jowar, and atta. Rice is the main cereal crop, followed by ragi, jowar, atta, and millet. Groundnut, sunflower, and pigeon pea are also grown. About 20% of the cultivable area is irrigated. 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% of the 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. Table 1) 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.
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 ranges from 25°C to 27°C. The highest is recorded in the mountainous portions of the North-Eastern states being above 25°C.

The salient feature of the North-Eastern region is shown in Table 2.1.

### Table 2.1: North-Eastern region: Various Indicators

<table>
<thead>
<tr>
<th>S.No</th>
<th>State</th>
<th>Forest coverage (%)</th>
<th>Area (sq. km.)</th>
<th>Population (lakh persons)</th>
<th>Literacy Rate % (2001)</th>
<th>Poverty ratio based on MRP consumption2004-05</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Arunachal Pradesh</td>
<td>61.55</td>
<td>83,743</td>
<td>10.98</td>
<td>54.3</td>
<td>13.4</td>
</tr>
<tr>
<td>2.</td>
<td>Assam</td>
<td>34.45</td>
<td>78,438</td>
<td>266.55</td>
<td>64.3</td>
<td>15.0</td>
</tr>
<tr>
<td>3.</td>
<td>Manipur</td>
<td>78.01</td>
<td>42.34</td>
<td>22,327</td>
<td>22.94</td>
<td>70.5</td>
</tr>
<tr>
<td>4.</td>
<td>Meghalaya</td>
<td>75.71</td>
<td>22,429</td>
<td>23.19</td>
<td>62.6</td>
<td>14.1</td>
</tr>
<tr>
<td>5.</td>
<td>Mizoram</td>
<td>52.05</td>
<td>22,081</td>
<td>8.98</td>
<td>88.8</td>
<td>9.5</td>
</tr>
<tr>
<td>6.</td>
<td>Nagaland</td>
<td>82.29</td>
<td>16,579</td>
<td>19.90</td>
<td>66.6</td>
<td>16.5</td>
</tr>
<tr>
<td>7.</td>
<td>Sikkim</td>
<td>60.01</td>
<td>7,098</td>
<td>5.41</td>
<td>68.8</td>
<td>15.2</td>
</tr>
<tr>
<td>8.</td>
<td>Tripura</td>
<td>54.52</td>
<td>10,486</td>
<td>31.99</td>
<td>73.2</td>
<td>14.4</td>
</tr>
<tr>
<td>9.</td>
<td>NER</td>
<td>23.57</td>
<td>2,62,179</td>
<td>389.84</td>
<td>68.5</td>
<td>13.9#</td>
</tr>
<tr>
<td>10.</td>
<td>India</td>
<td>23.57</td>
<td>32,87,240</td>
<td>10,287.37</td>
<td>64.8</td>
<td>23.6</td>
</tr>
</tbody>
</table>

Sources:
3. NEDFi Data Quarterly (2005), Vol. 4, No. II, April
4. Chapter 8 on Human Development Report
5. [www.mospi.nic.in](http://www.mospi.nic.in) used for Col. 6.
6. [http://www.planningcommission.nic.in](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 India region is lower than other parts of the country. The average per-capita income in this region is below the national average. 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 the coastal region. The coastal plains of India lie to both the eastern and western sides 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 km² and a population of over 1.5 million. Some areas have a high population density of over 300 people / km². 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 in 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. 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.
The Malabar coastal zone is 550 km long and 20 to 100 km wide. Sand dunes, locally known 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 / km² and the Karnataka coast has the least with 200 people / km².

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 km² 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 km² 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 km² 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 km² 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-
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 are considered. 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 1o x 1o 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 database (World Soil Information), data on crop management practices as followed by the farmer, genetic coefficients 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 occurring 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 water, a decent home, protection against disasters, a reasonable income and good health and access to basic social and community services. 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, drought, 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 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.
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 whose primary economic activity is in the agricultural sector. Estimates in recent reports on global production as a major source of protein show that the developing world will be more affected than the industrialized world. The projected changes in climate, particularly in terms of the increased frequency of extreme weather events, could have significant impacts on agricultural production. This could in turn affect food security, especially in regions that are already vulnerable to food scarcity.

The assessment examines the trends in observed climate and climate change projections using a century-long data set. 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 is 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 change scenarios 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 Intercomparison Project 3 (CMIP3).
that these features are also found in the global
monsoon. The critical processes to simulate the
global monsoon, however, are the large-scale
circulation and the interplay of the atmosphere
and ocean, which is the subject of this chapter.
There are several models that have been used to
study the monsoon in the past, including regional
modeling systems and climate models. However,
the global models, such as the Hadley Centre
model, are limited in their ability to resolve the
small-scale features of the monsoon, leading to
underestimations of the regional climate effects
of the monsoon. The development of regional
climate models, such as the PRECIS model, has
allowed for more detailed simulations of the
monsoon climate, providing insights into the
regional impacts of climate change.

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

<table>
<thead>
<tr>
<th>Temperature Change (°C at 2090-2099 relative to 1980-1999)</th>
<th>Sea Level Rise (m at 2090-2099 relative to 1980-1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>Best estimate</td>
</tr>
<tr>
<td>Constant Year 2000 concentrations</td>
<td>0.6</td>
</tr>
<tr>
<td>B1 scenario</td>
<td>1.8</td>
</tr>
<tr>
<td>A1T scenario</td>
<td>2.4</td>
</tr>
<tr>
<td>B2 scenario</td>
<td>2.4</td>
</tr>
<tr>
<td>A1B scenario</td>
<td>2.8</td>
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<tr>
<td>A2 scenario</td>
<td>3.4</td>
</tr>
<tr>
<td>A1FI scenario</td>
<td>4.0</td>
</tr>
</tbody>
</table>

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 primarily depend on understanding fundamental and property constraints that generate climate change, using statistical tools to identify the relationships that exist between climate change and changes in the climate system. This section provides a brief overview 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 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 parameterization schemes, which is a major source of uncertainty. A hierarchy of models, such as AOGCMs, sub-models, and regional models, have been developed and used to address these uncertainties.

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 models 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 climate models on a global scale is not only computationally expensive but also requires the use of high-resolution data sets that are not always readily available. 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 and other geographic characteristics.
- The ability to study the impact of climate change on specific regions that may be more vulnerable or sensitive to changes in climate.
- The provision of more detailed and region-specific information that can be used for policy-making and planning.

The use of RCMs allows for a more detailed understanding of how local climate conditions are affected by global climate change, which is crucial for adaptation and mitigation strategies at regional and local scales.
More detailed predictions of future climate changes, taking into account local features and their 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)
- 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 years (figure 3.1a, middle panel) and the spatial patterns indicate a warming trend for all the regions under consideration (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 ascertained that the all-India annual minimum temperature anomaly trend from 1901 to 2003 was not statistically significant. The spatial trend presented is based on the data during the period 1901-2007. 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
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 except one show increasing trend in frequency of hot days. However, the increase in the eastern coast, the West Bengal, the north-eastern part of India is statistically significant. The frequency of cold days is decreasing all over India. The frequency of cold nights is decreasing over the entire country, and the number of cold days has been decreasing over all the homogeneous regions. The decreasing trend is statistically significant for all homogeneous regions except the north-eastern region. The 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 4 to 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 rainfall

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. -0.4 mm/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.](image-url)
The rainfall is deficient or in excess if all-India monsoon rainfall for that year is less than or greater than the 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 the 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 deficient 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 rainfall

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 3.4b). North west India, west coast and peninsular India show 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 30 cm/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 1ox1o. 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.
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.

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

<table>
<thead>
<tr>
<th>Station</th>
<th>Region</th>
<th>Max EPRE upto 1980</th>
<th>Max EPRE recorded between 1980 and 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Himalayas</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leh</td>
<td>250 mm/hr</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Aug 03, 2004)</td>
<td></td>
</tr>
<tr>
<td>Santacruz Mumbai</td>
<td></td>
<td>38 (July 05, 1974)</td>
<td>94 (July 27, 2005)</td>
</tr>
<tr>
<td>Male Gaon Mumbai</td>
<td></td>
<td>16 (July 26, 1896)</td>
<td>29 (Oct 11, 2001)</td>
</tr>
<tr>
<td>Bhira Konkan &amp; Goa</td>
<td></td>
<td>43 (June 29, 1967)</td>
<td>71 (July 24, 1984)</td>
</tr>
<tr>
<td>Sand Heads Anadaman</td>
<td></td>
<td>37 (July 14, 1972)</td>
<td>51 (June 12, 1981)</td>
</tr>
<tr>
<td>Sagar West Bengal</td>
<td></td>
<td>38 (July 30, 1973)</td>
<td>48 (April 07, 2005)</td>
</tr>
<tr>
<td>North East</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cherrapunji Assam</td>
<td></td>
<td>19 (Sept 13, 1974)</td>
<td>156 (June 16, 1995)</td>
</tr>
<tr>
<td>Silchar Assam</td>
<td></td>
<td>29 (May 30, 1893)</td>
<td>47 (July 7, 1991)</td>
</tr>
<tr>
<td>Jalpaiguri North Bengal</td>
<td></td>
<td>39 (July 8, 1892)</td>
<td>47 (July 10, 1989)</td>
</tr>
<tr>
<td>Malda North Bengal</td>
<td></td>
<td>24 (Oct 1, 1971)</td>
<td>57 (Sept 28, 1995)</td>
</tr>
<tr>
<td>North West</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaipur Rajasthan</td>
<td></td>
<td>19 (August 16, 1959)</td>
<td>22 (July 19 (1981)</td>
</tr>
</tbody>
</table>

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.
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 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 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), which describe divergent futures defining various future concentrations of greenhouse gases arising from different paths of development.

While global atmosphere-ocean coupled models have been used in the future climate simulations, the representation of the physical processes on regional scales remains limited due to their coarse spatial resolution (~300 km). 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 the 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 1901-2000 by Hadley Centre and the period 2001-2098 by HadCM3 and are validated to assess and forecast seasonal and interannual variations of climate variables. These simulations are part of the seventeen member Perturbed Physics ensemble (PPE) produced using HadCM3 under the scenario of the Indian monsoon simulations using lateral boundary forcing from the High-resolution regional climate model (PRECIS) with fine horizontal resolution (50x50km). The simulations are made at 50x50km region. These simulations are utilised to generate an ensemble mean climate mean sea level pressure and winds are analysed to get the projection scenarios towards the end of present century (Rupa Kumar et al, 2006).

The model simulations are carried out for the period 2001-2098 and are validated to assess and forecast seasonal and interannual variations of climate variables. These simulations are part of the seventeen member Perturbed Physics ensemble (PPE) produced using HadCM3 under the scenario of the Indian monsoon simulations using lateral boundary forcing from the High-resolution regional climate model (PRECIS) with fine horizontal resolution (50x50km). The simulations are made at 50x50km region. These simulations are utilised to generate an ensemble mean climate mean sea level pressure and winds are analysed to get the projection scenarios towards the end of present century (Rupa Kumar et al, 2006).

3.4.2 Projections of precipitation

The projections of precipitation indicate a 3% to 7% increase in October, November and December. Spatial projections of precipitation show a decrease in winter period as well as pre-summer period. Spatial patterns of monsoon rainfall indicate a significant increase in the Himalayan region and some parts of the southern peninsula. See figure 3.6 and Tables 3.3 a, b, c and d for spatial distribution of precipitation.
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...
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 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.
3.4.3 Projections of mean annual surface temperature

Analyses performed by the IPCC indicate an all-round warming over the Indian subcontinent associated with increasing greenhouse gas concentrations. The annual mean surface air temperature rise by 2030s ranges from 1.7°C to 2°C as in the three simulations. The seasons may be warmer by around 2°C towards 2030s. 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 2030s. The net increase in temperature is ranging from 0.7°C to 1.7°C in 2030s. The temperature increase is more in December and January and least in August. The net increase in temperature is 0.7°C to 1.7°C in 2030s.

<table>
<thead>
<tr>
<th>Season</th>
<th>Precipitation (mm)</th>
<th>Temperature (°C)</th>
<th>Mean Temperature (°C)</th>
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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.

West Coast region:
The annual temperature is projected to increase from 0.9±0.6 °C to 2.6±0.7°C in 2030s. The net increase in temperature is ranging from 0.7°C to 1.7°C in 2030s. The temperature increase is more in December and January and least in August. The net increase in temperature is 0.7°C to 1.7°C in 2030s.

<table>
<thead>
<tr>
<th>Season</th>
<th>Precipitation (mm)</th>
<th>Temperature (°C)</th>
<th>Mean Temperature (°C)</th>
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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.
### 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.

#### West Coast Rainfall (mm) Mean Temperature (°C)

<table>
<thead>
<tr>
<th></th>
<th>Q1</th>
<th>JF</th>
<th>MAM</th>
<th>JJAS</th>
<th>OND</th>
<th>Annual</th>
<th>JF</th>
<th>MAM</th>
<th>JJAS</th>
<th>OND</th>
<th>Annual</th>
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<tr>
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<tr>
<td></td>
<td>8</td>
<td>74</td>
<td>66</td>
<td>866</td>
<td>23.5</td>
<td>28.4</td>
<td>25.4</td>
<td>24.2</td>
<td>25.5</td>
<td></td>
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<tr>
<td><strong>2030s</strong></td>
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<tr>
<td></td>
<td>6</td>
<td>808</td>
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<td>935</td>
<td>25.3</td>
<td>30.0</td>
<td>27.0</td>
<td>25.7</td>
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#### Standard Deviations

<table>
<thead>
<tr>
<th></th>
<th>1970s</th>
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<th>2030s</th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>6.8</td>
<td>17.2</td>
<td>219.1</td>
<td>24</td>
<td>217.7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
<td>0.9</td>
<td>0.5</td>
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</tr>
<tr>
<td></td>
<td>1.7</td>
<td>17.7</td>
<td>173.8</td>
<td>22</td>
<td>185.3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.9</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### East Coast Rainfall (mm) Mean Temperature (°C)

<table>
<thead>
<tr>
<th></th>
<th>Q1</th>
<th>JF</th>
<th>MAM</th>
<th>JJAS</th>
<th>OND</th>
<th>Annual</th>
<th>JF</th>
<th>MAM</th>
<th>JJAS</th>
<th>OND</th>
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<td><strong>1970s</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>1463</td>
<td>91</td>
<td>1685</td>
<td>23.9</td>
<td>28.8</td>
<td>25.0</td>
<td>24.6</td>
<td>25.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2030s</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>16</td>
<td>1577</td>
<td>91</td>
<td>1794</td>
<td>26.0</td>
<td>30.7</td>
<td>26.5</td>
<td>26.7</td>
<td>27.5</td>
<td></td>
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</tbody>
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#### Standard Deviations

<table>
<thead>
<tr>
<th></th>
<th>1970s</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>2030s</th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21.3</td>
<td>78.9</td>
<td>205.1</td>
<td>39.9</td>
<td>226.2</td>
<td>0.7</td>
<td>0.5</td>
<td>0.4</td>
<td>0.7</td>
<td>0.4</td>
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<tr>
<td></td>
<td>8.6</td>
<td>61.7</td>
<td>228.9</td>
<td>32</td>
<td>247.1</td>
<td>0.8</td>
<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Region</th>
<th>JF</th>
<th>MAM</th>
<th>JJAS</th>
<th>OND</th>
<th>Annual</th>
<th>JF</th>
<th>MAM</th>
<th>JJAS</th>
<th>OND</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>North East Rainfall (mm) Mean Temperature (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1970s</td>
<td>26</td>
<td>157</td>
<td>963</td>
<td>118</td>
<td>1265</td>
<td>16.6</td>
<td>30.9</td>
<td>26.5</td>
<td>17.6</td>
<td>23.7</td>
</tr>
<tr>
<td>2030s</td>
<td>28</td>
<td>155</td>
<td>1013</td>
<td>126</td>
<td>1321</td>
<td>19.2</td>
<td>35.0</td>
<td>28.2</td>
<td>20.1</td>
<td>25.8</td>
</tr>
</tbody>
</table>

| North East Rainfall (mm) Mean Temperature (°C) |   |     |      |     |        |    |     |      |     |        |
| 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   |

| North East Rainfall (mm) Mean Temperature (°C) |   |     |      |     |        |    |     |      |     |        |
| 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   |

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 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 rainy days. Both changes are observed in 2030s with respect to 1970s.

The 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. Simulations also indicate that there will be minimal changes along the upper eastern coast of India.

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 2030s 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.

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 4°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. Dotted line shows the significant linear trend.
44850hPa, 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 frequency of monsoon season storms. 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).

Table 3.3: Frequency of monthly cyclonic disturbances in monsoon season simulated by PRECIS (Max. intensity in brackets (m/s))

<table>
<thead>
<tr>
<th></th>
<th>Q0</th>
<th>Q1</th>
<th>Q2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>30</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>July</td>
<td>42</td>
<td>35</td>
<td>27</td>
</tr>
<tr>
<td>August</td>
<td>31</td>
<td>50</td>
<td>23</td>
</tr>
<tr>
<td>September</td>
<td>37</td>
<td>42</td>
<td>27</td>
</tr>
<tr>
<td>JJAS</td>
<td>140</td>
<td>144</td>
<td>95</td>
</tr>
<tr>
<td>2030s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>6</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>July</td>
<td>37</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td>August</td>
<td>31</td>
<td>48</td>
<td>22</td>
</tr>
<tr>
<td>September</td>
<td>50</td>
<td>38</td>
<td>31</td>
</tr>
<tr>
<td>JJAS</td>
<td>124</td>
<td>134</td>
<td>102</td>
</tr>
</tbody>
</table>
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.
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 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 trends.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Thermal expansion</td>
<td>0.42 ± 0.12</td>
<td>1.6 ± 0.5</td>
</tr>
<tr>
<td>Glaciers and ice caps</td>
<td>0.50 ± 0.18</td>
<td>0.77 ± 0.22</td>
</tr>
<tr>
<td>Greenland Ice Sheet</td>
<td>0.05 ± 0.12</td>
<td>0.21 ± 0.07</td>
</tr>
<tr>
<td>Antarctic Ice Sheet</td>
<td>0.14 ± 0.41</td>
<td>0.21 ± 0.35</td>
</tr>
<tr>
<td>Sum of individual climate contributions to sea level rise</td>
<td>1.1 ± 0.5</td>
<td>2.8 ± 0.7</td>
</tr>
<tr>
<td>Observed total sea level rise</td>
<td>1.8 ± 0.5</td>
<td>3.1 ± 0.7</td>
</tr>
<tr>
<td>Difference (Observed minus sum of estimated climate contributions)</td>
<td>0.7 ± 0.7</td>
<td>0.3 ± 1.0</td>
</tr>
</tbody>
</table>

Table note: Data prior to 1993 are from tide gauges and after 1993 are from satellite altimetry.

Source: Bindoff et al., 2007, IPCC, WGI.
More than 50 years ago, most tide gauges 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).

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

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

#### 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 to a maximum of 0.59 m (See Table 4.3).
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

The North Indian Ocean basin has an average of 5.5 cyclones per year. Further, their frequency in the Indian Seas shows a bi-modal 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 temperature is higher than that of Arabian Sea which is a contributing factor to the intensity of storms.
Atlantic Ocean (Elsner et al., 2008) that higher Sea Surface Temperatures (SSTs) over this region increase the intensity of Atlantic tropical cyclones. Emanuel (1987, 1988; Holland, 1997; Knutson et al., 1998; Pielke et al., 1998) indicate that tropical cyclones, as well as their intensity and duration, are impacted by the SSTs in the tropical oceans. Though direct observational evidence is still lacking, several studies (Emanuel, 1987, 1988; Holland, 1997; Knutson et al., 1998; Pielke et al., 1998; Elsner et al., 2005, Elsner et al., 2008) have suggested that higher SSTs have increased the frequency of intense hurricanes. Figure 4.3 shows the trends during the last century. An analysis of the cyclone data for the last 118-year period (1891-2008) by Niyas et al. (2009) shows that an increase in the intensity of the cyclones is seen to be increasing during this period.

During epoch I (1891—1978), the SSTA is positive for all the months and seasons except the pre-monsoon season when the SSTA is decreasing. During epoch II (1979-2007), the SSTA is small and negative for the pre-monsoon season and positive for the monsoon and post-monsoon seasons. During epoch III (2008—2018), the SSTA is small and negative for all the months and seasons. The SFA and the Storm Frequency Anomaly (SFA) for the seasonal Sea Surface Temperature Anomaly (SSTA) during the pre-monsoon, monsoon and post-monsoon seasons are shown in Figure 4.2. The SFA is small and positive for all the three seasons during epoch I, small and zero for the pre-monsoon and monsoon seasons and small and negative for the post-monsoon season during epoch II. During epoch III, the SFA is small and negative for the pre-monsoon and post-monsoon seasons and small and positive for the monsoon season. During the same period, the SSTAs are positive for the pre-monsoon and monsoon seasons and small and negative for the post-monsoon season.

An important feature of the recurring tropical cyclones over the Bay of Bengal is the intensity of the coastal storm. The cyclones are characterized by destructive winds, heavy rainfall and storm surges. The storm surge and the associated floodwater can cause massive destruction to the infrastructure and the environment. The coastal areas are most vulnerable to the storm surge and the associated floodwater. The coastal areas are also most vulnerable to the damage caused by the storm surge and the associated floodwater. The storm surge and the associated floodwater can cause massive destruction to the infrastructure and the environment. The coastal areas are most vulnerable to the storm surge and the associated floodwater. The coastal areas are also most vulnerable to the damage caused by the storm surge and the associated floodwater.
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 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.

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.
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, Bl (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 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 Bl 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).
Fig. 4.4: Composite track of cyclones during baseline Bl (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
al., 2006) is used for developing a storm surge model for the Bay of Bengal. The southern open boundary (Fig. 4.7) is along 9.50 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 coast, Sagar and Kolkata, the difference in return levels due to sea-level rise are relatively small.
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 km² for a 1.0 m rise in sea level in the region surrounding Nagapattinam. But for the same sea-level rise projections, about 169 km² 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.

In Paradip, the variations in topography are not smooth and low-lying areas are connected by tidal creeks and river inlets. This area seems to be the most vulnerable, as about 478 km² 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. 4.15: IRS satellite map of the Nagapattinam region
Fig. 4.16: Digital Elevation map of Nagapattinam region.
Fig. 4.17: Coastal inundation map in the Nagapattinam region for a 1.0 m sea-level rise.
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 CO2.

A recent meta-analysis of CO2 enrichment experiments in fields has shown that in field environment, 550 ppm CO2 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 1oC temperature throughout the growing period with current land use (Aggarwal, 2008). In March 2004, temperatures were higher in the Indo-Gangetic plains by 3-6oC, which is equivalent to almost 1 oC 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 2oC rise may not be attained even after doubling of rainfall (Srivastava et al., 2010).

While the above reviews summarize 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° x 1° 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° x 1° 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, CO2 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 CO2 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 on 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 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).

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...
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.

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 observed. Some of the recorded impacts of climate-related events on agriculture are provided below.

The analysis of past weather data from different locations represents the major coconut growing Western Ghats 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 °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 °C/year. Dry spells are in increasing trends in these districts of Karnataka and Kerala, whereas reducing trends in coastal Maharashtra. 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.
Coconut: Coconut yields are projected to increase by up to 30% in most 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 CO2 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 5.1b). 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 CO2 fertilization effect as compared to rain-fed rice, which is supplied with less amount of fertilizers. Farmers in Western Ghats 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 5.1c). These crops have C4 photosynthetic systems and hence do not have relative advantages at higher CO2 concentrations.

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 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 5.3a.
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

<table>
<thead>
<tr>
<th>Crop</th>
<th>Area ('000 ha)</th>
<th>Production ('000 t)</th>
<th>Productivity (Kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>6248</td>
<td>15520</td>
<td>2300</td>
</tr>
<tr>
<td>Groundnut</td>
<td>1777</td>
<td>2153</td>
<td>1559</td>
</tr>
<tr>
<td>Urad</td>
<td>692</td>
<td>376</td>
<td>477</td>
</tr>
<tr>
<td>Red gram</td>
<td>579</td>
<td>248</td>
<td>433</td>
</tr>
<tr>
<td>Cotton (lint)</td>
<td>796</td>
<td>1528</td>
<td>2104</td>
</tr>
<tr>
<td>Coconut</td>
<td>1003</td>
<td>7077</td>
<td>8243</td>
</tr>
<tr>
<td>Cashew</td>
<td>796</td>
<td>1528</td>
<td>2104</td>
</tr>
</tbody>
</table>

Table 5.3b: Marine catch in coastal India

<table>
<thead>
<tr>
<th>Sector</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine fish</td>
<td>29.2 lakh tonnes</td>
</tr>
<tr>
<td>Shrimps</td>
<td>144.4 thousand tonnes</td>
</tr>
<tr>
<td>Scampi</td>
<td>42.8 thousand tonnes</td>
</tr>
</tbody>
</table>

Apart from the crops, production from marine fisheries and fresh water fisheries 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.

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 the 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 and Tamil Nadu may experience an increase of 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.
growth of most of the species are pelagic, directly exposed to temperature and oxygen availability. Oxygen transport to tissues will be limited as temperatures increase, because oxygen transport to tissues will be limited as temperatures increase. This constraint in physiology may have negative impacts on the physiology of fish in tropical coastal and small pelagic fish, forming massive fisheries (21% of marine fish catch of India). Some evidence for the responses in terms of extension of depth of occurrence; and (ii) Extension of distributional boundary of small pelagic 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.

Temperature is known to affect fish distribution and abundance. Changes in the timing of life history events will result in changes in distributions, recruitment and abundance of many species will be acute at the extremes of species' ranges. Changes in the timing of life history events such as plankton and turn over of generations such as plankton and sea-surface temperatures in those periods. These changes  in the net primary production and its transfer to higher trophic levels are possible. Most models changes in the structure and functions of the ecosystems. At long time scales of multi-decades, 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.

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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. A box shows the change in the southwest monsoon pattern.
77. 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 m³/s during 1997-2007 (Fig. 5.4c).

This substantial increase in CUI elevated the chlorophyll-a concentration from 4.54 mg/m³ (1997) to 13.85 mg/m³ (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
The 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

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 be the reason for the change in spawning season.
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 in the 1970s, 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. Fig 5.6. Change in spawning season of Nemipterus japonicus and N. mesoprion off Chennai (from Vivekanandan and Rajagopalan, 2009)

Table 5.4: Important Crops in the North Eastern Region

<table>
<thead>
<tr>
<th>CROP</th>
<th>Area ( '000ha)</th>
<th>Production ('000 t)</th>
<th>Yield (Kg/ha)</th>
<th>Production ('000 t)</th>
<th>Productivity (Kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tea</td>
<td>284</td>
<td>443</td>
<td>1211</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arecanut</td>
<td>82</td>
<td>75</td>
<td>947</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>3259</td>
<td>5195</td>
<td>1636</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>78</td>
<td>98</td>
<td>1433</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapeseed &amp; Mustard</td>
<td>278</td>
<td>151</td>
<td>612</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 hills 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.
hydrological imbalances (Maikhuri et al., 2001). These encompass concerns such as global warming which is significant and affects a whole range of issues. These include land degradation and invasion, growing human population, imposition of conservation policies, and various environmental perturbations. Crop productivity is already very low. This may cause lower availability of fodder and can adversely affect livestock sector. Decline in area under field crops in Theog Region (above 2000m) has also recorded a decrease of about 2 to 3% over the past 15% over a decade period. The productivity of apple has registered an increase of about 32% over the present period. The total farm income of the farmers has also recorded a marginal decline of 1 to 2% in the present 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. Productivity of apple has increased to the extent of about 8 to 9%. The area under cash crops, mainly off-season vegetables have shared more than 84% of the total fruits production. Apple trees account for 46% of the total area under fruit crops and 76% of the total fruits production. Apple is a cash crop in Himachal Pradesh and productivity of apple is 800-1100oF. chilling hours requirement for a standard variety of apple is 45.1oF. Temperatures of approximately 35.1o to 55oF provide most of the chilling effect needed by fruit plants; however, the most efficient temperature at which a plant receives chilling is 45.1oF . Temperatures of 69.8oF and higher for 4 or more days can actually negate chilling that was received by the plant during the previous 24 to 36 hours. The actual chilling being received by the plant is reduced by the plant during the previous 24 to 36 hours. The daily temperatures of 32oF and lower, contribute little or nothing to the chill accumulation for fruit buds. If the buds do not receive sufficient chilling temperatures during winter to completely break dormancy, trees will express delayed foliation, shorter day lengths and cooler temperatures. This dormancy or sleeping stage protects these buds from physiological symptoms consequently affect the yield reduced fruit set and increased buttoning. These developed buds become dormant in response to shorter day lengths and cooler temperatures. This summer, and as winter approaches, the already developed buds become dormant in response to shorter day lengths and cooler temperatures. This dormancy also prevents bud development. Once buds have entered dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures. If the buds do not receive sufficient chilling temperatures during winter to completely break dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures. Once buds have entered dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures. Once buds have entered dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures. Once buds have entered dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures. Once buds have entered dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures. Once buds have entered dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures. Once buds have entered dormancy, they will be tolerant to temperatures much lower than freezing and will not grow in response to mid-winter temperatures.
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°F to 78.1°F.

The second study site is located in the district Shimla and represents elevation above 2200-3250 m 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.

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:

\[
THI = 0.72 (T_{db} + T_{wb}) + 40.6
\]

Here \(T_{db}\) represents Dry bulb temperature and \(T_{wb}\) is the wet bulb temperature and have been obtained from CRIDA, Hyderabad.
Fig. 5.9: Cumulative chill units trends for Shimla for different months.

Fig. 5.10: Apple productivity trends in Himachal Pradesh.
on $T_{max}$ and $T_{min}$, 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 0.70 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 2.00 p.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 Uttarakhand 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 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.
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 in the Himalayan and the North-East region and severe changes are 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 (left) 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. 5.12d: 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 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 Himalayan region, the North-East region, 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 baseline 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.
6.1 Introduction

Climate is one of the prime determinants of ecosystems development, varying from region to region and from season to season in the same region. 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 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.
6.2.1 Ecosystems—their response to climate change and key issues

Ecosystems are expected to tolerate some level of preservation under anthropogenic climate change (UNFCCC, 1992). In some form or another, ecosystems are increasingly being (Reid et al., 2005), as they have done several centuries (vegetation) or even possibly for adaptation responses. In the past several hundred millennia (e.g., Petit et al., 1999; Augustin et al., 2004; Siegenthaler et al., 2007) compared with projected future climate change and other human-induced pressures are virtually certain to be more severe in tropical regions, especially over the next several decades at a rate of 2 degrees C per decade (IPCC, 2007). These pressures, including climate change, are virtual certain to reduce societal options for adaptation and may result in a number of different scenarios that could be seen as critical effects. Projected future climate change and other human-induced pressures are virtually certain to have severe impacts in India. These impacts could be very significant, ranging from increased frequency and intensity of extreme events to changes in productivity for resilience are also very relevant. These may occur in certain terrestrial ecosystems due to reduced tropical cloudiness (Nemani et al. et al., 2004; Jump and Peñuelas, 2005). An understanding of time-lags in ecosystem responses to a changed climate is essential if a number of different, interacting, and nonlinear responses to a changed climate result in a plethora of changes, further emphasizing the need for proper management strategies. The implications of possibly transient increases in atmospheric CO2 levels, higher temperatures and lower soil moisture, while C3 plants exhibit the opposing traits.

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 temperature would favour C4 plants1. The outcome of climate change in India would thus be favor C3 plants over C4 grasses, but the projected increase in temperature would favour C4 plants1. The implications of possibly transient increases in atmospheric CO2 levels, higher temperatures and lower soil moisture, while C3 plants exhibit the opposing traits.

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

Projected future climate change and other human-induced pressures are virtually certain to have severe impacts in India. These impacts could be very significant, ranging from increased frequency and intensity of extreme events to changes in productivity for resilience are also very relevant. These may occur in certain terrestrial ecosystems due to reduced tropical cloudiness (Nemani et al. et al., 2004; Jump and Peñuelas, 2005). An understanding of time-lags in ecosystem responses to a changed climate is essential if a number of different, interacting, and nonlinear responses to a changed climate result in a plethora of changes, further emphasizing the need for proper management strategies. The implications of possibly transient increases in atmospheric CO2 levels, higher temperatures and lower soil moisture, while C3 plants exhibit the opposing traits.

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...
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 CO2) and B2 (575 ppm CO2) 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).
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)
- 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 CO2 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
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)

Key:

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.
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...
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 in 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 6.6: 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.

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
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.
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...
Table 6.2: Region-wise projections of the percent of grids where vegetation-type change is expected under A1B climate scenario by 2035.

<table>
<thead>
<tr>
<th>Region</th>
<th>Total number of grids</th>
<th>Number of grids projected to change</th>
<th>% projected to change</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Himalayas</td>
<td>98</td>
<td>55</td>
<td>56.0</td>
<td>Most vulnerable</td>
</tr>
<tr>
<td>Coastal region</td>
<td>96</td>
<td>29</td>
<td>30.0</td>
<td>Moderately vulnerable</td>
</tr>
<tr>
<td>Western Ghats</td>
<td>54</td>
<td>10</td>
<td>18.0</td>
<td>Moderately vulnerable</td>
</tr>
<tr>
<td>North-East</td>
<td>73</td>
<td>6</td>
<td>8.2</td>
<td>Least vulnerable</td>
</tr>
</tbody>
</table>

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.

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.
7.1 Introduction

Climate plays a key role in the propagation of most diseases. The direct and indirect impacts of climate on disease transmission can be significant. For example, heat waves can lead to heat strokes, while flooding can increase the risk of diarrhoeal diseases from water contamination. Changes in temperature and precipitation patterns can also affect the distribution and abundance of disease vectors, such as mosquitoes.

In the future, with projected increases in temperature and changes in precipitation patterns, human health impacts are likely to escalate. This will be particularly true for regions that are already vulnerable to climate change. For example, in India, malaria and other vector-borne diseases are expected to spread into new regions due to changes in climate conditions.

The chapter focuses on the potential impacts of climate change on human health. It discusses the role of climate in disease transmission and examines the potential changes that could occur in the future. The chapter also highlights the importance of understanding the relationship between climate and health to develop effective preparedness plans.

7.2 Public health in India and Climate Change

Public health in India is highly dependent on climate conditions. For example, in areas with high temperatures and humidity, the incidence of vector-borne diseases such as malaria and dengue increases. Similarly, changes in precipitation patterns can affect the availability of clean drinking water, which is crucial for public health.

In the future, with projected increases in temperature and changes in precipitation patterns, public health in India will be significantly impacted. This will require a comprehensive approach to addressing the challenges of climate change, including the development of effective preparedness plans, the promotion of healthy lifestyles, and the implementation of sustainable development strategies.
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 increased 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.

### 7.3.3 Climate change and malaria

#### 7.3.3.1 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°C while for *P. falciparum* it is 16.5 –18°C (Martens et al., 1995). At 16°C it will take 55 days for the *P. vivax* to complete sporogony, while at 28°C, the process can be completed in 7 days, and at 18°C it will take 29 days (WHO 1975). The duration of sporogony in *Anopheles* mosquitoes decreases with increase in temperature from 20 to 25°C (Table 7.2). From 32°C to 39°C, there is high mortality in mosquitoes (Martens, 1997) and at 40°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.

#### Table 7.2 Average duration of sporogony of human Plasmodium at different temperatures

<table>
<thead>
<tr>
<th>Parasite species</th>
<th>No of days required for sporogony at different temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>P. falciparum</em></td>
<td>22-23, 12-14</td>
</tr>
<tr>
<td><em>P. vivax</em></td>
<td>16-17, 9-10</td>
</tr>
<tr>
<td><em>P. malariae</em></td>
<td>30-35, 23-24</td>
</tr>
<tr>
<td><em>P. ovale</em></td>
<td>Not known, 15-16</td>
</tr>
</tbody>
</table>

(Adapted from WHO, 1975)
<table>
<thead>
<tr>
<th>Regions</th>
<th>Climate parameters</th>
<th>Probable impacts on ecosystems</th>
<th>Probable impacts on health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Himalayan Region</td>
<td>Increase in temperature by 0.9°C to 2.6°C by 2030s with respect to 1970s</td>
<td>Increase in intensity by 2-12% in 2030s with respect to 1970s</td>
<td>Increase in Forest fires</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased glacier melt</td>
<td>Increased glacier melt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss in forest litter &amp; wood used for heating purposes in the cold season – morbidity due to extreme cold</td>
<td>Flash floods leading to large scale landslides and hence loss of agriculture area affecting food security</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increase in incidence of malaria due to opening up transmission windows at higher latitudes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increase in morbidity due to unprecedented rise in temperature</td>
</tr>
<tr>
<td>Western Ghats</td>
<td>Temperature may rise by 1.7°C to 1.8°C in 2030s with respect to 1970s</td>
<td>Decrease in rainfall over tropical montane cloud forests of Gavi, Periyar, High Ways and Venniyar</td>
<td>Adverse effect on cash crops such as coffee and tea.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Large scale flooding and soil erosion as a result of increased rainfall.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increase in morbidity and mortality due to flooding</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reduction in employment due to impact on cash crops leading to negative impacts on health and life expectancy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Forced migration, loss of housing and drowning will result due to sea-level rise.</td>
</tr>
<tr>
<td>Coastal Zone</td>
<td>In the west coast temperature may rise by 1.7°C to 1.8°C in 2030s with respect to 1970s</td>
<td>Increase in sea surface temperatures</td>
<td>Increase in morbidity and mortality due to increase in water borne diseases associated with cholera epidemics and increase in salinity of water</td>
</tr>
<tr>
<td></td>
<td>In the east coast the surface annual air temperature is set to rise by 1.6 to 2.1°C.</td>
<td>Increase in rain fall intensity</td>
<td>Loss of livelihoods due to effect on agriculture, tourism, fisheries and hence impacting health and life expectancy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rising sea levels</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increase in intensity of cyclones and storm surges, especially in the east coast</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Decrease in coconut production</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>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</td>
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<td></td>
<td></td>
<td></td>
<td>Changes in distribution and productivity of marine as well as fresh water fisheries</td>
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<td></td>
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<td></td>
<td>Submergence of habitats and special ecosystems such as the mangroves</td>
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<td></td>
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<td></td>
<td>Increase in morbidity and mortality due to increase in water borne diseases</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Loss of livelihoods due to effect on agriculture, tourism, fisheries and hence impacting health and life expectancy</td>
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</tr>
<tr>
<td>North-East India</td>
<td>Surface air temperature is projected to increase between 0.8 to 2.1°C</td>
<td>Decrease in winter precipitation</td>
<td>Cereal production likely to be benefited, but yield of paddy will be negatively affected due to projected increase of night-time temperature.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increase in intensity of summer precipitation</td>
<td>Tea plantations to be affected due to soil erosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increase in night-time temperatures</td>
<td>Increase runoff and landslides during summer precipitation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Decrease in yields in winters</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Loss of employment and adverse effect on health expected to face an increase in incidence of Malaria due to temperature and humidity increase.</td>
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</tbody>
</table>
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°C and upper cut-off as 32°C (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

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 for baseline scenario 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 scenario 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 ghatas. 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.
Fig 7.1: Transmission window of malaria based on temperature: (a) Baseline (1960-1990) and (b) by the year 2030.

Fig 7.2: Transmission window of malaria based on minimum required temperature and RH – (a) Baseline (1960-1990) and (b) for 2030s.
### Table 7.3: TWs of Malaria in Himalayan region based on temperature (A1B Baseline and projected scenario by 2030)

<table>
<thead>
<tr>
<th>State</th>
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**Fig 7.3:** TWs of malaria based on minimum required T under (a) baseline and (b) projected scenario (2030) in the Himalayan Region.

### 7.6 Regional projections

#### 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 the projected scenario. In Uttarakhand, 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.
### Table 7.4 **TWs of Malaria based on T and RH in Himalayan region** (A1B Baseline and projected scenario by 2030)

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<th>State</th>
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**Fig 7.4:** TWs of malaria based on minimum required T and RH under (a) baseline and (b) projected scenario (2030) in the Himalayan Region.

In the 2030's, there is no change in transmission windows due to the baseline scenario. When transmission windows were determined in combination with relative humidity, transmission windows are not open beyond 6 months (Fig 7.4 and Table 7.4).
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 indicates 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 2030s, however, with increase in temperature, majority
Table 7.6 TWs of Malaria in North-Eastern region based on temperature and RH (A1B Baseline and projected scenario by 2030)

<table>
<thead>
<tr>
<th>State</th>
<th>No. of Districts</th>
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<tr>
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<td>0 0 0 2 39 7 11</td>
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Fig 7.6: TWs of malaria based on minimum required T and RH (a) baseline and (b) projected scenario (2030) in the North-Eastern Region.

- Of the districts in this region, 48% have transmission windows open for 10-12 months, and only 6% have transmission windows open for 7-9 months, indicating more stability of malaria transmission in these states (see Fig 7.5b). 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...
Table 7.7 TWs of Malaria in Western Ghats based on temperature (A1B Baseline and projected scenario by 2030)

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<td>0 0 0 0 0 2 0</td>
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Fig 7.7: TWs of malaria based on minimum required T (a) baseline and (b) projected scenario (2030) in the Western Ghats.

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 (Fig 7.8 and Table 7.8). If we compare the existing transmission of malaria in Gujarat and Karnataka, transmission continues for more than 7-9 months.
Table 7.8 TWs of Malaria in Western Ghats based on minimum required temperature and RH (A1B Baseline and projected scenario by 2030)

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<th>State</th>
<th>No. of Districts</th>
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<tr>
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Fig 7.8: TWs of malaria based on minimum required T and RH (a) baseline and (b) projected scenario (2030) in the Western Ghats.

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, with respect to 7-9 months in the baseline scenario. Similar changes are seen along the coastline when transmission windows are determined...
Table 7.9: TWs of malaria in coastal area based on minimum required T (a) baseline and (b) projected scenario (2030).

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Fig 7.9: TWs of malaria in coastal area based on minimum required T (a) baseline and (b) projected scenario (2030).
Table 7.10 TWs of malaria based on minimum required T and RH (a) baseline and (b) projected scenario (2030).

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<tr>
<td>Daman and Diu</td>
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<td>Dadra and Nagar Haveli</td>
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<td>Karnataka</td>
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<tr>
<td>Kerala</td>
<td>9</td>
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<td>0 0 0 0 0 6 3</td>
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<tr>
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<td>13</td>
<td>0 0 0 1 6 6 0</td>
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<td>0 0 0 7 4 2 0</td>
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<tr>
<td>Andhra Pradesh</td>
<td>9</td>
<td>0 0 0 0 7 2 0</td>
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<td>0 0 1 6 2 0</td>
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<tr>
<td>Pondicherry</td>
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<tr>
<td>Orissa</td>
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<td>0 0 0 0 7 0 0</td>
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<tr>
<td>West Bengal</td>
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<td>0 0 0 0 2 1 0</td>
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<td>0 0 0 0 3 0 0</td>
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<tr>
<td>Andaman Nicobar Islands</td>
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<tr>
<td>Lakshadweep Islands</td>
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<td>0 0 0 0 0 0 1</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>0 1 4 12 26 20 11</td>
<td></td>
</tr>
</tbody>
</table>

Fig 7.10 TWs of malaria in coastal Region based on minimum required T and RH (a) baseline and (b) projected scenario (2030)
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 category in 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 indicates transmission for more than 7-9 months. This observation indicates that mosquito vectors are finding micro-niches (e.g. accumulation of water) to get the required RH even if climatically the RH requirement is not satisfied for their transmission.
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 (km³/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 1,869km³. It has been estimated that only about 1,123km³, including 690km³ from surface water and 433km³ 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 (m³/year) in 1951 to 1,654m³/year in 2007. Gupta and Deshpande (2004) estimated that the gross per capita water availability in India will decline from about 1,820m³/yr in 2001 to as low as about 1,140 m³/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 increased water stress and reduced water availability.
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 4,000 km$^3$. The resource potential of the country,
which occurs as natural runoff in rivers, is about
1,869 km$^3$, 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
Figure 8.1: INCCA Regions showing proportion of river systems falling in them
In the 2001 census, the per capita freshwater availability is about 1,820 m$^3$. Due to various constraints of topography, uneven distribution of resources over space and time, it has been estimated that only about 1,122 km$^3$ of the total potential of 1,869 km$^3$—of which 690 km$^3$ 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 quite low and is 23% and 34%, respectively. Per capita gross water availability in the Brahmaputra and Barak basins is of the order of 14,057 m$^3$ per annum and in Sabarmati basin, the water availability is as low as 307 m$^3$ (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 Brahmaputra. 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 the 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 33,679 km$^2$ and total ice volume of 363.10 km$^3$. The Ganga basin has 968 glaciers with a total glacier cover of 2,857 km$^2$ and total ice volume of 209.37 km$^3$ (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 97,020 km$^2$, with a volume of 12,930 km$^3$. 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 500 km$^3$ per year, while another study reports about 515 km$^3$ 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 Groundwater

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 8.3: Recent retreat pattern of selected glaciers in the three North-Western Himalayan States of India

<table>
<thead>
<tr>
<th>Name of the Glacier</th>
<th>State</th>
<th>Retreat of snout (m)</th>
<th>Observation Period</th>
<th>Trend Avg. retreat rate (m/yr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dokriani</td>
<td>Uttarakhand</td>
<td>550</td>
<td>1962–95</td>
<td>Retreating</td>
<td>16.67</td>
</tr>
<tr>
<td>Durung Drung</td>
<td>Jammu &amp; Kashmir</td>
<td>-</td>
<td>2004-07</td>
<td>No Change</td>
<td>-</td>
</tr>
<tr>
<td>Kangriz</td>
<td>Jammu &amp; Kashmir</td>
<td>-</td>
<td>1913-2007</td>
<td>No Change</td>
<td>-</td>
</tr>
<tr>
<td>Siachin</td>
<td>Jammu &amp; Kashmir</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

### Table 8.2: Major glaciers in the three North-Western Himalayan States of India

<table>
<thead>
<tr>
<th>Basin</th>
<th>No. of glaciers</th>
<th>Glacier covered Area (km²)</th>
<th>Ice volume (km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Indus Basin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ravi</td>
<td>172</td>
<td>193</td>
<td>8.04</td>
</tr>
<tr>
<td>Chenab</td>
<td>1,278</td>
<td>3,059</td>
<td>206.30</td>
</tr>
<tr>
<td>Jhelum</td>
<td>133</td>
<td>94</td>
<td>3.30</td>
</tr>
<tr>
<td>Beas</td>
<td>277</td>
<td>579</td>
<td>36.93</td>
</tr>
<tr>
<td>Satluj</td>
<td>926</td>
<td>635</td>
<td>34.95</td>
</tr>
<tr>
<td>Upper Indus</td>
<td>1,796</td>
<td>8,370</td>
<td>73.58</td>
</tr>
<tr>
<td>Shyok</td>
<td>2,454</td>
<td>10,810</td>
<td>NA</td>
</tr>
<tr>
<td>Nubra</td>
<td>204</td>
<td>1,536</td>
<td>NA</td>
</tr>
<tr>
<td>Gilgit</td>
<td>535</td>
<td>8,240</td>
<td>NA</td>
</tr>
<tr>
<td>Kishenganga</td>
<td>222</td>
<td>163</td>
<td>NA</td>
</tr>
<tr>
<td>Total</td>
<td>7,997</td>
<td>33,679</td>
<td>363.10</td>
</tr>
<tr>
<td>B. Ganga Basin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yamuna</td>
<td>52</td>
<td>144</td>
<td>12.20</td>
</tr>
<tr>
<td>Bhagirathi</td>
<td>238</td>
<td>755</td>
<td>67.02</td>
</tr>
<tr>
<td>Alaknanada</td>
<td>407</td>
<td>1,229</td>
<td>86.38</td>
</tr>
<tr>
<td>Ghaghra</td>
<td>271</td>
<td>729</td>
<td>43.77</td>
</tr>
<tr>
<td>Total</td>
<td>968</td>
<td>2857</td>
<td>209.37</td>
</tr>
</tbody>
</table>

Source: Raina and Srivastava, 2008. 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, Jharkhand, 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 3,957m². 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 994.99km² in 1969 to 932.90km² in 1989. However, small change in the area (932.90km² to 930km²) 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 2,077km² to 1,628km² 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 of 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 50–80 m 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 50 km.

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 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 RCM 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 calculated by selecting the regions, the monthly precipitation, evapotranspiration and drainage data from the IPCC SRES A1B baseline and 2030s scenarios and GIS data. The analysis has been carried out for all Indian river basins and the results have been 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.
The increase in ET results from an increase in the amount of moisture in the soil and land surface and an 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 the Indus River for the 2030s.

The general impact of increase in 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 has been up to about 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 an 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 most of the areas which are expected to see an 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 see a decrease 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 most 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%.
an increase in sediment yield of up to 25%. The increase in sediment yield 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 Andhra 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 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 for a region without using spatial explicit information. The Palmer Drought Severity Index (Palmer 1965), which is based on precipitation deficit, is one such widely used index that incorporates information on rainfall, land use, and soil properties in a lumped manner. 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 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 in some areas due to precipitation decrease, which may lead to a decrease in water availability. The increase in drought days will be a result of the change in climate and the vulnerability of the region to drought.
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 potential future changes in flood hazard 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 to 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 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 8.7 Change in magnitude of flood (stream discharge at 99th percentile) towards 2030s with respect to 1970s
This chapter synthesises the salient findings on the sectoral concerns about climate change 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 1961–1990, 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.

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.
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.

**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±174.5 mm. 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±185.33 mm to 1794±247 mm, 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±85.8 mm to 1280±204.8 mm 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±185.33 mm to 1794±247 mm, which is an increase of 6%–8% with respect to the 1970s.

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

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

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

3. Western Ghats: In the Western ghats region, minimum temperatures may rise by 2.0 oC to 4.5 oC, 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 oC–3 oC.

4. 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 oC to 4.5 oC, 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 oC and 3.5 oC. 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 rainfall on 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, the intensity of the rainy days 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 rainfall is likely to increase by 1-2 mm/day.

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

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 these variations.

Observations based on tide gauge measurements show virtual sea level changes ranging from a few inches to several feet. These changes are significantly greater than the resolution of most tide gauge measurements, but can be accounted through time series analysis of the data. The time series analysis has included a plot of the number of stations showing a significant trend and the number of years over which these trends are statistically significant. The analysis has been undertaken for the entire available data set, and in some cases for sub-periods. The results are presented as the magnitude of the trend, the number of stations showing the trend, and the number of years over which the trend is significant at a range of confidence levels. The analysis has been undertaken for the entire available data set, and in some cases for sub-periods. The results are presented as the magnitude of the trend, the number of stations showing the trend, and the number of years over which the trend is significant at a range of confidence levels.
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 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 CO2 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 CO2 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 CO2 fertilization benefits. However, some areas like south-west Karnataka, parts of Tamil Nadu and parts of Maharashtra may show reductions in yields 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...
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:** *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**

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 output of the regional climate models, 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.
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.
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 human 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 9.5: Projected changes in forest productivity in 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 to 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 the 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 in,...
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,showed a reduction in the water yield.
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 can be sub-divided into six regions based on the major physiographical features; the northern mountainous region, the central plateau, the eastern coastal regions, the western coastal regions, the northeastern region, and the southern coastal regions. The eastern coastal region includes West Bengal, Odisha, Andhra Pradesh, and the coastal areas of Tamil Nadu. The western coastal region includes Gujarat, Maharashtra, Goa, and the coastal areas of Karnataka. The north-eastern region includes Assam, Tripura, Mizoram, Meghalaya, Arunachal Pradesh, Nagaland, and Manipur. The southern coastal region includes Kerala and the coastal areas of Tamil Nadu. The northern mountainous region includes Himachal Pradesh, Jammu and Kashmir, and Uttarakhand. The central plateau includes Madhya Pradesh, Chhattisgarh, and Orissa.

These regions are characterized by different climatic and ecological conditions. For example, the eastern coastal region has a tropical monsoon climate with high rainfall and humidity, while the western coastal region has a Mediterranean climate with mild winters and hot summers. The north-eastern region has a subtropical climate with high rainfall and humidity, while the southern coastal region has a tropical climate with high rainfall and humidity.

9.2.2. Data gaps and Uncertainty in Modeling

Climate modeling is a complex process that involves the use of mathematical models to simulate the Earth’s climate system. The models are based on physical laws and empirical relationships and are used to predict future climate conditions. However, there are several uncertainties associated with climate modeling, including uncertainty in climate forcing, model parameterization, and model structure.

Climate forcing refers to the inputs to the model, such as greenhouse gas emissions, aerosol emissions, and solar radiation. There is uncertainty in the magnitude and timing of these forcings, which can lead to uncertainties in the climate predictions.

Model parameterization refers to the way the model simulates physical processes, such as cloud formation, precipitation, and ocean circulation. There is uncertainty in the model parameterizations, which can lead to uncertainties in the climate predictions.

Model structure refers to the way the model is organized and the way the physical processes are represented. There is uncertainty in the model structure, which can lead to uncertainties in the climate predictions.

Uncertainty also arises due to the incomplete understanding of some of the processes involved in climate modeling. For example, the carbon cycle is a complex system that involves biological, chemical, and physical processes. The uncertainties in the carbon cycle can lead to uncertainties in the climate predictions.

Uncertainties can also arise due to the incomplete understanding of the interaction between the physical climate models used by the IPCC and the socio-economic scenarios. The uncertainties in the socio-economic scenarios can lead to uncertainties in the climate predictions.

Presently, the climate projections are based on the IPCC Fourth Assessment Report (IPCC, 2007). However, the IPCC model projections have shown considerable differences in the projected climate change, with some models predicting a faster warming than others. This uncertainty can be reduced by running ensembles of multiple models and considering a range of emissions scenarios.

Further, regionalization techniques carry with them the uncertainties related to the regionalization process, which can be significant. For example, the uncertainties in the regionalization process can lead to uncertainties in the climate predictions.

9.2.3. Sea-level rise: Model-based and Semi-empirical approaches

Sea-level rise is a significant threat to coastal and riparian ecosystems. The increase in sea-level rise can lead to flooding, erosion, and loss of habitat. There are two main approaches to modeling sea-level rise: model-based and semi-empirical approaches.

Model-based approaches are based on the use of physical climate models, such as the Hadley Centre Coupled Model (HadCM3), which are used to simulate the Earth’s climate system. Semi-empirical approaches are based on the use of statistical models, such as the_emerging IPCC projections, which are used to estimate the sea-level rise.

The semi-empirical models are based on the use of statistical models, such as the IPCC projections, which are used to estimate the sea-level rise. The semi-empirical models are based on the use of statistical models, such as the IPCC projections, which are used to estimate the sea-level rise.
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 multi-model ensembles take into account the variations in model output and provide a better understanding of the future climate change.
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.

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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A1B: The A1B scenario assumes significant innovations in energy technologies, which improves energy efficiency and reduces 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-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, characterized 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 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. Climate change is defined 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, 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 member of the most important class of pigments that absorbs energy from light and 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 interactions and feedbacks of five major components: atmosphere, hydrosphere, cryosphere, land surface, and biosphere. Climate system changes are driven by both internal and external forcing, such as volcanic eruptions, solar variations, or human-induced modifications of the planetary radiative balance, for instance via anthropogenic emissions of greenhouse gases and 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 irreversible, or recoverable only on very long time scales, such as widespread bleaching of coral reefs.

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 climatological assessments, the coastal region covers the eastern coast and the western coast, including the western ghat.

Communicable disease: An infectious disease caused by transmission of an infective biological agent (virus, bacterium, protozoan, or multicellular macroparasite).
Control run: A model simulation conducted to provide a baseline for comparison with climate change experiments. This involves running a model with constant values for variables such as greenhouse gas concentrations and aerosol emissions to establish a reference state.

Coastal Upwelling Index (CUI): A measure of the volume of water that upwells along the coast, identifying 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.

Drought: The phenomenon that occurs 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, driven by climate and other environmental changes.

East coast: Refers to the coastal areas in the eastern side of an area, such as the East coast 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 like a small pond.

Ecosystem services: Ecological processes or functions having monetary or non-monetary value to individuals or society at large. They are categorized into four main types: (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 coherent and internally consistent sets of assumptions about driving forces such as demographic and socio-economic development, technological change, and their key relationships. In 1992, the Intergovernmental Panel on Climate Change (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—known as the 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 infrared radiation at specific wavelengths. The primary greenhouse gases include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and water vapor (H₂O). 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**


**InfoCrop**

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 the periodic occurrence of events such as flowering or budding in relation to climatic 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 or transpire.

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 greenhouse gas 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'.


**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.
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