Vulnerability Assessment and Adaptation

Chapter 3

Climate change is not only a major global environmental problem, but is also an issue of great concern to a developing country like India. The earth's climate has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities. The changes observed in the regional climate have already affected many of the physical and biological systems and there are indications that social and economic systems have also been affected. Climate change is likely to threaten food production, increase water stress and decrease its availability, result in sea-level rise that could flood crop fields and coastal settlements, and increase the occurrence of diseases, such as malaria. Given the lack of resources, and access to technology and finances, developing countries such as India have limited capacity to develop and adopt strategies to reduce their vulnerability to changes in climate.

Article 2 of the UNFCCC refers to the dangerous human influences on climate, in terms of whether they would allow ecosystems to adapt, ensure that food production is not threatened and chart a path of sustainable economic development. Global, national and local level measures are needed to combat the adverse impacts of climate change induced damages.

India is a large developing country with a population of over one billion, whose growth is projected to continue in the coming decades. In India, nearly two-thirds of the population is rural, whose dependence on climate-sensitive natural resources is very high. Its rural populations depend largely on the agriculture sector, followed by forests and fisheries for their livelihood. Indian agriculture is monsoon dependent, with over 60 per cent of the crop area under rainfed agriculture that is highly vulnerable to climate variability and change.

An assessment of the impact of projected climate change on natural and socio-economic systems is central to the whole issue of climate change. Climate change impact assessment involves the following:

- To identify, analyze and evaluate the impact of climate variability and change on natural ecosystems, socio-economic systems and human health.
- To assess the vulnerabilities, which also depend on the institutional and financial capacities of the affected communities, such as farmers, forest dwellers and fishermen.
- To assess the potential adaptation responses.
- To develop technical, institutional and financial strategies to reduce the vulnerability of the ecosystems and populations.

Developing countries such as India have low adaptive capacity to withstand the adverse impacts of climate change due to the high dependence of a majority of the population on climate-sensitive sectors, such as agriculture, forestry and fisheries, coupled with poor infrastructure facilities, weak institutional mechanisms and lack of financial resources. India is therefore, seriously concerned with the possible impacts of climate change, such as:

- Water stress and reduction in the availability of fresh water due to potential decline in rainfall.
- Threats to agriculture and food security, since agriculture is monsoon dependent and rainfed agriculture dominates in many states.
- Shifts in area and boundary of different forest types and threats to biodiversity with adverse implications for forest-dependent communities.
- Adverse impact on natural ecosystems, such as wetlands, mangroves and coral reefs, grasslands and mountain ecosystems.
- Adverse impact of sea-level rise on coastal

agriculture and settlements.

- Impact on human health due to the increase in vector and water-borne diseases, such as malaria.
- Increased energy requirements and impact on climate-sensitive industry and infrastructure.

The assessment of climate change impacts, and vulnerability and adaptation to climate change, require a wide range of physical, biological and socio-economic models, methods, tools and data. The methods for assessing the vulnerability, impact and adaptation are gradually improving, but are still inadequate to help policy-makers formulate appropriate adaptation measures. This is due to uncertainties in regional climate projections, unpredictable response of natural and socio-economic systems and the inability to foresee future technological developments. See Box 3.1 for definitions of vulnerability, adaptability and adaptive capacity.

In this assessment, the vulnerability of natural ecosystems and socio-economic systems, and the impacts of climate change on them are presented. The sectors considered for the assessment of climate change impacts include water resources, agriculture, forest and natural ecosystems, coastal zones, health, energy and infrastructure. First, the climate change projections for the Indian subcontinent are presented. Second, the impact and vulnerability of different sectors are assessed that includes the current status of the sector, impact of climate change, and socio-economic implications of these impacts. Third, adaptation strategies are suggested, along with the current policies and their implications for the vulnerability of the different sectors. Finally, the barriers to adaptation followed by examples of potential technical, institutional and financial strategies to reduce the vulnerability of natural and human systems are presented.

CURRENT CLIMATE AND ITS VARIABILITY IN INDIA

India is subject to a wide range of climatic conditions from the freezing Himalayan winters in the north to the tropical climate of the southern peninsula, from the damp, rainy climate in the north-east to the arid Great Indian Desert in the north-west, and from the marine climates of its vast coastline and islands to the dry continental climate in the interior. The most important feature in the meteorology of the Indian subcontinent and, hence, its economy, is the Indian summer monsoon. Almost all regions of the country receive their entire annual rainfall during the summer monsoon (also called the SW monsoon), while some parts of the south-eastern states also receive rainfall during early winter from the north-east monsoon. Rainfall increases by almost three orders of magnitude from west to east across the country.

The Monsoon

The monsoon is associated with the seasonal heating of the landmasses of Asia in summer and cooling in

Box 3.1: Definitions of Vulnerability, Adaptability and Adaptive Capacity

Vulnerability is the degree to which a system will respond to a given change in climate, including beneficial and harmful effects (IPCC Working Group II, 2001).

Vulnerability is the degree to which a system is susceptible to or unable to cope with, adverse effects of climate change including climate variability and extremes.

Vulnerability is also 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 [Summary for Policy Makers (IPCC Working Group II)].

Adaptability refers to the degree to which adjustments are possible in practices, processes, structures of systems to projected or actual changes of climate. Adaptation can be spontaneous, or planned, and can be carried out in response to or in anticipation of changes in conditions (IPCC, 1996).

Adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities or to cope with the consequences [Summary for Policy Makers (IPCC Working Group II)].

winter, compared to the waters of the Indian Ocean and the China Seas. While the Indian summer monsoon is a consequence of the thermal differences between the land and the sea in general terms, it is primarily due to the seasonal shifting of thermally produced planetary belts of pressure and winds under continental influences. Further aided by complex seasonal changes in the upper-air circulation during summer under the influence of the Central Asian highlands, especially the Tibetan Plateau, favourable conditions are created for the Asian summer monsoon to develop into a powerful air stream. During winter, the presence of an extensive high-pressure area over the cold continent of Central Asia extending into northern India, and low pressure over the Indian Ocean facilitates the flow of air from the north towards the Indian Ocean at lower levels. This flow, in the form of north-easterlies (also known as the north-east monsoon), brings winter rains to the southern parts of India. Apart from the monsoons, the north-western parts of India receive considerable precipitation from the western disturbances. However, for a major part of the country, almost the whole of the annual rainfall is realized during the SW monsoon season, making the people and, hence the economy critically dependent on it.

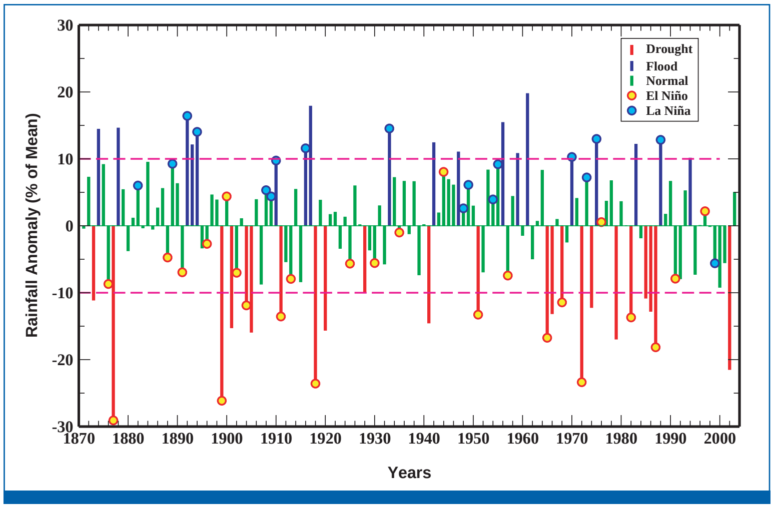


Figure 3.1: Variation of all-India monsoon rainfall during 1871-2001.

The Indian monsoon has a direct link with the Southern Oscillation Index (SOI). Weak Indian monsoons in the country are associated with a large negative SOI and occurrence of *El Niño*. Whereas, strong monsoons have been linked to large positive SOIs and absence of *El Niño* events. Besides these, several global and regional parameters have been found to contribute to the interannual variability of the monsoon rainfall, which form the basis for its seasonal forecasting. However, the relationships between the Indian monsoon and regional/global circulation parameters are known to have undergone significant multi-decadal changes obscuring the causal mechanisms.

Rainfall and Surface Temperature Patterns

Rainfall: Meteorological records maintained since the 19th century indicate that the Indian summer monsoon is reasonably stable; however, simultaneous occurrence of devastating floods in some areas and parching droughts in others is a common feature. The interannual variability of the monsoon is the cause of such contrasting features[1] (Figure. 3.1). It has been observed that regions with low seasonal rainfall also experience high variability, making them chronically drought prone. The effect of droughts is further accentuated by the occurrence of two to three consecutive drought years in the same region.

Although the monsoon rainfall at the all-India level does not show any trend and seems mainly random in nature over a long period of time, the presence of pockets of significant long-term changes in rainfall have been recorded. Areas of increasing trend in the monsoon seasonal rainfall are found along the west coast, north Andhra Pradesh and north-west India (+10 to +12 per cent of normal/100 years) and those of decreasing trend over east Madhya Pradesh and adjoining areas, north-east India and parts of Gujarat and Kerala (-6 to -8 per cent of normal/100 years) (Figure. 3.2).

[1] A year is classified as deficient, normal (negative), normal (positive) or excess monsoon year, when the all-India summer monsoon rainfall is below -10 per cent, between -10 per cent and zero, between zero and +10 per cent, or above +10 per cent, respectively.

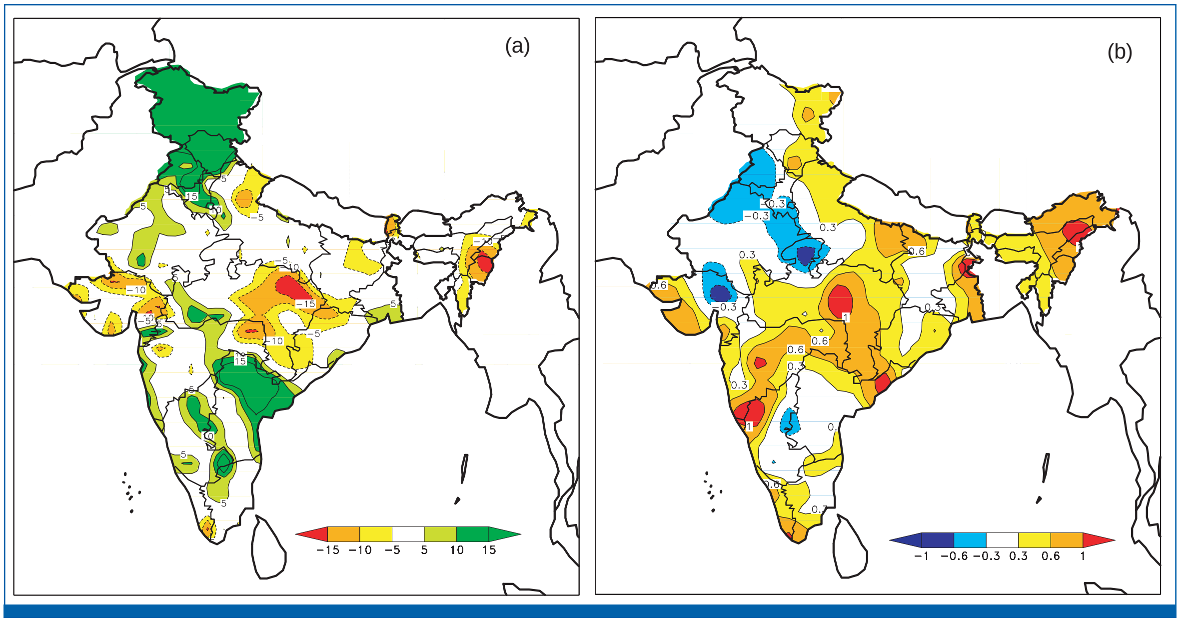


Figure 3.2: Spatial patterns of linear trends (percentageof mean/100 years) in (a) summer monsoon rainfall; and (b) annual mean surface temperature during 1871-1990.

Temperature: All-India and regional mean seasonal and annual surface air temperature for the period 1901-2000 indicate a significant warming of 0.4°C per hundred years. On a seasonal scale, the warming in the annual mean temperatures is mainly contributed by the post-monsoon and winter seasons. Also, data analyzed in terms of daytime and night-time temperatures indicate that the warming was predominantly due to an increase in the maximum temperatures, while the minimum temperatures remained practically constant during the past century. The seasonal/annual mean temperatures during 1901-2000 are based on data from 31 stations, while the annual mean maximum and minimum temperature during 1901-1990 are based on data from 121 stations. Spatially, a significant warming trend has been observed along the west coast, in central India, the interior peninsula and over north-east India, while a cooling trend has been observed in north-west India and a pocket in southern India (Figure 3.2).

Extreme weather and climate events

In India, the climate and weather are dominated by the largest seasonal mode of precipitation in the world, due to the summer monsoon circulation. Over and above this seasonal mode, the precipitation variability has predominant interannual and intra-seasonal components, giving rise to extremes in seasonal anomalies resulting in large-scale droughts and floods, and also short-period precipitation extremes in the form of heavy rainstorms or prolonged breaks on a synoptic scale. Indeed, rainfall during a typical monsoon season is by no means uniformly distributed in time on a regional/local scale, but is marked by a few active spells separated by weak monsoon or break periods of little or no rain. Thus, the daily distribution of rainfall at the local level has important consequences in terms of the occurrence of extremes. Further, the Indian climate is also marked by cold waves during winter in the north, and heat waves during the pre-monsoon season over most parts of the country. Tropical cyclones, affecting the coastal regions through heavy rainfall, high wind speeds and storm surges, often leave behind widespread destruction and loss of life, and constitute a major natural disaster associated with climatic extremes. Indeed, it is these extremes that have the most visible impact on human activities and therefore, receive greater attention by all sections of the society.

Droughts and Floods: It has already been noted that the Indian summer monsoon is a very stable and dependable source of water for the region. Superimposed on this stable picture are seemingly

Box 3.2: Impacts of Droughts and floods in India.

There are four major reasons for droughts in India-delay in the onset of monsoon/ failure of monsoon, variability of monsoon rainfall, long break in monsoon and areal difference in the persistence of monsoon. Almost a quarter of India's land area is prone to drought. Areas that receive up to 60 centimeters of rainfall annually are the most drought prone. The drought is almost directly linked to the areal variation in the monsoon, the effect of which lasts for much longer than the actual span of the monsoon. The most affected community are the marginal farmers dependent on rainfed agriculture.


Droughts affecting marginal farmers.

Compared to drought, a smaller area is affected by large-scale flooding. However the loss in terms of lives and property is much higher. From the approximately 19 Mha affected by floods in India about five decades ago, the figure today stands at about 36 Mha - almost double (CWC,1997). Some of the causes of floods are: Unusually high rainfall in a short period of time, which leads to high volume of run-offs, Rivers or other water bodies overflowing their banks, Excessive deforestation of hills can cause floods lower downstream. Inadequate drainage facilities may cause water to stagnate. Change in the course of rivers and in the coastal regions and tropical cyclones can also cause flooding.


Devastation of crops due to extensive flooding.

small year-to-year changes that can be spatially quite extensive. However, even such small changes constitute significant interannual variability, leading to widespread drought and flood situations. Instrumental records over the past 130 years do not indicate any marked long-term trend in the frequencies of large-scale droughts or floods in the summer monsoon season. The only slow change discernible is the alternating sequence of multi-decadal periods of more frequent droughts, followed by periods of less frequent droughts. This feature is part of the well-known epochal behaviour of the summer monsoon. See Box 3.2 for impacts of floods and droughts in India.

***Aridity*:** There are large tracts in north-western India and the interior peninsula that experience arid conditions. Although desertification is a complex environmental process involving geomorphologic and atmospheric processes, it is observed that the rainfall regimes generally closely demarcate the arid region boundaries. In general, during extreme deficient years of SW monsoon over the Indian subcontinent, aridity takes over the semi-arid areas and its spatial extent continues deep down south to the peninsula. On an average, about 19 per cent of the country experiences arid conditions every year, of which 15 per cent is in northern India and 4 per cent in the peninsula.

Short-duration rainfall extremes: The spatial patterns of the mean annual number of rainy days derived from observed rainfall data are presented in Figure 3.3. A rainy day is defined as a day with a rainfall of 2.5 mm and above, as per the operational practice of the India Meteorological Department (IMD). The mean annual number of rainy days over India varies from less than 20 days over the north-western parts (west Rajasthan and Kutchh region of Gujarat), to more than 180 days in the north-east (Meghalaya). North-eastern India and the southern parts of the west coast are major areas of relatively high mean annual number of rainy days (about 140 days). The mean annual number of rainy days increases from west to east, particularly in the northern parts of the country. Over central parts of India, the number of rainy days is around 40-60 days. Over the west coast, along the tracks of monsoon disturbances and near the foothills of the Himalayas, it is around

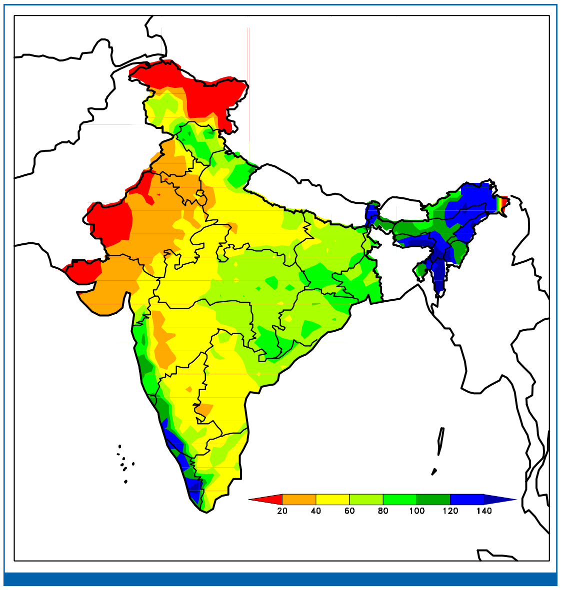


Figure 3.3: Spatial patterns of observed mean annual number of rainy days over India.

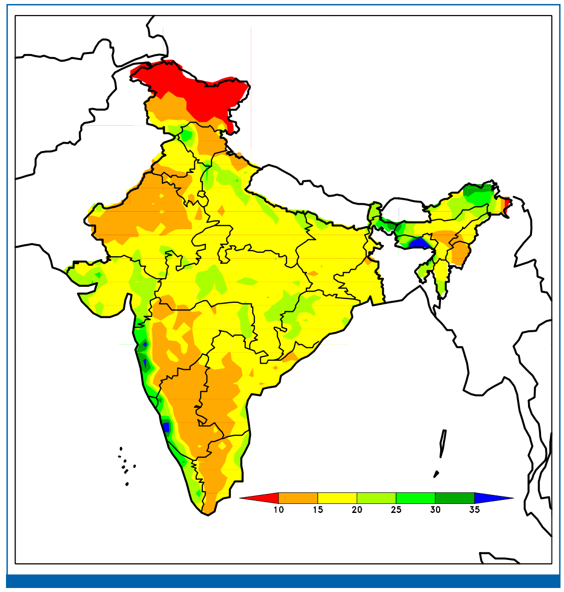


Figure 3.4: Spatial patterns of observed mean intensity of rainfall (mm/day) over India.

80 days. From the observed spatial pattern of the mean intensity of rainfall per rainy day (Figure. 3.4), it is seen that the intensity varies between 10 mm and 40 mm per rainy day over India. The lowest values of less than 10 mm/day occur in the extreme northern parts of the country. Over north-western India and the rain-shadow region to the east of the Western Ghats in the peninsula, the intensity is around 10-15 mm per rainy day. The highest value of about 40 mm/ day occurs along the west coast, as well as in some parts of north-eastern India. Over the rest of the country, the intensity of rainfall is of the order of 15-25 mm/day.

Extreme Temperatures: Spatial patterns of observed extreme daily maximum temperatures are shown in Figure 3.5. It has been observed that over the central parts of India, the maximum temperatures recorded exceed 45°C, while along the west coast, the extreme maximum temperatures recorded range between 35°-40°C. Smaller values of extreme maximum temperatures of around 25°C have been recorded in Himachal Pradesh in the north. Figure 3.6 shows the spatial pattern of extreme minimum temperatures, which represent the lowest temperature ever recorded in the respective regions. Low-temperature extremes dropping to less than -15°C have been recorded in the northernmost parts of India. Extreme minimum temperatures below 0°C have also been observed in the region north of 25°N and west of 80°E.

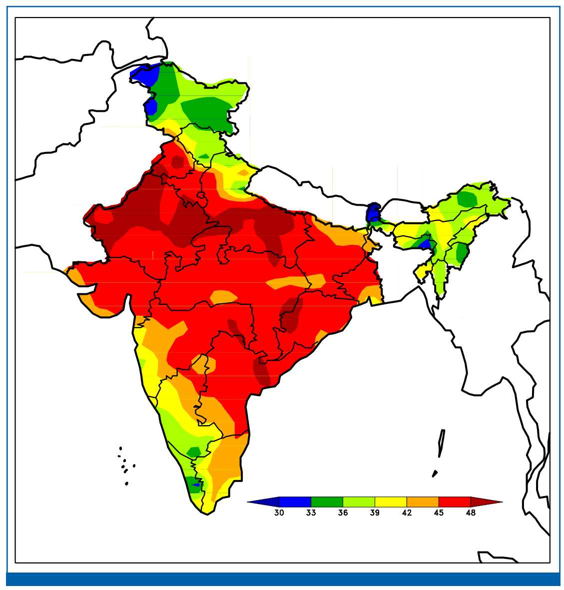


Figure 3.5: Spatial patterns of observed extreme daily maximum temperatures (ºC) over India.

Cyclonic storms: In the northern Indian Ocean, about 16 cyclonic disturbances occur each year, of which about six develop into cyclonic storms. The annual number of severe cyclonic storms with hurricane force winds averages to about 1.3 over the period 1891-1990. During the recent period 1965-1990, the number was 2.3. No clear variability pattern appears to be

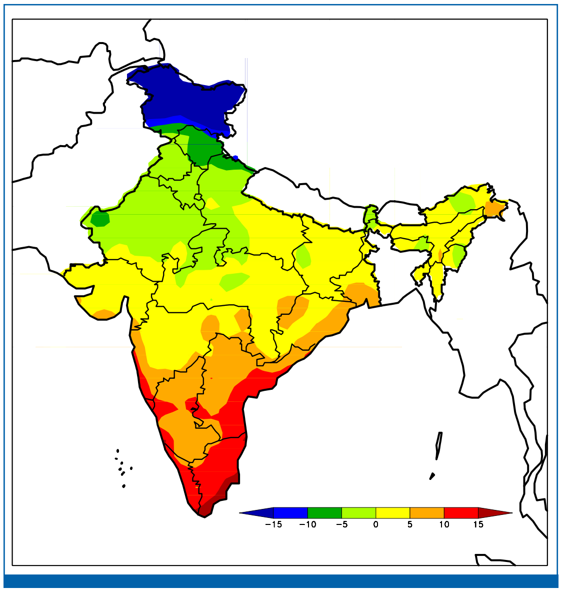


Figure 3.6: Spatial patterns of observed extreme daily minimum temperatures (ºC) over India.

associated with the occurrence of tropical cyclones. While the total frequency of cyclonic storms that form over the Bay of Bengal has remained almost constant over the period 1887-1997, an increase in the frequency of severe cyclonic storms appears to have taken place in recent decades (Figure 3.7). Whether this is real, or a product of recently enhanced monitoring technology is, however, not clear. A slight decreasing trend in the frequency of cyclonic disturbances and tropical cyclones is apparent during the monsoon season. High sea surface temperature is a necessary, though not sufficient, condition for the formation and growth of tropical cyclones. Over the Indian Ocean, Bay of Bengal and the Arabian Sea, significant and consistent warming of the sea surface has occurred during the 20th century. Sensitivity experiments with numerical models suggest that cyclone intensity may increase with the increasing sea surface temperatures.

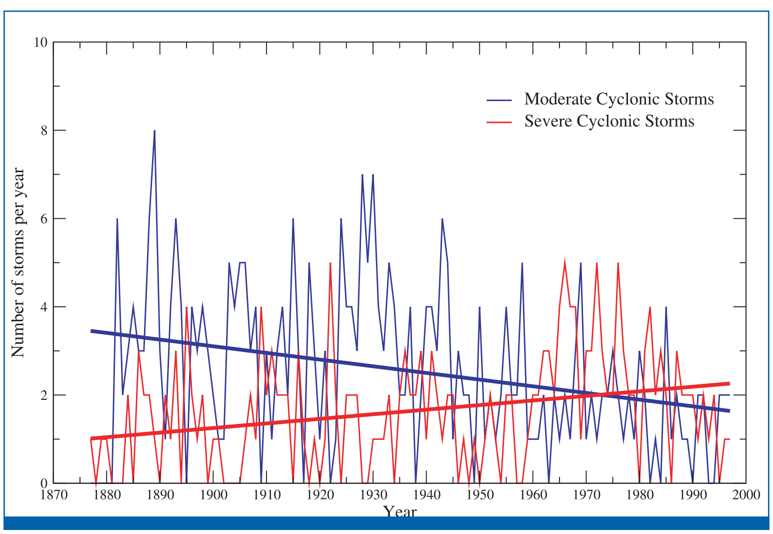


Figure 3.7: Variation of the frequency of moderate and severe cyclonic storms. over the Indian seas.

CLIMATE MODEL SIMULATIONS OF THE INDIAN CLIMATE

While most global climate models simulate the general migration of tropical rain belts from the austral summer to the boreal summer, some of them miss the rainfall maximum in the tropical Pacific Ocean. Apart from this, in the Indian monsoon context, the observed maximum rainfall during the monsoon season along the west coast of India, northern Bay of Bengal and adjoining north-east India is not quite realistically simulated in many models. This may possibly be linked to the coarse resolution of the models, as the heavy rainfall over these regions is generally in association with the steep orography. However, the annual cycle in the simulated precipitation over the Indian region (land and sea) comprising 8ºN; 30ºN and 65ºE; 95ºE showed remarkably similar patterns (Figure 3.8). Most models underestimate the rainfall during the rainy season. The simulated annual surface air temperature patterns over the Indian region generally agree with the observed gross features, though magnitudes differ from the observed values in most models. The possible biases associated with the coarse resolution of the Atmosphere-Ocean General Circulation Models (AOGCMs) need to be taken into account while interpreting the future climate change scenarios.

The global atmosphere-ocean coupled models have provided good representations of the planetary scale features, but their application to regional studies is limited by their coarse resolution (~300 km). Developing high resolution models on a global scale is not only computationally prohibitively expensive

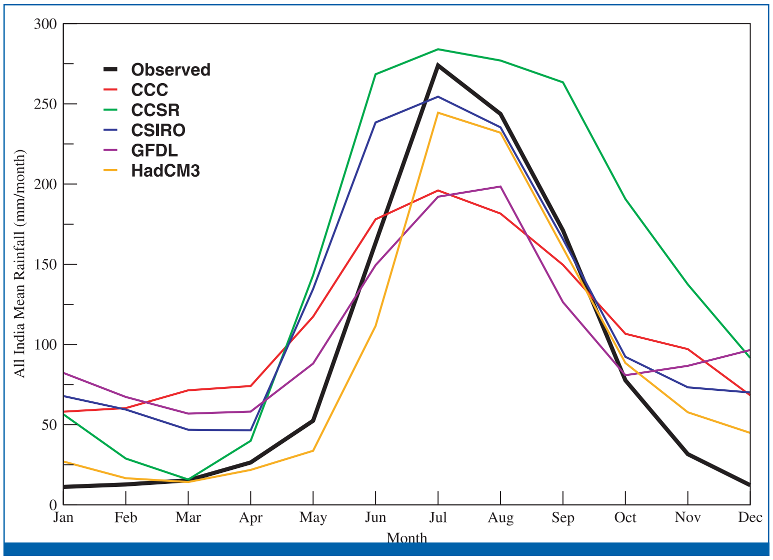


Figure 3.8: Observed and simulated Control (CTL) annual cycles of rainfall over India.

for climate change simulations, but also suffers from errors due to inadequate representation of high-resolution climate processes worldwide. 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) a realistic simulation of the current climate by taking into account fine-scale features of the terrain, etc.; (b) more detailed predictions of future climate changes, taking into account local features and responses; (ci) representation of the smaller islands and their unique features; (d) better simulation and prediction of extreme climatic events; and (e) generation of detailed regional data to drive other region-specific models analyzing local-scale impacts.

In the present assessment, the high-resolution simulations for India based on the second generation Hadley Centre regional climate model (HadRM2) are used. HadRM2 is a high-resolution climate model that covers a limited area of the globe, typically 5,000 km x 5,000 km. The typical horizontal resolution of HadRM2 is 50 km x 50 km. The regional model reproduces large-scale features of the General Circulation Model (GCM) climate and adds realistic local detail. For example, the rain-shadowing effect of the Western Ghats is closer to the observations (Figure 3.9). The annual cycles of rainfall and surface air temperature are also remarkably close to the observed patterns, which demonstrate that the regional model is able to overcome the large biases of the GCM in portraying these features.

In terms of short-duration rainfall, it is observed that the spatial pattern of rainy days is well-generated by the model over the west coast, north-western India and north-eastern India (except for Arunachal Pradesh, where it is overestimated to exceed 180 days). However, the regional model generally underestimates the intensity of rainfall over the country, except for some parts in Himachal Pradesh,

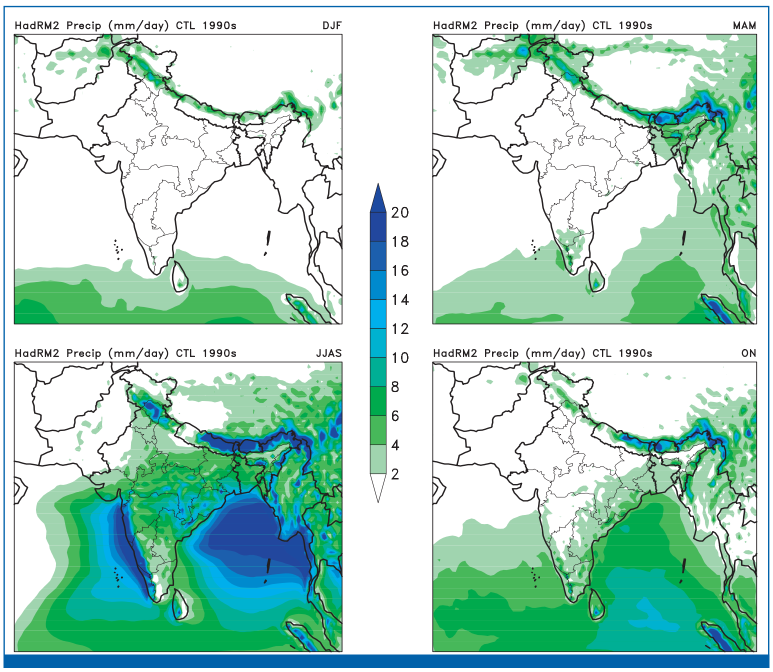


Figure 3.9: Spatial patterns of seasonal rainfall over India as simulated by a regional climate model (HadRM2; CTL).

north-eastern India and along the west coast. While the model represents the spatial variation reasonably well, there is a clear bias in terms of the magnitude, at least by 5 mm per rainy day over a major part of the country. Comparing the spatial pattern of one-day extreme rainfall as generated in control run, it can be concluded that rainfall extremes are reasonably well-simulated by the model in the region south of 20°N, but north of it, the model underestimates the extremes by around 10 cm/day.

Model-simulated data shows a balance between simulated and observed extreme maximum temperatures in the peninsular region. However, the model underestimates high-temperature extremes in the mountainous regions of Kashmir, Sikkim and Arunachal Pradesh, and overestimates the extreme maximum temperature by about 5°C over the northern plains. The patterns of extreme minimum temperatures are well-represented by the model over most of the country, except over some regions in Gujarat, Madhya Pradesh and Bihar, where it underestimates by about 5°C.

CLIMATE PROJECTIONS

Climate projections at the national level

For assessing the nature of the likely future climate in India at an all-India level, eight AOGCMs (Box 3.3) have been run using the IS92a and SRES A2 and B2 scenarios (Box 3.4).

The simulated climate approximately represents the period spanning the nominal time scale of 1860-2099, but the individual model years do not correspond to any specific years or events in this period. Considering all the land-points in India according to the resolution of each AOGCM, the arithmetic averages of rainfall and temperature fields are worked out to generate all-India monthly data for the entire duration of model simulations and for different experiments. This monthly data is then used to compute the seasonal totals/means of rainfall/temperature. Taking 1961-1990 as the baseline period, the seasonal quantities are then converted into anomalies (percentage departures in the case of rainfall). The resulting time series are examined for their likely future changes into the 21st century (Figure 3.10).

Box 3.3. Coupled AOGCM used for deriving climate change projections

- Canadian Center for Climate Modeling, Canada (CCC).
- Center for Climate System Research, Japan (CCSR).
- Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO).
- Deutsches Kilma Rechen Zentrum, Germany (DKRZ).
- Geophysical Fluid Dynamics Laboratory, USA (GFDL).
- Hadley Center for Climate Prediction and Research, UK (HadCM3).
- Max-Planck Institute, Germany (MPI).
- National Center for Atmospheric Research, USA (NCAR).

Box 3.4. Scenarios used in climate model experiments

- ***CTL*:** The control integration, in which the atmospheric forcing in terms of the GHG concentration is kept constant, typically at 1990 values, has been performed for a period of over several hundred years in length. The climatology constructed from the CTL run represents the current climate and serves as a reference for all the time-dependent forcing experiments.
- ***IS92a Scenario of GHG increase*:** In this experiment, the GHG forcing is increased gradually to represent the observed changes in forcing due to all the GHG from 1860 to 1990. For the future time period 1990-2099, the forcing is increased at a compounded rate of 1 per cent per year (relative to 1990 values), representing the IS92a emissions scenario.
- ***A2 Scenario of SRES (A2):*** A2 scenario falls in the category of 'Medium-High' emissions. The cumulative global carbon emissions between 2000 and 2100 for this scenario is taken to be 1862 GtC (1GtC = 1 giga or Bt of Carbon; 1 tonne of Carbon = 3.67 tonnes of CO_2).
- ***B2 Scenario of SRES (B2):*** B2 scenario falls in the category of 'Medium-Low' emissions.

GHG simulations with IS92a scenarios show marked increase in both rainfall and temperature by the end of the 21st century relative to the baseline. There is a considerable spread among the models in the

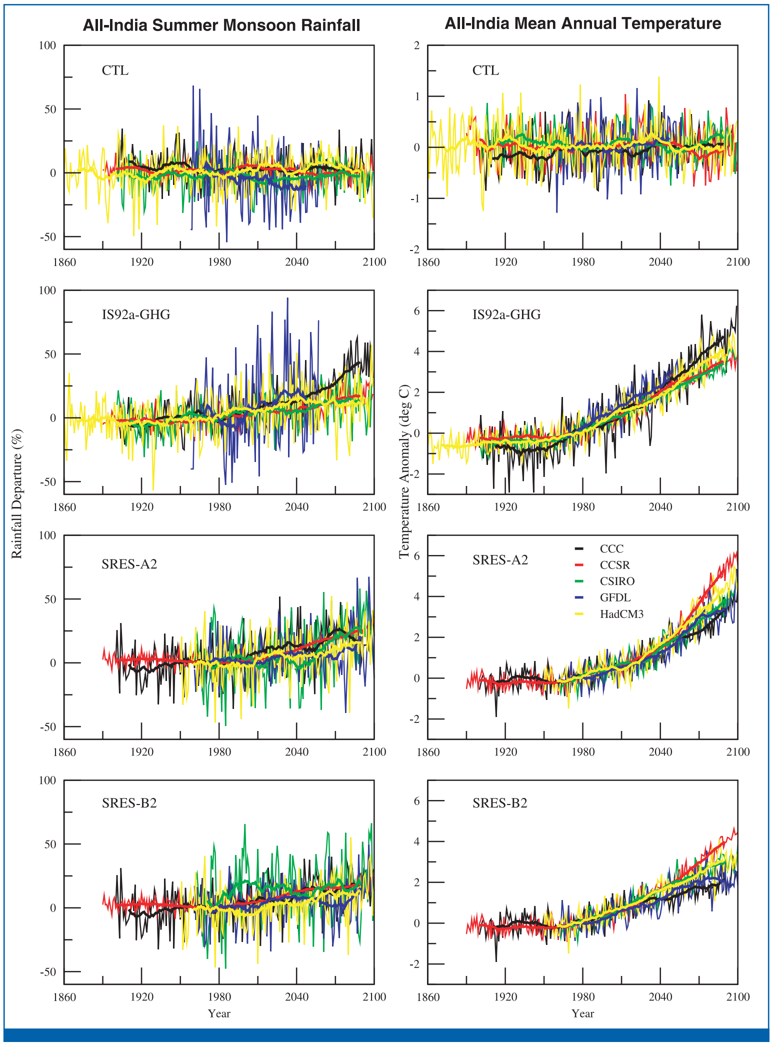


Figure 3.10: AOGCM projections of all-India mean summer monsoon rainfall and annual mean surface air temperature up to the year 2100, for CTL IS92a and SRES A2 and B2 scenarios.

GCM's project enhanced precipitation during the monsoon season, particularly over the north-western parts of India. However, the magnitudes of projected change differ considerably from one model to the other, when projections of rainfall are considered at state level (Figure 3.11). There is very little or no change noted in the monsoon rainfall over a major part of peninsular India. It is important to note here, that the maximum change in rainfall occurs over the climatologically low rainfall region of north-western India. The implications of such change over this region have to be carefully assessed in future studies. As far as the temperature trends in the future are concerned, all the models show positive trends indicating widespread warming into the future (Figure 3.11). Examination of the spatial patterns of annual temperature changes in the two future time slices for different models indicates that the warming is more pronounced over the northern states of India. The different models/experiments generally indicate the increase of temperature to be of the order of 2-5°C across the country. The warming is generally higher in the IS92a scenario runs compared to A2 and B2 simulations. Also, the warming is more pronounced during winter and post-monsoon months, compared to the rest of the year. Interestingly, this is a conspicuous feature of the observed temperature trends from the instrumental data analyses over India.

magnitudes of both precipitation and temperature projections, but more conspicuously in the case of summer monsoon rainfall. The increase in rainfall from the baseline period (1961-1990) to the end of the 21st century ranges between 15 per cent and 40 per cent among the models. In the case of mean annual temperature, the increase is of the order of 3ºC to 6ºC. It is apparent that the change in rainfall under A2 and B2 scenarios is not as high as that noted earlier in IS92a scenarios (Figure 3.10). Compared to the A2 scenario, the B2 simulations show subdued trends in the future. The temperature, however, shows comparable increasing trends in IS92a and A2, but B2 shows slightly lower trends.

Climate Projections at the regional level

To provide a general idea of the scenarios for different states of India, the expected changes in monsoon rainfall and mean annual temperature have been computed for the 2050s (Figure 3.11). It can be seen that there is an all-round increase in temperatures, and a general increase in monsoon precipitation.

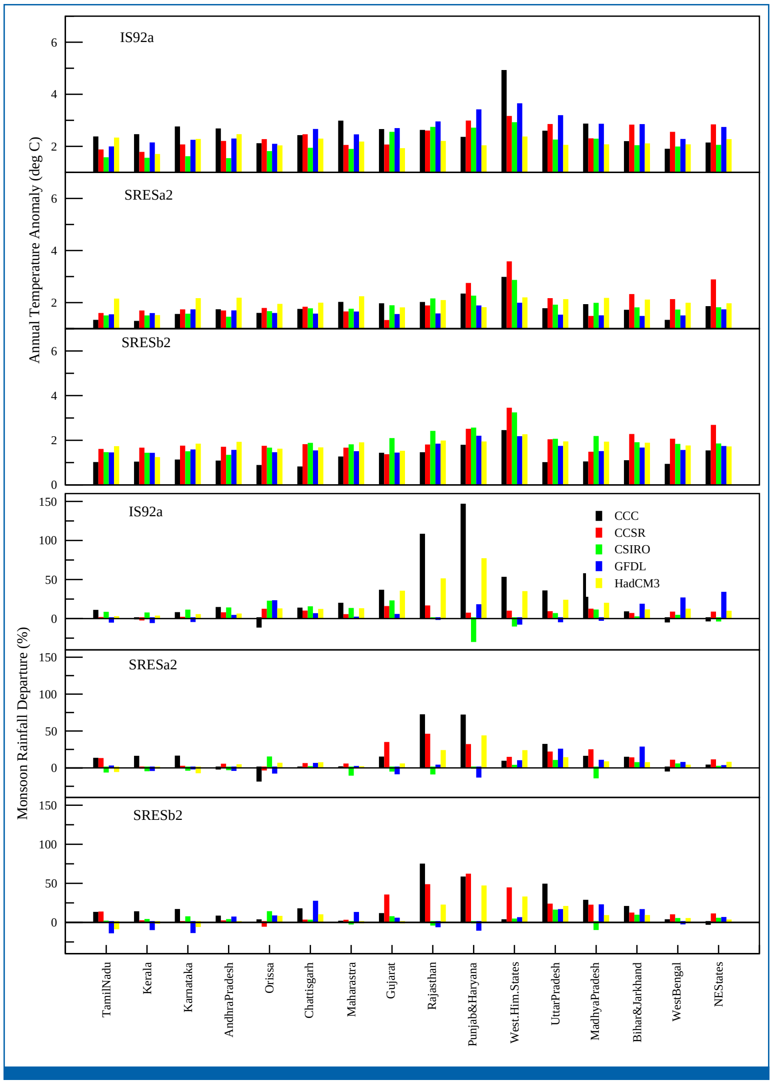


Figure 3.11:. AOGCM-based projections for the 2050s, of summer monsoon rainfall and mean annual temperature of different states of India, relative to the baseline period of 1961-90.

However, there is a large spatial variation in the relative increase in monsoon precipitation, obviously due to the climatological patterns of rainfall.

It must be mentioned here that these scenarios are based on very coarse resolution global climate models, and the values for the smaller states are based on one or two grid points and therefore, may be subject to large biases related to orography and other local characteristics. To overcome this limitation, it is useful to consider the projections based on high-resolution regional climate models. Work on this aspect is in progress, but some preliminary scenarios based on HadRM2, for the IS92a scenario for the future time slice of 2041-2060 may be considered here. In the regional climate model, under increasing atmospheric GHG concentrations, the mean surface temperatures are seen to increase everywhere in the region, in all the seasons (Figure 3.12). The warming is more pronounced over land areas, with the maximum increase over northern India. The warming is also relatively greater in winter and post-monsoon seasons. The summer monsoon season is marked by a relatively lower magnitude of warming. This seasonal asymmetry of greenhouse warming over India has a remarkable resemblance to that seen in the case of observed trends in all-India mean surface temperatures over the past century. However, the spatial patterns of warming during the monsoon season indicate that the maximum warming occurs over northern India, with a secondary maximum over the eastern peninsula.

Regarding the precipitation response, the monsoon season is of prime importance, given the region's critical dependence on summer monsoon rainfall. In this season, the precipitation response is more variable with a decrease seen over the land towards the west and increase over the Indian Ocean. The central and the eastern regions of the country do not show much variability with respect to the control runs (Figure 3.13). In general, on an annual scale, large decreases are seen over the western part of India mainly over the oceanic areas, and increases over the north-eastern parts of the country. These differences in future rainfall change patterns in HadRM2, compared to the AOGCMs, are possibly related to the use of the Hadley Center Model (HadCM2) projections to drive the HadRM2. Significant differences have been noted in the future rainfall change patterns between HadCM2 and

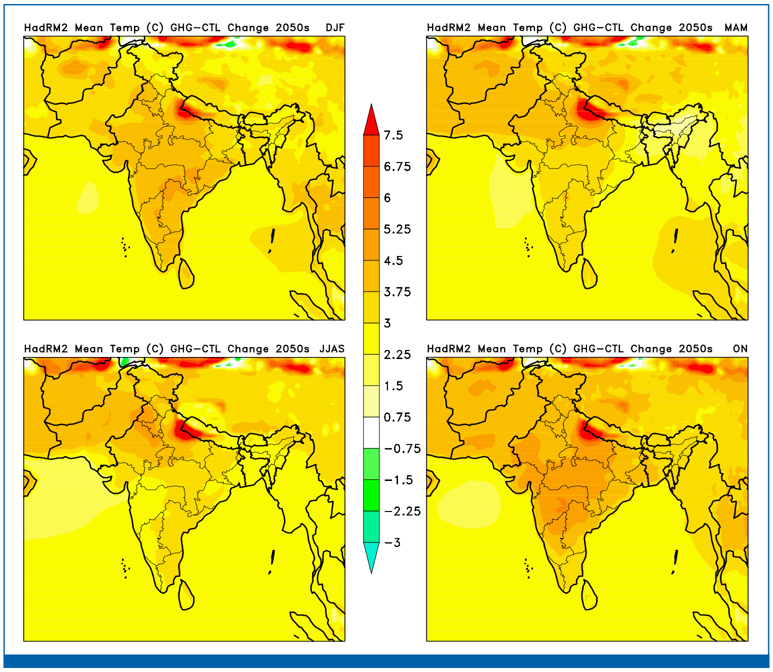


Figure 3.12:. Projections of seasonal surface air temperature for the period 2041-2060, based on the regional climate model HadRM2.

HadCM3. While HadCM2 shows a tendency for reduced rainfall over India, HadCM3 shows increased rainfall into the 21st century. Further work using more recent versions of the regional model as well as its boundary forcing is in progress to reduce such uncertainties.

Projections of extremes in rainfall and temperature

Keeping in view the need to analyze the changes on a smaller space-time scale to derive information related to the extremes, only regional climate model results are discussed here. HadRM2 is more reliable in representing the observed patterns of extremes in rainfall and temperature. Considering the control run of the model as the baseline Climatology representing the present day conditions, the future scenarios representing the 2050s, under the IS92a scenario of GHG emissions, are derived. In the IS92a scenario, the model showed an overall decrease in the number of rainy days over a major part of the country (Figure 3.14). This decrease is more in western and central parts of the country (by more than 15 days) while along the foothills of Himalayas (Uttaranchal) and in north-east India the number of rainy days is found to increase by 5-10 days. An increase in GHG concentrations may lead to overall increase in the rainy day intensity by 1-4 mm/day, except for small areas in north-western India, where the rainfall intensities decrease by 1 mm/day (Figure 3.15). The model results also indicate that there will be an overall increase in the highest one-day rainfall over a major part of the Indian region. This increase may be up to 20 cm/day. However, in some parts of north-western India, a decrease in extreme rainfall up to about 10 cm/day has been noticed in the GHG experiment.

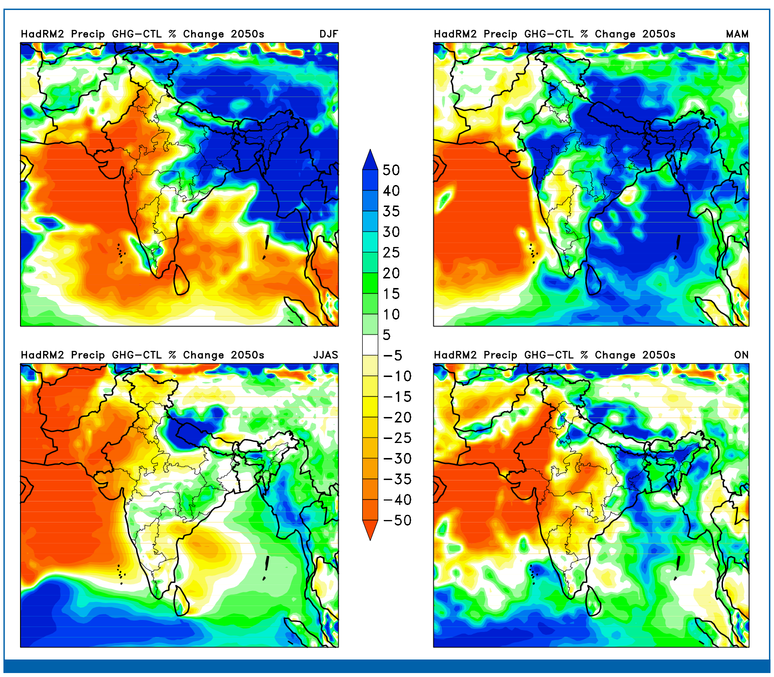


Figure 3.13:. Projections of seasonal precipitation for the period 2041-2060, based on the regional climate model HadRM2.

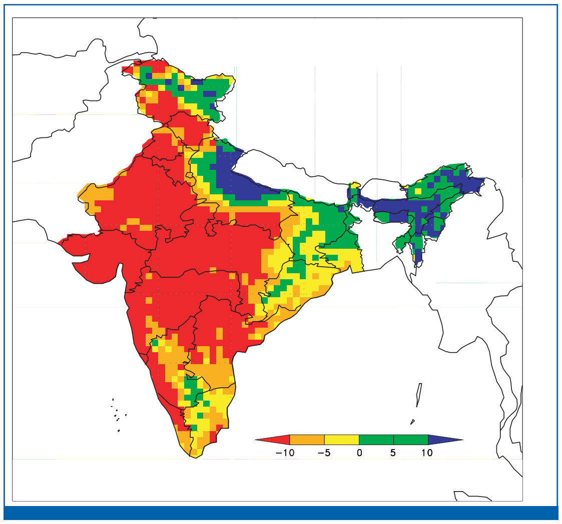


Figure 3.14: Projections of mean incremental annual number of rainy days for the period 2041-2060, based on the regional climate model HadRM2.

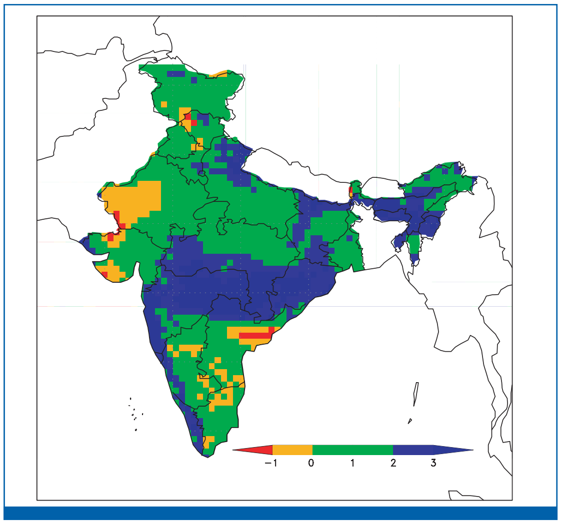


Figure 3.15: Projections of mean incremental rainy day intensity (mm/day) for the period 2041-2060, based on the regional climate model HadRM2.

Summary

The regional model (HadRM2, IS92a scenario) is able to overcome the large biases of the GCM in portraying the annual cycles of rainfall and surface air temperature. The projections of climate variables for the 2050s, under the IS92a scenario of GHG emissions are summarized below;

- An all-round increase in temperatures, and a general increase in monsoon precipitation in the monsoon season. The precipitation response is more variable with a decrease over the land towards the west and an increase over the Indian Ocean.
- A large spatial variation in the relative increase in monsoon precipitation
- An overall decrease in the number of rainy days over a major part of the country
- An overall increase in the rainy day intensity by 1-4 mm/day
- An increase in the temperature (maximum and minimum) of the order of 2-4°C over the southern region which may exceed 4°C over the northern region

Uncertainties in prediction: Regionally, there are large differences among different GCMs, especially in precipitation-change patterns over the Indian subcontinent. Most GCM models project enhanced precipitation during the monsoon season, particularly over the north-western parts of India. However, the magnitudes of projected change differ considerably from one model to the other. Uncertainties exist in the projections of climate models specifically concerning their spatial resolutions. The GCMs are robust in projecting temperature changes rather than rainfall changes. Regional climate models also have large uncertainty (rainfall projection using HadRM2 versus HadRM3), but are still evolving. It is expected that uncertainty would reduce as the regional climate models evolve. Thus, caution must be exercised when using climate projections, though there is a robust projection of significant warming.

Climate Change Scenario Links to other Sectors: According to the Second and Third Assessment Report of the IPCC at the global and continental level, the projected climate change is likely to impact the natural ecosystems and socio-economic systems Under the National Communications project the impacts of projected climate change are analyzed for different sectors in the following sections. The assessment of climate change impacts are made using RCM projections for some sectors (for example, water resources and forest ecosystems). The impacts, vulnerability and adaptation options are presented for different sectors in the following sections.

CLIMATE CHANGE IMPACTS ON WATER RESOURCES

Present Indian Water Resources Scenario

India is a land of many rivers and mountains. Its geographical area of 328.726 Mha is covered by a large number of small and big rivers. Over 70 per cent of India's population of one billion is rural and agriculturally oriented, for whom these rivers are the source of their livelihood and prosperity.

Climate plays a very decisive factor in water resource availability of a country. Rainfall in India is mainly dependent on the SW monsoon between June to September, and the north-east monsoon between October and November. The variations in temperature are also marked over the Indian subcontinent. During the winter season from November to February, the temperature decreases from south to north due to the effect of continental winds over most of the country. Evapotranspiration rates closely follow the climatic seasons, and reach their peak in the summer months of April and May. The central areas of the country display the highest evapotranspiration rates during this period. After the onset of monsoon, potential evapotranspiration decreases generally all over the country.

There are 12 major rivers in India (with individual catchment areas of more than 10 Mha), with a cumulative catchment area of 252.8 Mha. Of the major rivers, the Ganga-Brahmaputra-Meghna system is the largest, with a catchment area of about 110 Mha, that is more than 43 per cent of the cumulative catchment area of all the major rivers in the country. This river system is the major contributor to the surface water resources potential of the country. Its share is about 60 per cent of the total water resource potential of the various rivers.

The other major rivers with a catchment area of more than 10 Mha each are the Indus (32.1 Mha); Godavari (31.3 Mha); Krishna (25.9 Mha); and the Mahanadi (14.2 Mha). The total catchment area of medium rivers is about 25 Mha and Subernarekha, with a 1.9 Mha catchment area, is the largest river amongst the medium rivers in the country.

The annual precipitation, including snowfall, which is the main source of the water in the country, is estimated to be of the order of 4'000 km^3. There are 35 meteorological sub-divisions with respect to the rainfall variability. The water resources potential of the country (occurring as natural run-off in the rivers) is about 1,869 km^3, as per the latest basin-wise estimates made by the Central Water Commission. While India is considered rich in terms of annual rainfall and total water resources, its uneven geographical distribution causes severe regional and temporal shortages.

Water Demand: Water is the most critical component of life support systems. India shares about 16 per cent of the global population but it has only 4 per cent of the total water resource. The irrigation sector with 83 per cent of use is the main consumer of water. Based on the 1991 Census, the per capita availability of water works out to 1,967 m^3. Due to various constraints of topography, and uneven distribution of resources over space and time, it has been estimated that only about 1,122 km^3 of its total potential can be put to beneficial use, of which 690 km^3 is surface water resources. Further, about 40 per cent of the utilizable surface water resources are presently in the Ganga-Brahmaputra-Meghna system. In a majority of river basins, the present utilization is significantly high and is in the range of 50 per cent to 95 per cent of utilizable surface resources. However, in rivers such as the Narmada and Mahanadi, the percentage utilization is quite low. The corresponding values for these basins are 23 per cent and 34 per cent, respectively.

On the other hand, the ground water is another major component of the total available water resources. In the coming years the ground water utilization is likely to increase manifold for the expansion of irrigated agriculture and to achieve national targets of food production. Although the ground water is an annually replenishable resource, its availability is non-uniform in space and time.

Based on the norms given by the Ground Water Overexploitation Committee, the state governments and the Central Ground Water Board computed the gross ground water recharge as 431.42 km^3, and the net recharge (70 per cent of the gross) as 301.99 km^3.

With respect to total water requirements, as per the recent estimates made by the Ministry of Water Resources, the total withdrawal/utilization for various uses has been estimated for the present and the future years. (Table 3.1).

According to the Ministry of Water Resources, the water availability may be able to meet the requirements till the year 2050, through integrated water management plans. The issue of demand management has been given due importance in order to achieve higher levels of water use efficiencies. However, this analysis does not take into account any possible impact due to climate change. Based on the extent and level of climate change impacts, all these computations will have to be reworked.

Methods and Model Used for Simulation of Surface Runoff at River Basin Level

The present assessment aims to determine the water availability under a projected climate change scenario, initially for the HadRM2 control scenario case, without incorporating any man-made changes such as dams, diversions, etc. Second, the same framework is used to predict the impact of climate change, using the HadRM2 climate change scenario on the current availability of water resources, with the assumption that the land use will not change over time.

SWAT Model: The SWAT water balance model has been used for the river basins to carry out the hydrologic modelling of the country. The SWAT model simulates the hydrologic cycle in daily time steps. The SWAT Model routes water from individual watersheds, through the major river basin systems. SWAT is a distributed, continuous, daily hydrological model with a GIS interface for pre- and post-processing of the data and outputs.

Data used for modelling: The SWAT model requires data on terrain, land-use, soil and weather for assessment of water resources availability at the desired locations of the drainage basin. Data (1:250,000 scale) for all the river basins of the country, barring the Brahmaputra and Indus, been used. The snowbound areas of the Ganga have also not been modelled due to the lack of appropriate data.

Table 3.1: Utilizable Water, Requirement and Return Flow Based on National Average (in km^3).

Particulars	1997–1998	2010		2025		2050	
		Low Demand	High Demand	Low Demand	High Demand	Low Demand	High Demand
Utilizable Water							
Surface	690	690	690	690	690	690	690
Ground	396	396	396	396	396	396	396
Canal irrigation	90	90	90	90	90	90	90
Total	996	996	996	996	996	996	996
Total Water Requirement							
Surface	399	447	458	497	545	641	752
Ground	230	247	252	287	298	332	428
Total	629	694	710	784	843	973	1180
Return flow							
Surface	43	52	52	70	74	91	104
Ground	143	144	148	127	141	122	155
Total	186	196	200	197	215	213	259
Residual Utilizable Water							
Surface	334	295	284	263	219	140	42
Ground	219	203	202	146	149	96	33
Total	553	498	486	409	368	236	75

Source: NCIWRD, 1999.

Digital Elevation Model (DEM); is generated using contours taken from the 1:250,000 scale ADC world topographic map.

Watershed (sub basin); automatic delineated watersheds by using the DEM as input and the final outflow point on each river basin as the pour point. Figure 3.16 depicts the modelled river basins (automatically delineated using GIS), with their respective sub-basins

Daily Weather Data; generated in transient experiments by the Hadley Center for Climate Prediction, UK, at a resolution of 0.44° X 0.44° latitude by longitude grid points (red dots in Figure 3.16 for present/control (1981–2000) and future/GHG (2041–2060) climate data.

Land Cover/Land-Use Layer; classified land cover using remote sensing by the University of Maryland Global Land Cover Facility (13 categories, Source: Global Land Cover, University of Maryland Global Land cover Facility), with a resolution of 1 km grid cell size has been used.

Soil Layer; soil map adapted from FAO Digital Soil Map of the World and Derived Soil Properties (ver 3.5, FAO, 1995) with a resolution of 1: 5,000,000.

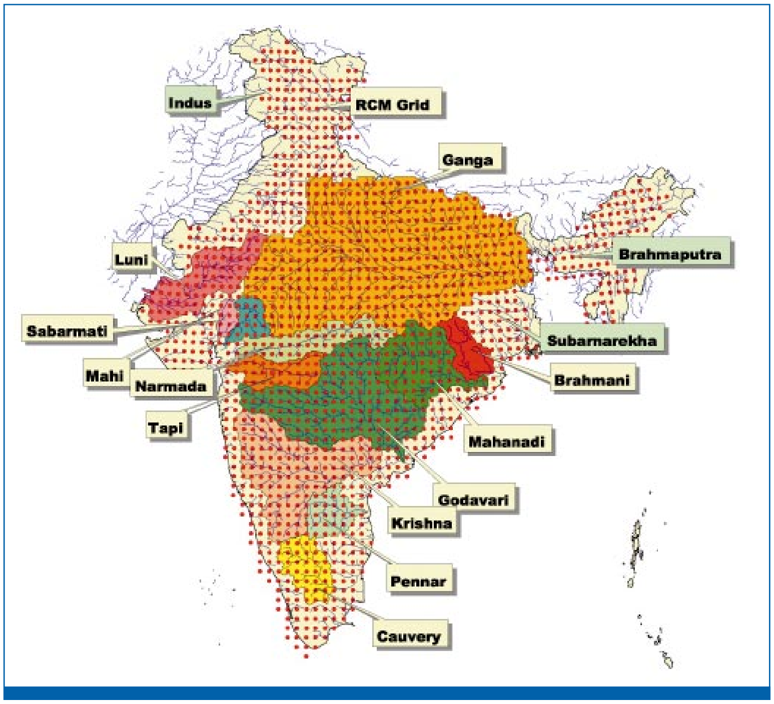


Figure 3.16: Modelled river basins along with RCM Grid Locations.

Simulated water balance at river-basin bevel: The SWAT model has been used on each of the river basins separately using daily weather generated by the HadRM2 control climate scenario (1981- 2000). The model has been used with the assumption that every river basin is a virgin area without any man-made change incorporated, which is reasonable for making a preliminary assessment. However, a general country-wide framework has been created that can be used conveniently for adding the additional information at various scales.

The model has been run using climate scenarios for the period 2041 to 2060, without changing the land-use pattern. The outputs of these two scenarios have been analyzed with respect to the possible impacts on the run-off, soil moisture and actual evapotranspiration.

The model generates detailed outputs at daily interval on flow at sub-basin outflow points, actual evapotranspiration and soil moisture status. Further sub-divisions of the total flow, such as surface and sub-surface run-off are also available. It is also possible to evaluate the recharge to the ground water on a daily basis.

Implications of Climate Change on Water Availability

Figure 3.17 shows the plot of these water balance components for the control and Climate Change Scenarios for the 12 river basins. Table 3.2 depicts the comparison of water balance components expressed as percentage of rainfall for control as well as Climate Change Scenarios. One can observe that the impacts are different in different catchments. The increase in rainfall due to climate change does not result in an increase in the surface run-off as may be generally predicted. For example, in the case of the Cauvery river basin, an

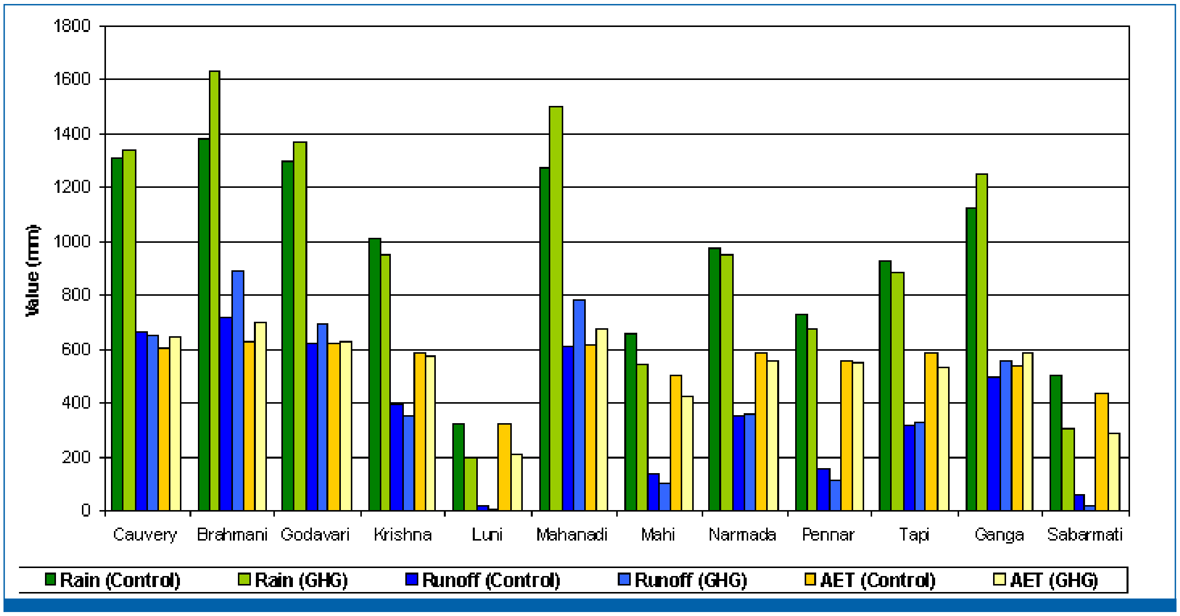


Figure 3.17: Trends in water balance for CTL and GHG climate scenarios.

Table 3.2: Comparison of change in Water Balance Components as a percentage of rainfall.

Basins	Scenario	Rainfall mm	Run-off mm	As a proportion of Rainfall (%)	Actual ET mm	As a proportion of Rainfall (%)
Cauvery	Control	1309.0	661.2	50.5	601.6	46.0
	GHG	1344.0	650.4	48.4	646.8	48.1
Brahmani	Control	1384.8	711.5	51.4	628.8	45.4
	GHG	1633.7	886.1	54.2	698.8	42.8
Godavari	Control	1292.8	622.8	48.2	624.1	48.3
	GHG	1368.6	691.5	50.5	628.3	45.9
Krishna	Control	1013.0	393.6	38.9	585.0	57.7
	GHG	954.4	346.9	36.4	575.6	60.3
Luni	Control	317.3	15.5	4.9	316.5	99.7
	GHG	195.3	6.6	3.4	207.3	106.1
Mahanadi	Control	1269.5	612.3	48.2	613.5	48.3
	GHG	1505.3	784.0	52.1	674.1	44.8
Mahi	Control	655.1	133.9	20.4	501.0	76.5
	GHG	539.3	100.0	18.5	422.7	78.4
Narmada	Control	973.5	353.4	36.3	586.8	60.3
	GHG	949.8	359.4	37.8	556.6	58.6
Pennar	Control	723.2	148.6	20.6	556.7	77.0
	GHG	676.2	110.2	16.3	551.7	81.6
Tapi	Control	928.6	311.2	33.5	587.9	63.3
	GHG	884.2	324.9	36.7	529.3	59.9
Ganga	Control	1126.9	495.4	44.0	535.0	47.5
	GHG	1249.6	554.6	44.4	587.2	47.0
Sabarmati	Control	499.4	57.0	11.4	433.1	86.7
	GHG	303.0	16.6	5.5	286.0	94.4

increase of 2.7 per cent has been projected in the rainfall, but the run-off is projected to reduce by about 2 per cent and the evapotranspiration to increase by about 2 per cent. This may be either due to increase in temperature and/or change in rainfall distribution in time. Similarly, a reduction in rainfall in the Narmada is likely to result in an increase in the run-off and a reduction in the evapotranspiration, that is again contrary to the usual myth. This increase in run-off may be due to intense rainfall as a consequence of climate change. Therefore, it is important to note here that these inferences have become possible since a daily computational time step has been used in the distributed hydrological modelling framework. This realistically simulates the complex spatial and temporal variability inherent in the natural systems.

It may be observed that even though an increase in precipitation is projected for the Mahanadi, Brahmani, Ganga, Godavari, and Cauvery basins for the Climate Change Scenario, the corresponding total run-off for all these basins has not necessarily increased (Figure 3.18). For example, the Cauvery and Ganga show a decrease in the total run-off. This may be due to an increase in evapotranspiration on account of increased temperatures or variation in the distribution of rainfall.

In the remaining basins, a decrease in precipitation is projected. The resultant total run-off for the majority of the cases, except for the Narmada and Tapi, is projected to decline. As expected, the magnitude of such variations is not uniform, since they are governed by many factors such as land use, soil characteristics and the status of soil moisture. The Sabarmati and Luni basins are likely to experience a decrease in precipitation and consequent decrease of total run-off to the tune of two-thirds of the prevailing run-off. This may lead to severe drought conditions under a future Climate Change Scenario.

The vulnerability of water resources has been assessed with respect to droughts and floods. Rainfall, run-off and actual evapotranspiration have been selected from the available model outputs, since they mainly govern these two extreme impacts due to climate change.

Droughts: Drought indices are widely used for the assessment of drought severity by indicating relative dryness or wetness affecting water sensitive regions. A soil moisture index has been developed to assess drought severity, using SWAT output that incorporates the spatial variability, to focus on agricultural drought where severity implies cumulative water deficiency.

The spatial and temporal distribution of drought conditions has been depicted in Figure 3.19. The

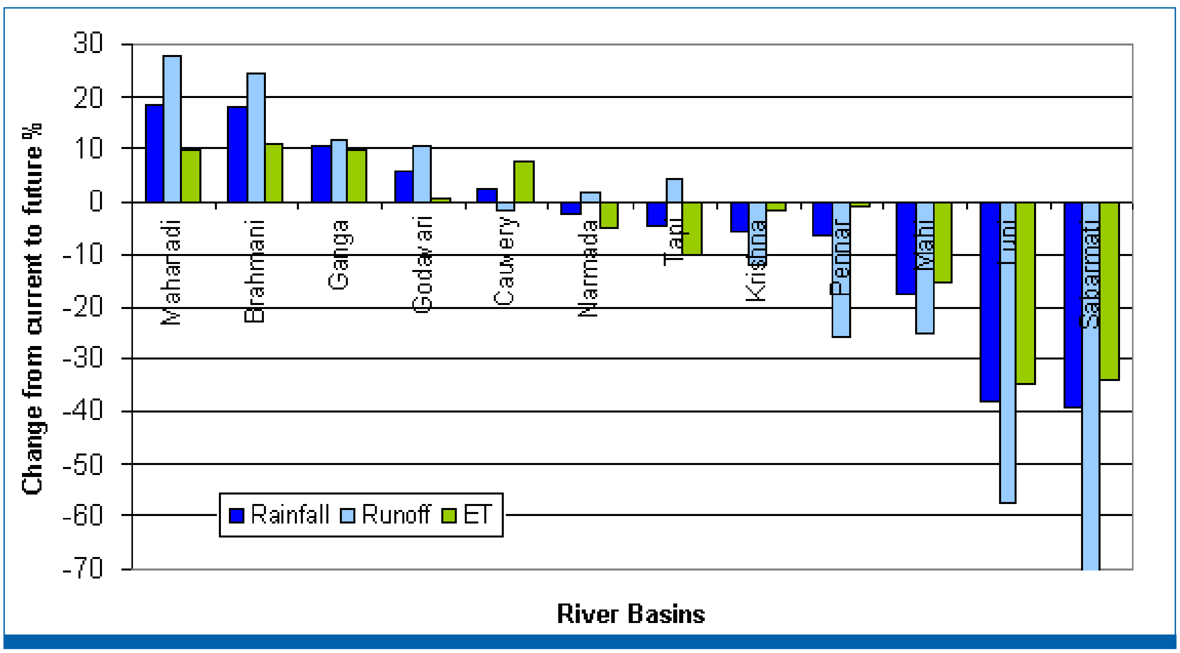


Figure 3.18: Change in water balance for CTL and GHG climate scenarios.

spatial variability of concurrent severity of drought is depicted by picking up the most severe years (in terms of number of drought weeks) in each sub-basin (depicted by graduated colour in the figure). The legend also shows the number of sub-basins where severe concurrent conditions prevailed in that year. This depiction is only with respect to the severest years for each sub-basin. It may be observed that there are three years, namely 1981, 1982 and 1983, that had on an average, one-fourth of the sub-basins covered under severe drought conditions simultaneously. The corresponding analysis on the Climate Change Scenario projects that there is only one year where the drought conditions are expected over one-third of India (61 out of 188 sub-basins). For the next two years, a relatively smaller part (less than 30 sub-basins) is likely to experience severe drought conditions simultaneously. In other words, the drought situation under the Climate change scenario may be marginally lower in terms of concurrent drought conditions.

Figure 3.19 also depicts the results of the drought analysis with respect to the intensity of drought weeks over the next 20 years in each sub-basin. The size of the green dot reveals the number of such drought weeks. A closer look at the figure suggests that there are varying trends with respect to this criterion. There are two pockets that have been identified (refer to circle 1 and circle 2 in Figure 3.19). In the one covering parts of the Sabarmati and Mahi (circle 1), the Climate Change Scenario may result in severe drought conditions in comparison to the control scenario. In areas covering parts of the Mahanadi and Brahmani (circle 2), the drought conditions are likely to be less severe under the Climate Change Scenario.

Floods: A Vulnerability assessment with respect to floods has been carried out using the daily outflow discharge from each sub-basin of the SWAT output. These discharges have been analyzed with respect to the peaks only in the absence of other relevant information, such as gauge discharge data and gauge locations. The maximum daily peak discharge has been identified for each year and for each sub-basin. A simple analysis has been performed to identify those basins where flooding conditions may deteriorate under the Climate Change Scenario.

Figure 3.20 shows the spatial distribution of annual maximum daily peak for the 19th year for the control scenario (as a sample year) along with the 20-year bar charts for control and Climate Change Scenarios, for each of the sub-basins of the Mahanadi. The figure also depicts two maximum annual peaks for the Climate Change Scenario for the furthest downstream

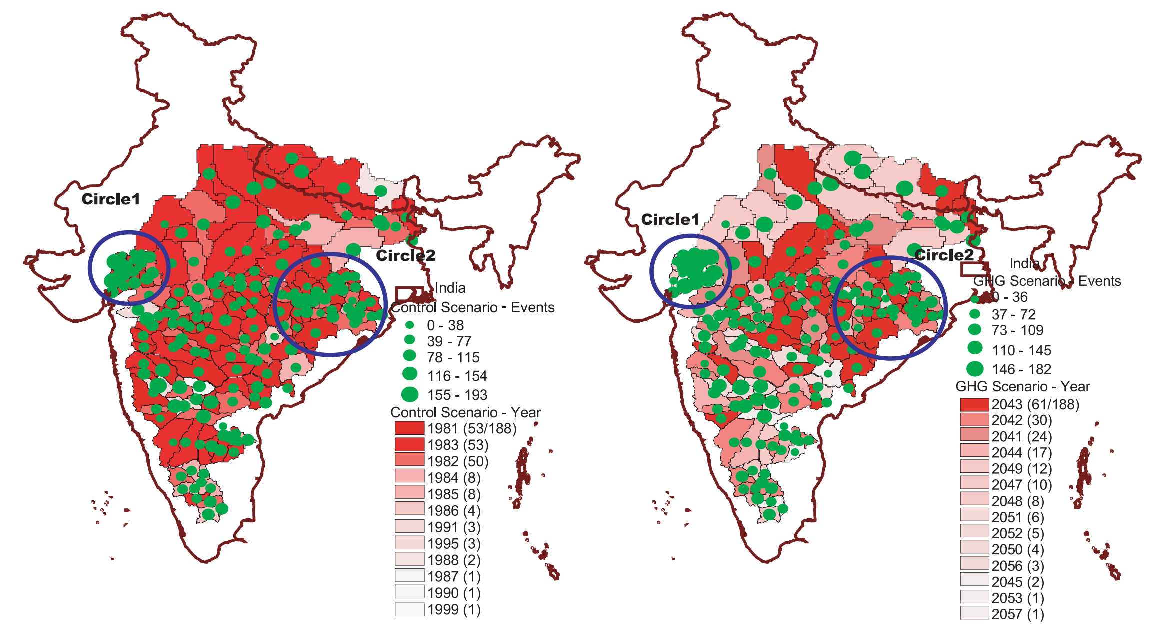


Figure 3.19: Spatial and temporal distribution of drought conditions.

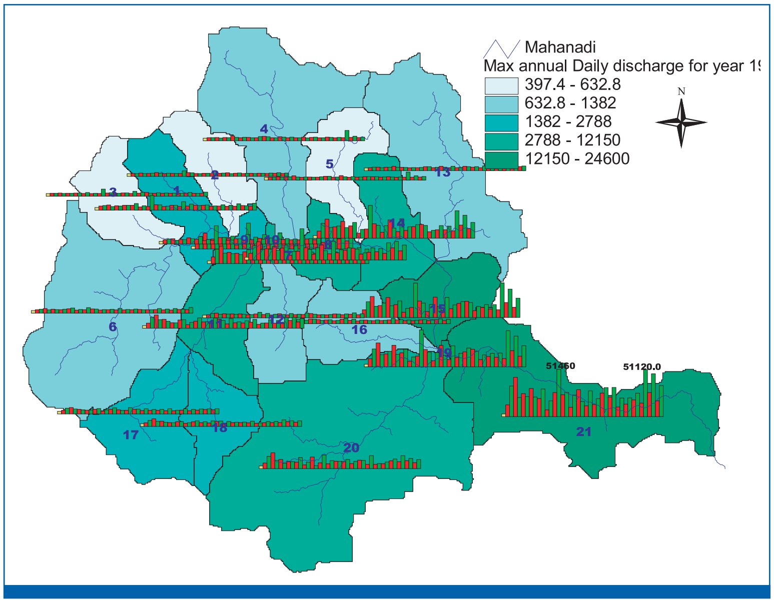


Figure 3.20: Annual maximum daily peak discharges for sub-basins of the Mahanadi.

sub-basin (21). It may be observed that these peaks are more than double the magnitude of the maximum peak of the control scenario.

Overall impact and vulnerability: The preliminary assessment has revealed that under the GHG scenario, the severity of droughts and intensity of floods in various parts of India is projected to increase. Further, there is a general reduction in the quantity of the available run-off under the GHG scenario (Figure 3.21). Luni, the west flowing river of Kutchh and Saurastra occupying about one-fourths of the area of Gujarat and 60 per cent of the area of Rajasthan are likely to experience acute physical water scarce conditions. The river basins of Mahi, Pennar, Sabarmati and Tapi are likely to experience constant water scarcities and shortage. The river basins of Cauvery, Ganga, Narmada and Krishna are likely to experience seasonal or regular water-stressed conditions. The river basins of the Godavari, Brahmani and Mahanadi are projected to experience water shortages only in a few locations.

Limitations of the Study: The water availability derived for the HadRM2 control scenario case in space and time does not incorporate any human interventions such as dams and diversions. The same framework has then been used to predict the impact of climate change (using the HadRM2 GHG scenario), with the assumption that the land use will not change over time. The 'hot spots' have been identified only with respect to the natural boundaries in the form of sub-basins of the river systems. Before the adaptation issues are addressed, it is imperative to develop a better understanding of these hot spots by qualifying these geographic areas with respect to their populations and ecosystems. Box 3.5 lists some

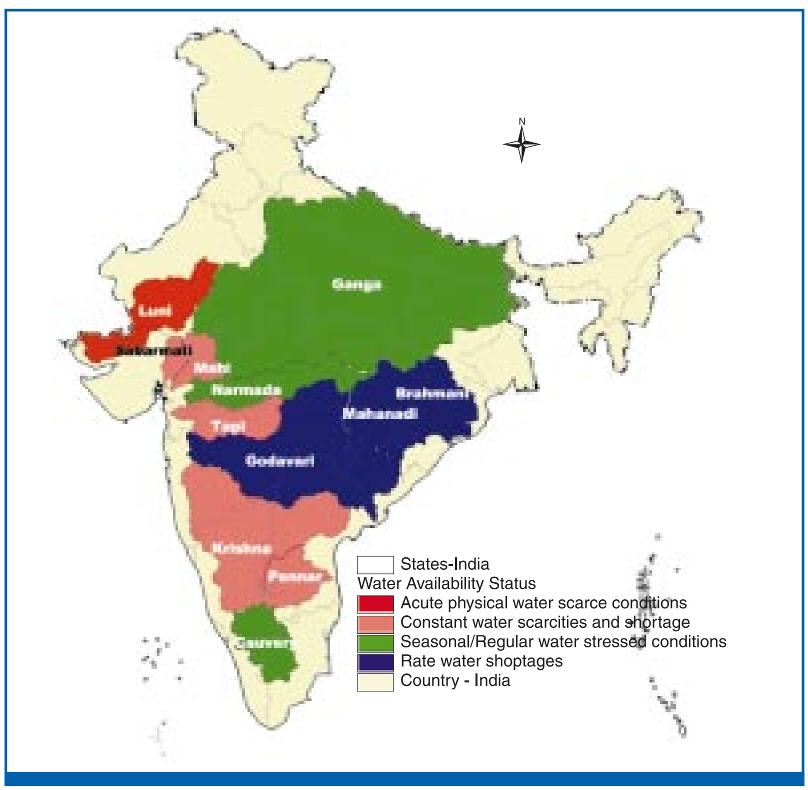


Figure 3.21: Broad variation in vulnerability of different regions to projected climate change.

of the likely effects of climate change on ground water resources and on the glaciers in India.

Practices for Vulnerability Reduction

Government Policies and Programmes

The Government of India, as well as several state governments have launched various programmes to conserve and develop water resources for agricultural and domestic sectors. These programmes, which aim at conservation and sustainable use of water resources, also reduce vulnerability to water stress. The centrally-sponsored scheme for soil conservation for the enhancement of productivity of degraded areas in the catchments of River Valley Projects and Flood Prone Rivers (RVP and FPR) is being implemented on a watershed basis in 45 selected catchments throughout the country. Other schemes include the Drought Prone Areas Programme (DPAP), Desert Development Programme (DDP), National Watershed Development Programme for Rainfed Areas (NWDPRA), Soil, Water and Tree Conservation (Operation Soil Watch), Operational research projects on Integrated Watershed Management, and the Jawahar Rojgar Yojana (JRY). All these programmes had definite objectives: improvement of productivity of catchment areas, optimum use of soil, land, water and their conservation, employment generation, etc.

Watershed Development Programme: This programme has been in operation for nearly 40 years. It has emphasized the importance of soil and water conservation and people's participation through Watershed Associations in planning and management. Overall national objectives of reducing the adverse impact of droughts, improving/stabilizing the production of important rainfed crops like pulses and oilseeds, and controlling siltation of reservoirs, have not been achieved to a satisfactory level. However, the impact of some of the watershed projects in reducing siltation, expansion of cropped area, increase in cropping intensity and grain/biomass yields has been very pronounced and visible on the ground. The

Box 3.5: Ground Water

It is estimated that ground water levels have already declined in about 0.34 million km^2. Although efforts are being made for improved water management practices, like water conservation, artificial recharge and watershed management, utilization of non-conventional energy and integrated water development, the projected water demand of a minimum 980 BCM during 2050 will require intensive development of ground water resources, exploiting both dynamic and in-storage potential. It is apparent that the projected climate change leading to global warming, sea-level rise and melting of glaciers will disturb the water balance in different parts of India and quality of ground water along the coastal track. Possible effects of climate change on ground water are:

- changes in precipitation and evapotranspiration may influence ground water recharge;
- rising sea levels may lead to increased saline intrusion of coastal and island aquifers;
- increased rainfall intensity may lead to higher run-off and less recharge; and
- increased flood events may affect groundwater quality in alluvial aquifers.

Climate Change Impact Assessment on Uttaranchal Himalayan Glaciers

- The glaciers and the snowfields in the Himalayas are on the decline.
- The rate of retreat of the snout of Gangotri glacier demonstrated a sharp rise in the first half of the 20th century. This trend continued up to around the 1970s, and subsequently there has been a gradual decline in its rate of retreat.
- The diminishing rate of retreat of the snout of the Gangotri glacier could be a consequence of the diminishing rate of rise in the temperatures.
- Although the warming processes continue unabated, the rate of rise in temperatures in the Gangotri glacier area has nevertheless demonstrated a marked gradual decline since the last quarter of the past century.

watershed development programme has emphasized soil and water conservation efforts/methods, but not on productivity-linked best agronomic practices.

Command Area Development Programme (CAD): This programme has a positive impact on irrigation water utilization, irrigation intensity, agricultural productivity, and soil and water environment. It has been felt that the main emphasis of CAD has so far been on physical works, such as construction of field channels and on-farm development work.

Crop Diversification: Crop diversification methods such as crop rotation, mixed cropping and double cropping, reduce the vulnerability of crop yields. Crop diversification has also been found to result in reduced erosion, improved soil fertility, improved crop yield, reduced risk of crop failure and enhanced water savings.

Expansion of Irrigation and Irrigation Water Management: Irrigation reduces the vulnerability of crop yields to the vagaries of rainfall. India has implemented a large programme to expand irrigation from diverse sources. However, about 60 per cent of the net sown area is still under rainfed cropping. Further, the water resources need to be managed efficiently so that wastage is minimized. Management issues should include linkages with the farmers, command area development, water conservation techniques, participatory irrigation management and institutional reforms. All reforms must be backed by research and diagnostic analysis for optimal results. The efficiency of existing systems needs to be enhanced such that the savings in water is utilized to increase irrigation intensity. Irrigation consumes nearly 83 per cent of water being used at present. It is estimated that even in the year 2050, it will continue to consume about 79 per cent of the total consumption. Even a nominal saving of 10 per cent in irrigation water can result in an increase in the availability of water for domestic and industrial uses by about 40 per cent in the long term. Such increase may also be used to offset the impacts of climate change in areas where reduction in water availability is projected.

Flood Control and Flood Management: Flooding is a major problem in the Himalayan rivers. About 40 Mha, which is close to one-eighth of the geographical area of the country, is vulnerable to floods. Flood protection works in the form of flood embankments and reservoirs have not proved very useful. It has been felt that it may not be possible to provide complete protection against floods. It is recommended that India should lay more emphasis thus on the efficient management of flood plains, flood proofing, including disaster preparedness and response planning, flood forecasting and warning, and many other non-structural measures.

The National Flood Commission *(Rashtriya Barh Ayog)* was set up in 1976 by the Government of India to review and evaluate the flood protection measures undertaken since 1954, and to evolve a comprehensive approach to the problem of floods. .

In 1996, Government of India set up a Task Force to review the impact of recommendations of the *Rashtriya Barh Ayog* and analyze the strategies evolved so far for mitigating flood problems and suggest both short-term and long-term measures.

Some of the traditional water conservation techniques.

Farmers Practices

Traditionally, farmers observe a number of practices to adapt to climate variability, for example, inter-cropping, mixed cropping, agro-forestry and animal husbandry (sheep rearing).

The vulnerability to increased water stress can be reduced through the participation of farmers in improved management of irrigation, adopting local rainwater harvesting systems, watershed development, low-cost drip irrigation, resource conserving technologies, such as zero tillage, bed planting, and adoption of multiple crops or crop diversification, etc.

Adaptation Strategies

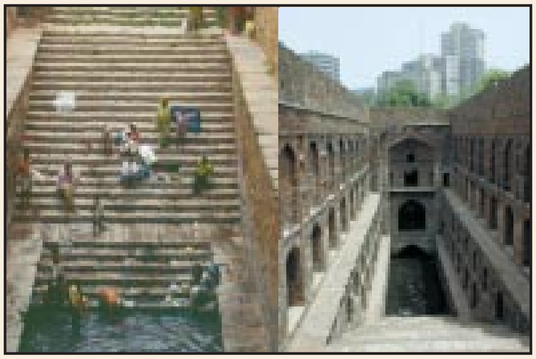
The projected impact of climate change is likely to exacerbate the water stress and shortages in some regions and also increased flooding in others. Thus, there is a need to develop and implement adaptation measures. These strategies may range from change in land use and cropping patterns to water conservation, flood warning systems, crop insurance, etc.

The strategy for coping with the climate change impacts on national water resources will be similar to the current strategies for coping with the ever-increasing demands and shortages. A prerequisite to adaptation is the application of an Integrated Water Resources Management strategy at different levels of usage from individual households to local communities, and watersheds to catchments. The current strategies to adapt to the two extreme events, namely floods and droughts, will hold good even to the projected impacts of climate change. The present structural or non-structural measures of flood protection will continue to be valid. Structural measures include the construction of dams for flood control by flattening flood peaks, and the construction of levies and dikes to safeguard the installations from flooding. Non-structural measures may include flood plain zoning, flood forecasting systems, flood insurance and flood preparedness.

Traditional as well as technological approaches are used to cope with the risk of drought. Technological management of drought uses medium (seasonal) to long-term (annual to decadal) forecasts that are formulated using appropriate models. This information is then translated into early warning, and subsequently appropriate drought protection measures are taken. Some of the possible supply side measures may include augmentation of the supply of water by sustainable extraction and use of surface water and groundwater in the local area, and long distance transfers of water from surface and groundwater water sources.

Box 3.6: Ground water harvesting for reviving traditional step wells

Many cities in India have traditional water harvesting and conservation structures, called *Baolis* or step wells. These can be revived and effectively used to recharge ground water. Water harvesting in neighbouring areas recharges these wells natuarally and can supply water to the neighbourhood during the lean period. The national capital Delhi is dotted with *Baolis* constructed by the Mughals in India. Water is a scarce commodity in Delhi specially during the summers. The Indian National Trust for Arts and Culture (INTACH) has taken an initiative to revive these step wells in Delhi.



Improving the water availability through the year, revival of diverse and community-based irrigation systems, soil and water conservation, equitable water distribution, traditional water conservation practices, and groundwater recharge, are examples of adaptation strategies (see Box 3.6). The Government of India is also envisaging the linking of rivers to mitigate droughts, as well as floods in the long term.

Common Framework for Adaptation Strategy: This implies that a common framework is essential to be created at the country level that should be used towards implementing the integrated watershed management strategy starting from the *Gram Panchayat* (village council) to the river-basin level in a unified manner. Integrated watershed management does not merely imply the amalgamation of different activities to be undertaken within a hydrological unit. It also requires the collation of relevant information, so as to evaluate the cause and effect of all the proposed actions. This framework will need regular maintenance and updating to fully reflect the most accurate ground truth data. Local planning and management strategies have to be evolved and validated through the proposed framework, so as to generate and evaluate various options suitable for local conditions.

One of the strategies may be to opt for artificial restoration of the hydrological system by the enhancement of water storage and infiltration of rainfall in urban areas and in river basins in order to maintain the original water balance. This will be useful for ecological and water resources restoration and implementation of nature-oriented river improvement works.

There is no single 'best' coping strategy. The best choice is a function of many factors pertaining to economic efficiency, risk reduction, robustness, resilience, reliability, etc. The emerging technologies for short-term weather forecast for real-time water management and operations have a large potential to enhance the coping capabilities to climate variability and change. Such advancements will greatly improve the irrigation water management efficiency. Biotechnology holds promise that may help in increasing crop yields while reducing the water requirement and developing crops that are less dependent on water. This has a large potential and relevance in water-stressed areas, as well as areas with low water quality.

In general, the financial, technological and institutional barriers usually hamper the implementation of adaptation measures to climate variability and change. Although, the current water policy of India aims at integrated water resources development and management to tackle water stress, its implementation is constrained by financial and technological limitations.

The projected impacts of climate change are likely to exacerbate the water stress and shortages in some regions and increase the frequency and intensity of floods and droughts. However, there are uncertainties in the climate change projections and impact assessment on water resources at the regional level. Thus, there is a need to improve the reliability of climate change projections at the regional level and its integration in the modelling to project impacts on water resources at the regional level, if not the local or watershed level.

CLIMATE CHANGE IMPACTS ON AGRICULTURE

Indian Agriculture scenario

Food grain production in India has increased spectacularly due to the Green Revolution from 50 Mt in 1951 to 212 Mt in 2002, and the mean cereal productivity has increased from 500 kg ha^{-1} to almost 1800 kg ha^{-1}. These increases were largely the result of area expansion, large-scale cultivation of new high-yielding semi-dwarf varieties since the early 1960s, and the increased application of irrigation, fertilizers and biocides, supported by progressive government policies (Figure 3.22). Today, we have 190 Mha gross sown area (142 Mha net sown area), and 40 per cent of this is irrigated. There have been similar revolutions in the production of milk, fish, eggs, sugar, and a few

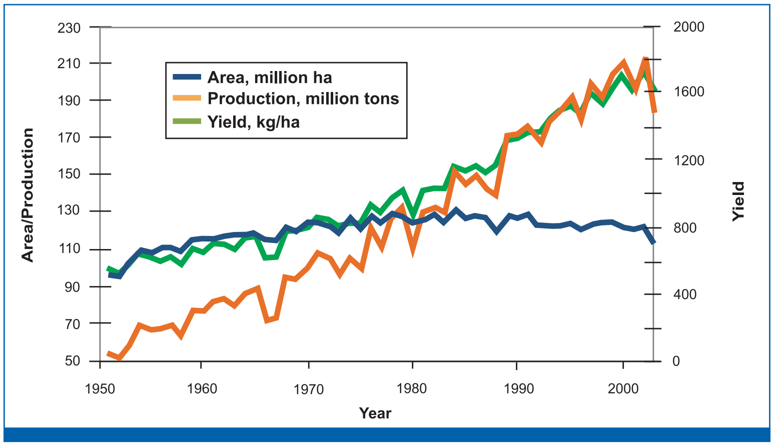


Figure 3.22: Change with time in area, production and yield of food grains.

Marginal farmers dependent on rain are at risk due to climate change.

other crops. India is now the largest producer of milk, fruits, cashew nuts, coconuts and tea in the world, the second largest producer of wheat, vegetables, sugar and fish, and the third largest producer of rice. As a consequence, the per capita availability of food grains has risen in the country from 350 gm in 1951, to about 500 gm per day at present, from less than 125 gm of milk to 210 gm per day, and from 5 to 30 eggs per annum despite the increase in population from 350 million to more than one billion. This growth in agricultural production has also led to considerable surplus food stocks with the government. The droughts of 1987, 1999-2000, and of 2002-2003 could generally be managed and did not lead to severe problems of food security because of these buffer stocks.

Table 3.3. Food demand assuming a 5 per cent GDP growth at constant prices.

Items	Production (Mt)	Demand (Mt)	
	1999-2000	2010	2020
Rice	85.4	103.6	122.1
Wheat	71.0	85.8	102.8
Coarse grains	29.9	34.9	40.9
Total cereals	184.7	224.3	265.8
Pulses	16.1	21.4	27.8
Fruits	41.1	56.3	77.0
Vegetables	84.5	112.7	149.7
Milk	75.3	103.7	142.7
Meat and eggs	3.7	5.4	7.8

Despite this progress, food production in India, on an aggregated scale, is still considerably dependent on the rainfall quantity and its distribution. The summer monsoon (June through September) contributes 78 per cent of India's annual rainfall and is a major water resource. It is important to recognize that the Green Revolution was largely confined to the irrigated areas. In the past 50 years, there have been around 15 major droughts, due to which the productivity of rainfed crops in those years was affected. Limited options of other income and widespread poverty continue to threaten the livelihood security of millions of small and marginal farmers in this region.

The food security of India may be at risk once again in the future, due to the continued population growth. By 2050, India's population is projected to grow to 1.6 billion. This rapid and continuing increase in the population implies a greater demand for food. The demand for rice and wheat, the predominant staple foods, is expected to increase to 122 and 103 Mt, respectively, by 2020, assuming medium income growth (Table 3.3). The demand for pulses, fruits, vegetables, milk, meat, eggs and marine products is also expected to increase very sharply. This additional food will have to be produced from the same or possibly shrinking land resource base, because there is no additional land available for cultivation. It is estimated that the average yields of rice, wheat, coarse grains, and pulses need to increase by 56, 62, 36 and 116 per cent, respectively, by 2020.

Although there is pressure to increase production in order to meet higher demands, there has lately been a significant slow-down of the growth rate in cultivated area, production and yield. The annual rate of growth in food production and yield peaked during the early years of the Green Revolution, but since the 1980s, it has declined.

The perceived gradual increase in environmental degradation, the early signs of which are becoming visible in areas that benefitted largely from the Green Revolution technologies, is further compounding the problem. There is now great concern about declining soil fertility, change in water table depth, rising salinity, resistance of harmful organisms to many pesticides, and degradation of irrigation water quality as, for example, in north-western India. Nutrient removal by crops over time has exceeded its application and consequently, farmers now have to apply more fertilizers to realize the same yield as achieved 20-30 years ago. The introduction of canal irrigation in Haryana has resulted in almost 0.5 Mha being affected by soil salinity. The rapid increase in the number of tube-wells during the last three decades has resulted in over-exploitation of groundwater in many blocks, leading to declining water tables. In some canal irrigated districts, on the other hand, the water table has risen, resulting in increased problems of salinity. Several pathogens and insect pests have also shown a tendency to increase under the intensive farming systems such as rice-wheat system.

In the 21st century, one of the great challenges for Indian agriculture will be, therefore, to ensure that food production is coupled with both poverty reduction and environmental preservation. The road-map of sustainable agricultural development may also have to consider two additional important global drivers of change in agriculture in the coming decades -globalization and climate change. The on-going globalization process and economic reforms associated with the World Trade Organization (WTO) is forcing India to make structural adjustments in the agricultural sector to increase its competitiveness and efficiency.

VULNERABILITY OF AGRICULTURE

Methods and models

All available methods have been utilized by the Indian scientific community for assessing the possible impact of climatic variability and climatic change on agriculture. Historical data analyses by various statistical tools and the analogue approach have traditionally been used to assess the impact of climatic variability. Since environmental control, particularly of CO_2, is very difficult and expensive, there have been only a few studies globally in estimating its direct impact on crop plants. Controlled environment facilities, such as open top chambers, Phytotron, and greenhouses, are

FACE set-up at the Indian Agricultural Research Institute to study the impact of increased CO_2 on crops.

now increasingly being used to understand the impact of temperature, humidity and CO_2 on crop growth and productivity. Greater efforts are now also being made to establish Free Air CO_2 Enrichment (FACE) facilities, where CO_2 is artificially increased in field conditions to quantify its possible impacts. One such facility has recently been set up at the Indian Agricultural Research Institute, New Delhi, to study the effect of increased CO_2 on crop photosynthesis and yield (see photograph above).

The interactive effects of CO_2, rainfall and temperature can be best studied through the use of crop growth simulation models. These models simulate the effect of daily changes on weather (including those caused by climatic change), for any location on growth and yield of a crop through the understanding of crop physiological and soil processes. Several crop models have also been used in India for impact assessment of climatic variability and climate change. Models of various crops included in the Decision Support System for Agro-technology Transfer (DSSAT) shell have been the most popular. For rice, the ORYZA series of models have been effectively used. Indian models, such as the Wheat Grown Simulator (WTGROWS) for wheat, have been the basis of a large number of studies. Greater use of such crop models for impact assessment of climate change is, however, limited, due to the lack of a user-friendly framework that requires limited inputs and considers yield reduction due to pests and diseases in the tropics. InfoCrop is one such indigenous decision support system, based on crop models that have been developed recently at the Indian Agricultural Research Institute to meet the stakeholders' need for information on vulnerability of agriculture to climate change and for optimizing crop management. The InfoCrop modelling framework requires limited inputs and also includes databases of typical Indian soils, weather and genotypes. The current version of the model deals with chickpea, cotton, groundnut, maize, mustard, pearl millet, pigeonpea, potato, rice, sorghum, soybean, sugarcane, and wheat.

Impact assessment

The net availability of food at any given time depends on a number of local, regional, national and international factors. Climate change associated variables such as CO_2 and temperature can influence food availability through their direct effect on growth processes and yield of crops. In addition, it may also impact crop production through indirect effects caused by, for example, change in rainfall induced irrigation availability, soil organic matter transformations, soil erosion, changes in pest profiles, and decline in arable areas due to the submergence of coastal lands. Equally important determinants of food supply are socio-economic environment including government policies, capital availability, prices and returns, infrastructure, land reforms, and intra- and international trade that might be affected by climatic change.

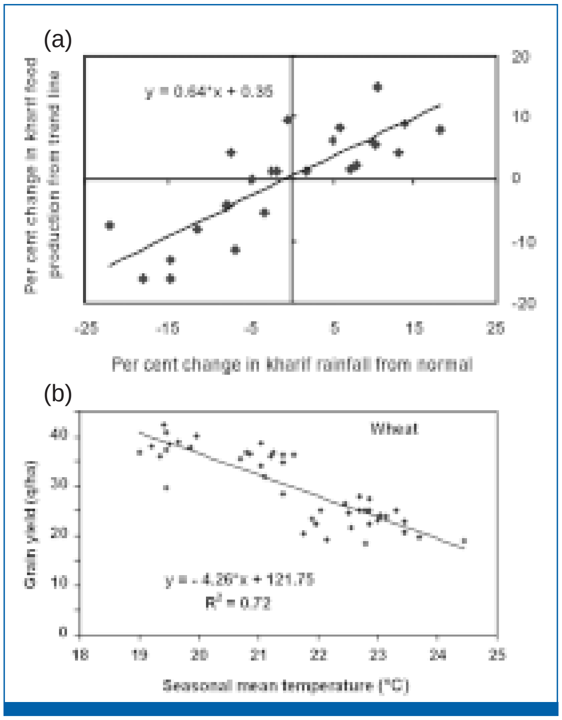


Figure 3.23. a) Relation of monsoon season food production with seasonal rainfall; and b) of regional wheat yields with seasonal temperature.

Direct effects on crop growth and yield

Several studies are available that relate crop yields/ production directly with one or more variables of weather. Many of these results are confounded by the differences in technological growth over space and time. Nevertheless, many of these studies have shown that the annual food production in the monsoon season (*kharif*) of the country has a positive relationship with the seasonal rainfall, even after considering the deviations from the technology trend line (Figure 3.23a). In the post-monsoon season, the rainfall is scanty, and crops such as wheat, that dominate food production are largely irrigated. Hence, such crops do not show any relation with the seasonal rainfall. However, the regional wheat yields do show a considerable relation with temperature, as shown in Figure 3.23b.

Such empirical relations of crop yield with weather are not universal, relate only to one element of weather, are data specific, and do not provide any insight into mechanisms of the associations. Dynamic simulation models are able to overcome these limitations. In recent years, such crop models have been used in India to assess the impact of climate change on crop production in different regions. In these studies, the sensitivity of crops to simultaneous, as well as independent changes of different magnitude in temperature and carbon dioxide, has been studied. The advantage of such an analysis is that the direct effects of all possible scenarios of climate change including those of the IPCC, even up to the year 2070, can be considered.

Most of the simulation studies have shown a decrease in the duration and yield of crops as temperature increased in different parts of India (Aggarwal et al., 2001). These reductions were, however, generally offset by the increase in CO_2; the magnitude of this response varied with crop, region and climate change scenario. The results of such studies for rice and wheat are illustrated in Figure 3.24. Yields of both crops decreased as temperature increased; a $2^{\circ}C$ increase resulted in 15-17 per cent decrease in the grain yield of both crops, but beyond that the decrease was very high in wheat. These decreases were compensated by

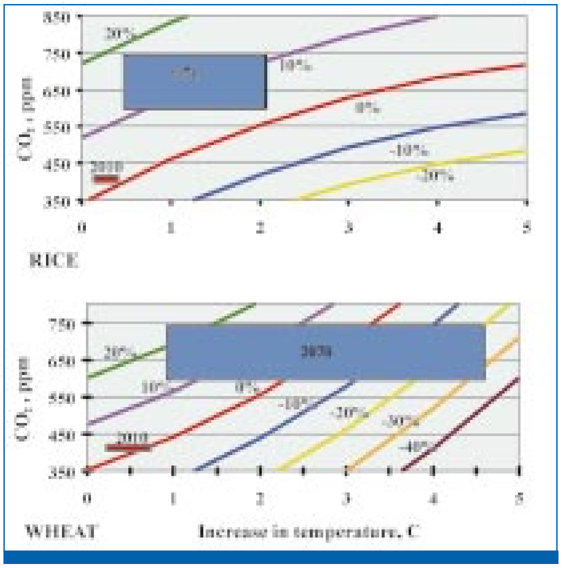


Figure 3.24. Simulated response of irrigated rice and wheat in northern India to changes in temperature and CO_2. The lines refer to the equal change in grain yield (percentage change, labelled values) at different values of CO_2 and increase in temperature. The large, shaded box refers to the total uncertainty in impact assessment due to uncertainties in the IPCC scenario of 2070. The small, hatched box refers to the total uncertainty due to uncertainties in the scenario of 2010.

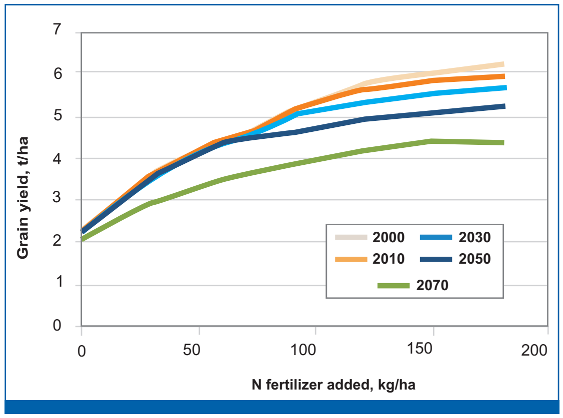


Figure 3.25. Simulated response of irrigated wheat in north India to improved management (N fertilizer) in global warming scenarios of future years.

an increase in CO_2, due to the latter's fertilizing effect on crop growth. Atmospheric CO_2 concentration has to rise to 450 ppm to nullify the negative effect of a 1°C increase in temperature, and to 550 ppm to nullify the 2°C increase in temperature.

The sensitivity analysis of yield to temperature and CO_2 as presented in Figure 3.24 can assist in assessing the direct impact of different climate change scenarios, and their uncertainties on different crops. Based on various IPCC scenarios, two specific scenarios of climate change-optimistic and pessimistic-for different years, from 2010, were used for further evaluation. The highest increase in temperature and lowest increase in CO_2 are detrimental to crop growth and, hence, this is labelled as a pessimistic scenario. On the other hand, large increase in CO_2 and a small change in temperature promote growth and, hence, is labelled as an optimistic scenario. The uncertainty in global warming and its impact during the period 2010 to 2070 are assumed to be in between these two scenarios. Superimposing these scenarios on the isolines in Figure 3.25 can guide us on the magnitude of the potential impact of change on crop productivity. Both rice and wheat showed a small positive effect with an increase in yield between 1 per cent and 5 per cent (area within the box). The effect remained positive (5-20 per cent) in the case of rice, even by 2070, due to the effect of a large increase in CO_2 compared to a relatively small reduction in *kharif*[2] temperature. By comparison, the effect on wheat could be positive (up to 25 per cent) or negative (up to 30 per cent), depending upon the magnitude of change in CO_2 and temperature. Since, there is greater probability of increase in temperature in *rabi*[3], it is likely that the productivity of wheat and other *rabi* crops would be significantly reduced. Therefore, if CO_2 stabilizes early and the temperature continues to rise for a longer time, Indian agriculture could suffer significantly in the long term.

This impact assessment analyses was extended for various cereal crops in different regions for the climate change scenarios of 2010. The results showed that irrigated rice yields register a small gain irrespective of the scenario at all places in India (Table 3.4). Wheat yields in central India are likely to suffer by up to 2 per cent in the pessimistic scenario but there is also a

[2] *Kharif* crops are sown in May-June and harvested in September-October. The important *Kharif* crops are cotton, rice, sugarcane, maize, jowar and bajra.

[3] *Rabi* crops are sown in October-November and harvested in February-March. The important *Rabi* crops are wheat, grams, barley, rapeseed and mustard.

Table 3.4: Simulated impact of climate change scenario of 2010 on yields (percentage change) of major cereals.

Crop and region	Impact of climate change on yield, %	
	Pessimistic scenario	Optimistic scenario
Rice		
East	2.3	5.4
South	1. 3	3.8
North	3.0	7.0
Wheat		
North	1.5	6.5
East	-0.3	7.7
Central	-2.0	6.5
Sorghum		
North	0.0	0.5
South	1.0	3.4
East	1.8	2.5
West	-0.8	0.5

Note: Pessimistic scenario reflects low increase in CO_2 and a high increase in temperature, whereas the optimistic scenario consists of a significant increase in CO_2 and a negligible increase in temperature.

possibility that these might improve by 6 per cent if the global change is optimistic. Sorghum, being a C4 plant, does not show any significant response to increase in CO_2 and hence the different scenarios do not affect its yield. However, if the temperature increases are higher, western India may experience some negative effect on productivity due to reduced crop durations. This effect can be mitigated easily by using varieties that are of relatively longer duration.

Concerns have been expressed lately that the rice-wheat system in north-western India is already showing signs of stagnation/decline in its productivity. A crop simulation study with weather as the only varying factor with the year also showed a similar trend, indicating that crop-weather interactions also have a role to play in explaining the trends. A closer examination of the weather data, the main drivers in the simulations, indeed indicated that a significant part of the yield decline/stagnation trend in rice and wheat could be ascribed to rising temperatures during the crop season. These changes are not statistically significant but do indicate a warming trend and their possible affects on crop production.

A large number of resource-poor farmers in India are not able to apply desired levels of fertilizers, irrigation and pest control. Simulation studies done at different levels at N management indicate that the crop response could vary depending upon the N management and the climate change scenario (Figure 3.25). At zero kg N/ha, the yields in different scenarios of climate change were similar. This was the case even at 75 kg N/ha, except in the scenario of 2070, when the temperatures had increased to 4.5^{o}C. The impact of warming scenarios becomes apparent at higher levels of fertilizer application from 2030 onwards. This indicates that in the agro-ecosystems where inputs used remains low, as in today's rainfed systems, the direct impact of climatic change would be small. It is also expected that the response of crops to the added fertilizer would be lower, as climate becomes warmer. In future, therefore, much higher levels of fertilizer may need to be applied to meet the increasing demand for food.

Impact assessment of climate change has also been studied for regional wheat production using crop models, Geographic Information Systems (GIS), remote sensing and regional databases. The actual dates of planting, varieties, and the fertilizer use obtained from the government survey reports, standard soil data, the irrigated regions demarcation, and weather data are input in Info-Crop to estimate crop yields. Together with remotely sensed area estimates, these are then translated into production figures in different states. This methodology has been validated with wheat production data at the state as well as national level, for three consecutive years. The results indicated, similar to the individual field level results, that we should not expect any significant effect on wheat production due to climate change up to 2010 (Figure 3.26). It was only when we consider scenarios of climate change beyond 2020, without any new technological interventions and adaptation mechanisms, a reduction in wheat production is noticed.

The increased climatic variability may affect our rainfed crops, such as pulses, significantly. A recent study analyzed the response of soybean at a few places in Madhya Pradesh, using a crop simulation model.

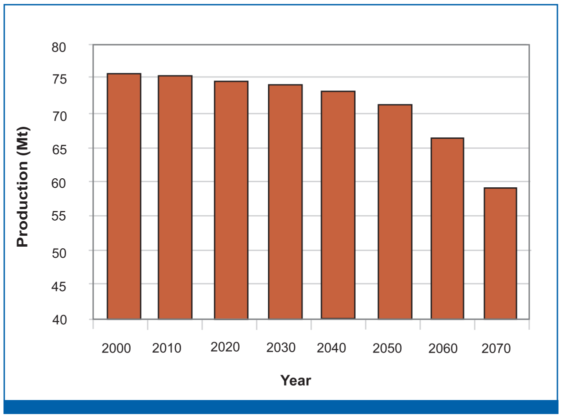


Figure 3.26. Possible impact of climate change on wheat production in India.

It showed that an increase of 3°C in temperature nullified the positive effect of doubled CO_2 on yield. The study has also shown that the magnitude of the beneficial effect of elevated CO_2 was significantly reduced under water stress conditions. Similarly, in rainfed groundnut, the simulation results have indicated that yields would increase under doubled CO_2, and temperature increase up to 3°C if the rainfall did not decline. Reduction of rainfall by 10 per cent reduced the yield by 12.4 per cent. The adaptation options should aim at increased water productivity under rainfed conditions.

There is a great probability of significant effects of increased climatic variability on short season crops such as vegetables, if changes occur during critical periods in growth. Such crops will have limited time to adapt to adverse environments. The production of fruits may be significantly affected if the changes in climate happen to coincide with the critical periods.

In the hills, the low temperature and shorter growing period limit the productivity of crops. These restrictions become conspicuous with increase in altitude. Global warming is likely to prolong the growing season and this could result in potentially higher crop yields, provided water remains available. However, the positive perspectives for total biomass production may not always ensure higher economic yields, since many temperate crops also need a minimum chilling period to stimulate better flowering. Global warming will push the snow line higher and dense vegetation will shift upwards. This shift will be selective and species specific due to the differential response of plants to changing environmental conditions. Species which are adapted to wider environmental gradients would spread faster and dominate the ecosystem, while those with narrow environmental adaptation would become marginalized. This may affect biodiversity. Corrective steps must be taken to avoid the elimination of plant species due to weather change.

The quality of food is significantly affected by temperature in most crops. An increase in temperature may have significant effect on the quality of cotton, fruits, vegetables, tea, coffee, aromatic and medicinal plants. The nutritional quality of cereals and pulses may also be moderately affected which, in turn, will have consequences for our nutritional security. Research has indeed shown that the decline in grain protein content in cereals could partly be related to increasing CO_2 concentrations.

The global environmental changes may aggravate the current problems of sustainability and profitability of agriculture in many regions of the country. These changes may alter the interactions between biophysical and socio-economic factors and the ways in which these are mediated by the institutions. Some preliminary studies have linked the biophysical response of crops, costs-benefits and the expected response of farmers to understand the socio-economic impact of global change. These indicate that the loss in farm-level net revenue may range between 9 per cent and 25 per cent for a temperature rise of 2-3.5°C.

Indirect effects on crops

Agricultural production may be much more affected by several other factors than the direct effects considered in the above analysis. Changes in pest scenario, soil moisture storage, irrigation water availability, mineralization of nutrients, and socio-economic changes can have larger effects on agricultural production. Some of these are considered below.

Crop-pest interactions

It is estimated that insect pests, pathogens and weeds result in almost 30 per cent loss in crop production at present. Avoidance of such loss constitutes one of the main sources of sustainability in crop production. The change in climate may bring about changes in population dynamics, growth and distribution of insects and pests. Besides having a significant direct influence on the pest population build up, the weather also affects the pest population indirectly through its effects on other factors like food availability, shelter and natural enemies.

Aphid is a major pest of wheat and its occurrence is highly influenced by weather conditions. Cloudy weather with sufficient relative humidity favours the occurrence of aphids in the field. Under most favourable conditions, a population density of a 1000 million per hectare wheat field has been reported. The weather changes may lead to aphid occurrence at a very juvenile and more susceptible stage of crop, leading to tremendous loss. In nature, aphids are checked by *Coccinella septumpunctata* and in case the weather limits their growth, the production losses could get further magnified. With small changes, the virulence of different pests changes. For example, at 16°C, the length of the latent period is small for yellow rust. Once the temperature goes beyond 18°C, this latent period increases but that of yellow and stem rusts decreases. The appearance of black rust in northern India in the 1960s and 1970s was related to the temperature-dependent movement of spores from southern to northern India (Figure 3.27). Thus, any small change in temperature can result in changed virulence as well as the appearance of new pests in a region.

Several pathogens such as the *Phytophtora* and *Puccinia* group produce an abundance of propagules from the infected lesion or spot. They also invariably possess very short incubation cycles or life-cycle periods. Such pathogens and pests are highly sensitive to even minor changes in temperature, humidity and sunlight. Any change in the weather conditions that further reduce the incubation period will result in the completion of more cycles, greater terminal severity and in more severe yield losses. Changes even to the extent of 1°C in maximum or minimum temperature will make a great deal of difference between moderate and severe terminal disease development. The swarms of locust produced in the Middle East usually fly eastward into Pakistan and India during the summer and they lay eggs during the monsoon. Changes in rainfall, temperature and wind speed pattern may influence the migratory behaviour of the locust.

Most crops have C3 photosynthesis (responsive to CO_2), while many weeds are C4 plants (non-responsive to CO_2). The climate change characterized by higher CO_2 concentration will

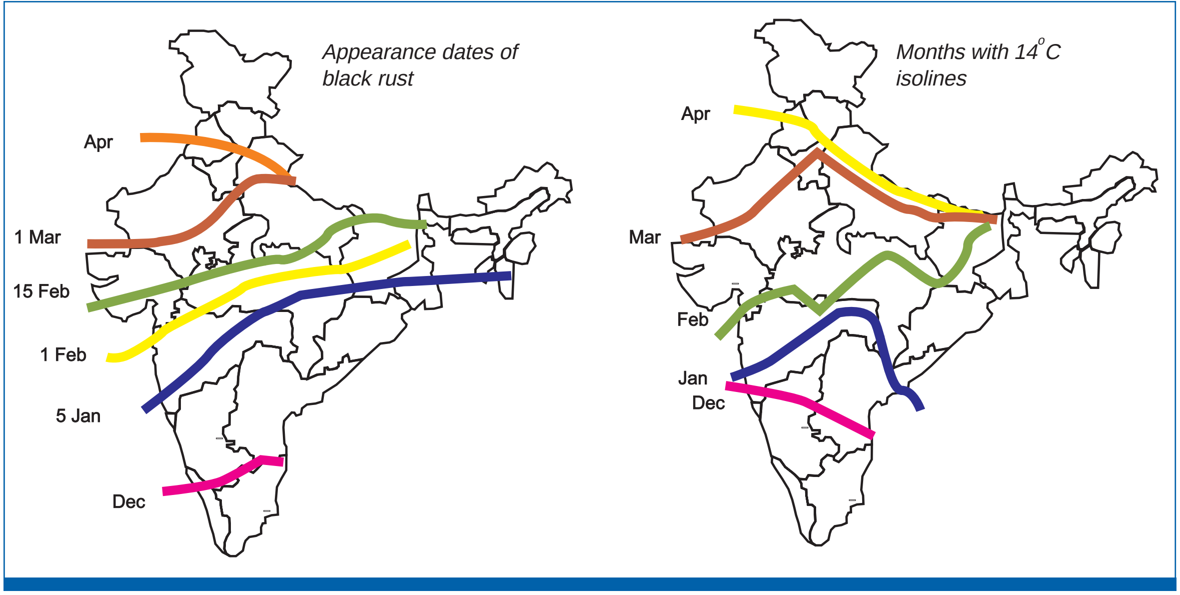


Figure 3.27. Appearance dates of black rust in 1972-73 and its relation to changes in temperatures in different regions of India. Rusts move from south to north of India, as the temperatures become suitable for them in northern regions

favour crop growth over weeds, although temperature increase may further accelerate crop-weed competition depending upon the threshold temperatures in different locations.

Water availability

The creation of irrigation potential has been a major key to India's agricultural development, production stability and food security. Apart from the monsoon rains, India has depended on the Himalayan rivers for centuries for its water resource development. Temperature increase associated with global warming will increase the rate of snow melting and consequently snow cover will decrease. In the short term, this may increase water flow in many rivers that, in turn, may lead to increased frequency of floods, especially in those systems where water carrying capacity has decreased due to sedimentation. In the long run, however, a receding snow line would result in reduced water flow in rivers. These issues have been discussed in detail elsewhere in this Communication.

Under the climate change scenario, the onset of the summer monsoon over India is projected to be delayed and often uncertain. This will have a direct effect not only on the rainfed crops, but water storage will also be affected, placing stress on the irrigation water. Since the availability of water for agriculture would have to face tremendous competition for other uses of water, agriculture would come under greater strain in future.

Soil processes

Practically all soil processes important for agriculture are directly affected in one way or the other by climate. Changes in precipitation patterns and amount, and temperature can influence soil water content, run-off and erosion, workability, temperature, salinization, biodiversity, and organic carbon and nitrogen content. Changes in soil water induced by global climate change may affect all soil processes and ultimately, crop growth. An increase in temperature would also lead to increased evapotranspiration, which may result in the lowering of the groundwater table at some places. Increased temperature coupled with reduced rainfall may lead to upward water movement, leading to accumulation of salts in upper soil layers. Similarly, a rise in sea level associated with increased temperature may lead to salt-water ingression in the coastal lands, making them unsuitable for conventional agriculture.

Organic matter content, which is already quite low in most parts of India, will continue to remain low but climatic change through temperature and precipitation mediated processes may affect its quality. An increase of 1°C in the soil temperature may lead to higher mineralization but N availability for crop growth may still decrease due to increased gaseous losses. Biological nitrogen fixation under elevated CO_2 may show an increase, provided other nutrients are not strongly limiting.

The change in rainfall amount and frequency, and wind may alter the severity, frequent and extent of soil erosion. These changes may further compound the direct effects of temperature and CO_2, on crop growth and yield.

Relative importance of the impact of climate change versus current climatic variability

While the impact assessment of future climatic change is quite important, most crops in India, even in irrigated environments, are quite sensitive to climatic variability. The latter has considerable effect on the country's food security, despite impressive development of irrigation potential. In field and regional situations, it is not always easy to quantify the impact of climatic variation on food production due to the confounding effects of changing technology used. India had a record harvest of 75.5 Mt of wheat in 1999-2000, an increase of 5 Mt over 1998-1999, with almost the same technology level. This change was largely due to very cool weather during January to March 2000, which was favourable to grain formation and filling. Similarly, the relatively very warm temperatures during March 2004 are expected to result in a production loss of almost 4.0 Mt of wheat. Such variations in food production would be much larger in rice, pulses and oilseeds, where a large portion of the crop area is rainfed. The gluts and shortages of rice, onions and potatoes in recent times, besides being caused by policy and management, are also a manifestation of the effects of climatic variability. If we can evolve strategies for managing climatic variability in agricultural production, adaptation required for climate change would presumably be automatically taken care of.

Adaptation strategies

Any disturbance in agriculture can considerably affect the food systems and thus increase the vulnerability of the large fraction of the resource-poor population. We need to understand the possible coping strategies by different sections and different categories of producers to global climatic change. Such adaptation strategies would need to simultaneously consider the background of changing demand due to globalization, population increase and income growth, as well as the socio-economic and environmental consequences of possible adaptation options. Developing adaptation strategies exclusively for minimizing the negative impact of climatic changes may be risky in view of large uncertainties associated with its spatial and temporal magnitude. We need to identify 'no-regrets' adaptation strategies that may be needed for sustainable development of agriculture. These adaptations can be at the level of the individual farmer, society, farm, village, watershed, or at the national level. Some of the possible adaptation options are discussed below.

Altered agronomy of crops

Small changes in climatic parameters can often be managed reasonably well by altering the dates of planting, spacing and input management. Alternate crops or cultivars more adapted to the changed environment can further ease the pressure. For example, in the case of wheat, early planting or the use of longer duration cultivars may offset most of the losses associated with increased temperatures. Available germplasm of various crops needs to be evaluated for heat and drought tolerance.

Watershed management

Watershed management programmes yield multiple benefits, such as sustainable production, resource conservation, ground water recharge, drought moderation, employment generation and social equity, as is evident from several studies already conducted in different agro-ecological regions of the country. For example, a consistent increase in the production of food grains, fruits as well as in milk, and decline in run-off, soil loss and dependency on forest for fodder and fuel-wood was noticed even after the withdrawal of the active intervention phase in the Fakot watershed project initiated in 1974 (Table 3.5).

Development of resource conserving technologies

Recent research has shown that surface seeding or zero-tillage establishment of upland crops after rice give similar yields as when planted under normal conventional tillage over a diverse set of soil conditions. This reduces the costs of production,

Table 3.5 : Production and protection impact of watershed management programme during pre-project, active Interventions and after withdrawal of interventions (Fakot, Uttaranchal hills, area – 327 ha).

Product	Pre-Project Period (1974-1975)	Average of	
		Intervention Phase (1975-1986)	Post Intervention Phase (1987-1995)
Food Crops (q)	882	4015	5843
Fruit (q)	Neg.	62	1962
Milk ('000 lit.)	56.6	184.8	237.6
Floriculture ('000 Rs.)	Nil	Nil	120.0*
Cash crops ('000 Rs.)	6.5	24.8	202.5
Animal rearing method	Heavily grazing	Partially grazing	Stall feeding
Dependency on forest fodder (%)	60	46	18
Run-off (%)	42	18.3	13.7
Soil loss (t/ha/annum)	11	4.5	2.0

*Community diversified into Floriculture in 1994.

allows earlier planting and, thus, results in higher yields, less weed growth, reduced use of natural resources such as fuel and steel for tractor parts, and improvements in efficiency of water and fertilizers. In addition, such resource conserving technologies restrict the release of soil carbon, thus mitigating the increase of CO_2 in the atmosphere. It is estimated that zero tillage saves at least 30 litres of diesel as compared to the conventional tillage. This leads to 80 kg/ha/year reduction in CO_2 production. If these savings could be translated even partially to large arable areas, substantial carbon dioxide emissions to the atmosphere could be reduced.

Augmenting production and its sustainability

The climatic factors allow very high yield potential of many crops in India. For example, the potential yields of rice and wheat are calculated to be more than six tons/ha whereas their average yields range between two and three tons/ha. Such yield gaps are very large in eastern India and, hence, this region can be a future source of food security for the whole country, under the scenario of adverse climatic impacts. Institutional support in the form of improved extension services, markets and infrastructure need to be provided in such regions to increase stability and bridge yield gaps.

Increasing income from agricultural enterprises

Rising unit costs of production and stagnating yield levels are adversely affecting the incomes of farmers. Global environmental changes, including climatic variability, may further increase the costs of production of crops due to its associated increases in nutrient losses, evapotranspiration and crop-weed interactions. Suitable actions such as accelerated evolution of location-specific fertilizer practices, improvement in extension services, fertilizer supply and distribution, and development of physical and institutional infrastructure, can improve efficiency of fertilizer use.

Improved land use and natural resource management policies and institutions

Adaptation to environmental change could be in the form of social cover such as crop insurance, subsidies, and pricing policies related to water and energy. Necessary provisions need to be included in the development plans to address these issues of attaining the twin objectives of containing environmental changes and improving resource use productivity. Rational pricing of surface and groundwater, for example, can arrest its excessive and injudicious use. The availability of assured prices and infrastructure could create a situation of better utilization of groundwater in eastern India. Policies such as financial compensation/incentive for green manuring should be evolved that would encourage farmers to enrich organic matter in the soil and, thus, improve soil health.

Improved risk management though early warning system and crop insurance

The increasing probability of floods and droughts and other uncertainties in climate may seriously increase the vulnerability of eastern India and of resource-poor farmers to global climate change. Policies that encourage crop insurance can provide protection to farmers in the event their farm production is reduced due to natural calamities. In view of these climatic changes and the uncertainties in future agricultural technologies and trade scenarios, it will be very useful to have an early warning system of environmental changes and their spatial and temporal magnitude. Such a system could help in determining the potential food insecure areas and communities, given the type of risk. Modern tools of information technology could greatly facilitate this.

Recycling waste water and solid wastes in agriculture

Since fresh water supplies are limited and have competing uses, agriculture has to start a vigorous evaluation of using industrial and sewage waste water. Such effluents, once properly treated, can also be a source of nutrients for crops. Since water serves multiple uses and users, effective inter-departmental coordination within the government is needed to develop the location-specific framework of sustainable water management and optimum recycling of water.

Reducing dependence on agriculture

The share of agriculture has declined to 24 per cent of the GDP, but 64 per cent of the population continues to remain dependent on agriculture for its livelihood. Such trends have resulted in fragmentation and decline in the size of land holdings, leading to inefficiency in agriculture and rise in unemployment, underemployment, low volume of marketable surplus and therefore, increased vulnerability to global change. Institutional arrangements, such as cooperatives and contract farming, that can bring small and marginal farmers together for increasing production and marketing efficiencies are needed.

Current programmes, policies, and projects

Some of the initiatives taken by the Government of India including the National Watershed Development Project for Rainfed Areas, improved access to credit for farmers (through *Kisan* Credit Card), creation of a Watershed Development Fund, and implementation of the National Agriculture Insurance Scheme can be considered of importance in adapting to global climatic change. Several schemes, currently being implemented in the Tenth plan (see Box 3.7), are also likely to reduce the vulnerability of agricultural production and conserve soil and water resources (see box for these schemes).

Box 3.7: Thrust Areas for the Tenth Plan in the Agriculture Sector

- Utilization of wastelands and un-utilized/ under-utilized lands.
- Reclamation/ development of problem soils/ lands.
- Rainwater harvesting and conservation for the development of rainfed areas.
- Development of irrigation, especially minor irrigation.
- Conservation and utilization of biological resources.
- Diversification to high value crops/activities.
- Increasing cropping intensity.
- Timely and adequate availability of inputs.
- Strengthening of marketing, processing/value addition infrastructure.
- Revamping and modernizing the extension systems and encouraging the private sector to initiate extension services.
- Bridging the gap between potential and farmer's yields.
- Cost-effectiveness while increasing productivity.
- Promotion of farming systems approach.
- Promotion of organic farming and utilization of organic waste.
- Development of eastern and north-eastern regions, hill and coastal areas.
- Reforms to introduce proactive policies for the farm sector

CONCLUSIONS

Changing demands, markets and agricultural technologies are expected to significantly transform Indian agriculture in the near future. The pace of these changes is expected to increase rapidly in the coming years and the whole agricultural scenario may become quite different in the next 10 to 20 years. To address multifarious challenges of sustainable development in the context of future climatic change, agricultural planning has to ensure sufficient food production, employment generation and rural income, while conserving natural resources. Global climatic changes and increasing climatic variability could have some adverse implications in achieving these goals. Therefore, its impact, adaptation measures and vulnerability need to be quantified for different regions. This assessment should include not only crops, but also the livestock and fish sector, important constituents of food supply. We need to develop better scenarios of regional climate change and validated agro-ecosystems models for impact assessment. 'No-regrets' adaptation strategies that would ensure livelihood security for millions of resource-poor small and marginal farmers need cataloguing and implementation. Such an assessment of agriculture and, therefore, policy and technological responses to manage climate change impacts needs an integrated study of biophysical, environmental and socio-economic sectors of agro-ecosystems. This requires unique partnerships, cutting across the barriers of disciplinary/ministerial specialization.

Effective handling of environmental change issues in agriculture also needs a close interaction between scientists, donors, policy makers, administrators, trade and industry, farmers' organizations and other stakeholders. Different types of capacity-building programmes need to be developed at various levels to ensure efficient management of natural resources for sustainable agricultural development.

CLIMATE CHANGE IMPACTS ON THE FOREST SECTOR IN INDIA

Importance of Forest Ecosystems in India

India is one of the 12 mega-diversity nations with a rich variety of flora and fauna. It is home to seven per cent of the world's biodiversity and supports 16 major vegetation types, varying from alpine pastures in the Himalayas to temperate, sub-tropical and tropical forests, and mangroves in the coastal areas. The area under forests is estimated to be about 67 Mha according to the State of Forest Reports. In India, about 200 million people depend on forests directly or indirectly for their livelihoods. Forests play an important role in environmental and economic sustainability. They provide numerous goods and services, and maintain life-support systems. In India, deforestation or forest conversion has declined significantly since 1980. However, forest degradation due to fuel wood and timber extraction, livestock grazing and fire, continues. The projected climate change is likely to further exacerbate the socio-economic stresses, leading to adverse impacts on forest ecosystems and forest product flows. Thus, it is very important to assess the impact of projected climate change on forest ecosystems, and develop and implement appropriate adaptation measures.

Some of the major life-support systems of economic and environmental importance of forests are as follows:

Biodiversity: The forests support a wide variety of flora and fauna. More than 5,150 species of plants, 16,214 species of insects, 44 mammals, 42 birds, 164 reptiles, 121 amphibians and 435 fish, are endemic to the country. However, in recent times, heavy biotic pressures have begun to exert tremendous stress on natural resources and, hence, many of the plant and animal species are under various degrees of threat. In order to conserve these, a Protected Area Network, comprising 80 National Parks and 441 Wildlife Sanctuaries have been created on about 14.8 Mha of forests, covering about 4.5 per cent of the geographic area of the country.

Biomass supply: Forests meet nearly 40 per cent of the country's energy needs and 30 per cent of the fodder needs. It is estimated that approximately 270 Mt of fuelwood, 280 Mt of fodder, and over 12 million m^3 of timber and several Non-Timber Forest Products (NTFPs) are removed from forests, annually.

Livelihoods to forest dependent communities: In India there are about 15,000 plant species out of which nearly 3,000 species (20 per cent) yield NTFPs. NTFP activities hold prospects for integrated development that yield higher rural incomes and conserve biodiversity, while not competing with agriculture. Millions of forest dwellers and agricultural communities depend on forests for a range of non-timber forest products, such as fruits, nuts, edible flowers, medicinal herbs, rattan and bamboo, honey and gum. Further, all forest sector activities are labour intensive and lead to rural employment generation.

Gross Domestic Product: The value of goods and services provided by the forest sector is estimated to be Rs. 25,984 crores. Of the GDP of Rs. 23,000 crores, approximately 54 per cent is from fuelwood, 9 per cent is from industrial wood, 16 per cent from NTFPs, and eco-tourism and carbon sequestration account for 14 per cent and 7 per cent, respectively.

Area under Forests and Forest Types in India

Area under forests

The State of Forest Report, 2001, estimates the forest cover in India as 67 Mha, constituting 20.5 per cent of the geographical area. This is composed of 41.7 Mha (12.7 per cent) of dense forest, 25.9 Mha (7.9 per cent) of open forest and 0.4 Mha (0.14 per cent) of mangroves. The forests in India are termed 'dense' if the canopy density is 40 per cent and above, or 'open' if lands have tree cover of canopy density between 10 per cent and 40 per cent. Mangroves are salt-tolerant forest ecosystems, found in inter-tidal regions in estuaries and coasts. There is also 4.73 Mha of scrub in addition to the reported forest cover of 67 Mha.

Forest types in India

According to the Forest Survey of India, the recorded forest area of India has been classified as Reserve Forests, Protected Forests and Unclassed Forests. The area under forests, according to the latest assessment for 2001 is 67 Mha, with reserve forest accounting for about 42 Mha.

Champion and Seth (1935) have broadly classified the forests of India into the following broad categories: (a) tropical forests; (b) montane sub-tropical forests; (c) montane temperate forests; (d) sub-alpine forests; and (e) alpine forests. These have been further classified into 16 sub-types (Figure 3.28). The dominant forest types are the tropical dry deciduous forest (38%) and tropical moist deciduous forest (32%). The other important forest types are tropical evergreen, tropical thorn, sub-tropical pine and alpine forest.

The Forest Survey of India has classified forests into 22 strata, based on the dominant tree species. The dominant forest stratum is the 'miscellaneous' category, accounting for 66 per cent of total forest area, where no dominant species could be identified. Sal, Teak, mixed conifers, upland hardwoods and Bamboo are the other dominant forest strata. The approximate extent of forests on a functional basis is: Protection Forests—10 Mha; Production Forests—15 Mha; Social Forests—25 Mha and Protected Area Network—14.8 Mha. Social Forests here do not include the small blocks of woodlands (less than 25 ha), trees in strips and farms.

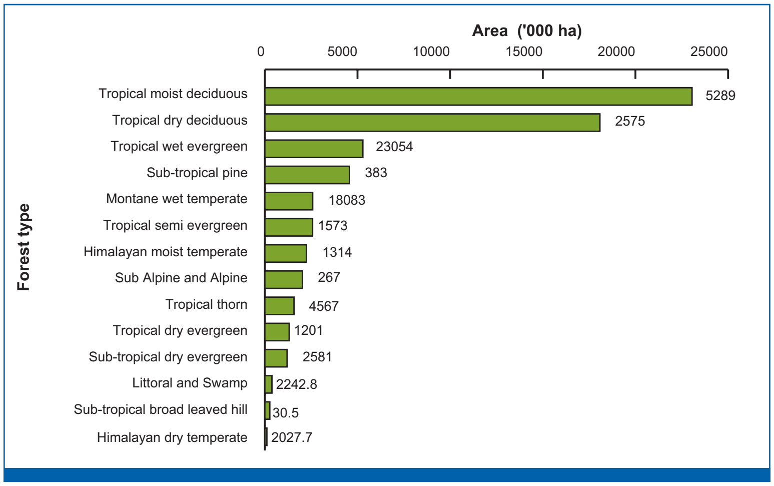


Figure 3.28: Different forest types in India (according to Champion and Seth, 1935).

Methods and Models for Climate Impact Assessment

The models developed to explore the impact of climate change on vegetation fall into two broad categories. Empirical-Statistical models attempt to elucidate the relationship between the existing climate and the existing vegetation. Once such a correspondence is obtained with a reasonable degree of reliability, it is possible to use it to project the distribution of these vegetation types for any future climate scenario. A comparison of such a projected distribution with the existing one can then serve as a basis for assessing the impact of climate change as expected under that scenario. Recently, more sophisticated methods of pattern recognition (for example, the use of neural networks and genetic algorithms), originating in the field of artificial intelligence are also being applied to the problem of impact of climate change. Simulation models explicitly evaluate the temporal changes in the various components of the system (root/shoot biomass, soil moisture levels, concentrations of different pools of nutrients, etc.) from a single step to the next. Equilibrium models predict the final composition, biomass, etc., expected at a location, based on the input parameters (precipitation, temperature, radiation, soil carbon, etc.). Dynamic models, on the other hand, enable one to track the changes expected during the course of the time interval used in the simulation. These models vary greatly in their spatial scales and fundamental processes included in the model, degree of complexity, etc.

Model selected for climate impact assessment; BIOME-3

An impact assessment was carried out using the BIOME-3 model by predicting the equilibrium composition of different vegetation types under the CTL and GHG scenarios.

BIOME-3 model determines equilibrium state vegetation combinations for each location. It combines the screening of biomes through the application of climatic constraints with the computation of net primary productivity (NPP) and leaf area index (LAI), both based on fully coupled photosynthesis and water balance calculations. The underlying hypothesis of the model is that the combination of vegetation types, which is calculated to achieve the maximum NPP, represents the equilibrium vegetation. Using the data on climatic parameters and soil characteristics, the model predicts the potential biome type likely to dominate at a given geographical location.

The climate at the location is specified in terms of mean monthly values of rainfall, temperature and cloud cover (expressed as a percentage). The soil characteristics include the water holding capacity (WHC), depth of the top soil and sub-soil, and the percolation rates. Based on these, the programme calculates the WHC of two layers of soil, 0-500 mm and 500-1500 mm, to be used for the water balance simulation.

The data requirements of BIOME-3 fall into three categories: location, climate and soil. The location information is included in all the climate data files as well, and consists of latitude, longitude and altitude, though the programme does not seem to make use of the input values of longitude and altitude. Only three climatic parameters are required, and mean monthly values of precipitation (mm), temperature (degrees C) and cloud cover (percentage) are supplied in three separate files. The soil parameters needed by the programme are: (a) the Available Water Capacity (AWC) of the top soil; (b) AWC of the sub soil; (c) depth of the topsoil; (d) depth of the subsoil; and (e) percolation rate (though a default value of 30 is used by the programme if data on percolation rate is not available).

The model uses nine Plant Functional Types (PFTs), such as Tropical Evergreen, Tropical Rain green, Temperate Broadleaved Evergreen, Temperate Summer green, Temperate Evergreen Conifer, Boreal Evergreen, Boreal Deciduous, Temperate Grass and Tropical/warm-temperate Grass. Based on the climatic parameters, the model computes the viability and wherever applicable, the productivity-related parameters of the PFTs, such as the LAI and the NPP.

Not all of these biomes are seen in India. Figure 3.29 depicts the distribution of vegetation in India, based on the Champion-Seth classification, which has a reasonably close correspondence with the biome types. The right panel of Figure 3.29 shows the distribution of biome types expected to prevail in India under the climate corresponding to the 'control' run of the HadRM2 model.

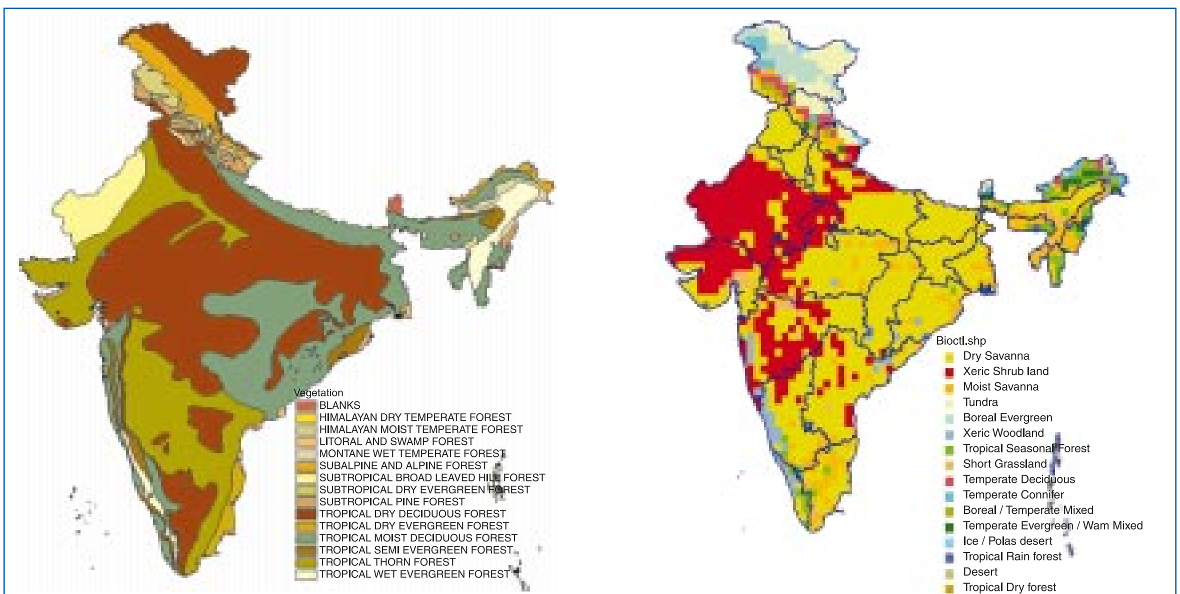


Figure 3.29. Current vegetation map and map for control run of HadRM2.

Choice of climate model and sources of data

Some of the data used in this investigation was obtained from the IPCC Data Distribution Centre. For obtaining monthly mean data, the main entry point of IPCC DDC is *http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html.* The two major alternative scenarios suggested by IPCC for which such data is available are the IPCC IS92a emission scenario and the IPCC SRES scenario. Data and information was downloaded from *http://ipcc-ddc.cru.uea.ac.uk/cru_data/datadownload/download_index.html* and used for analysis.

A number of datasets from modelling centres from different parts of the world are available from this site [UK Hadley Centre for Climate Prediction and Research (HadCM2), the German Climate Research Centre (ECHAM4), the Canadian Centre for Climate Modeling and Analysis (CGCM1), the US Geophysical Fluid Dynamics Laboratory (GFDL-R15), the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO-Mk2), the National Centre for Atmospheric Research (NCAR-DOE) and the Japanese Centre for Climate System Research (CCSR)].

The models differ from each other considerably in grid size or resolution. Many of them consider rather coarse grids, with one or both of longitude/latitude greater than four degrees. The two models with the best resolution are HadCM2 (3.75 by 2.5 degrees) and ECHAM4 (2.8125 X 2.8125 degrees), and seemed the most appropriate for the present investigation. The kinds of variables generated and made available by these models also differ from each other. Of these two models, the climate variable 'percentage of cloud cover' (required to obtain the value of 'percentage of sunshine hours' needed to run the BIOME-3 programme), was available only for the HadCM2. Second, the data at even finer (regional) scale (0.4425 X 0.4425 degrees) was available for HadRM2, derived from HadCM2. Projections from HadCM2 model have been used for analysis.

The RCM is obtained by downscaling from the boundary conditions of the GCM, and uses a much finer spatial (0.4425 degrees in longitude as well as latitude, corresponding approximately to a 50 km X 50 km grid), as well as temporal (daily) resolution. However, data for this model available only for a smaller duration, corresponding to the years 2041 to 2060, both for control as well as GHG Scenario 1. No data is available as yet for Scenario 2. The RCM dataset also contains fewer parameters (for example, only maximum and minimum temperature and not the average temperature separately).

In addition to the above, actual climate data (monthly values from 1901 to about 1995) for the Indian region, compiled by the Climate Research Unit of the University of East Anglia, also at a fine (0.5 degrees X 0.5 degrees, comparable to the RCM) spatial resolution, was also made use of in the present analysis.

Vulnerability of Forest Ecosystems in India to Projected Climate Change

The approach used in the present investigation for exploring the vulnerability of forest ecosystems to projected climate change is based on the application of BIOME-3 model to about 1500 grids (50 km X 50 km) across the Indian region. The climate-related parameters for these grids are from the HadRM2. The soil parameters for a grid were obtained from the nearest of the 78 locations for which soil data was available. (in fact, the sensitivity of the results to the soil parameters was also investigated by assigning several different soil parameters to the grids; the predictions were found to be quite robust). The outputs of the BIOME-3 (biome type, net primary productivity, etc. using climate from the control run of RCM indicated the current situation, while that from the GHG run described the vegetation that was likely to prevail around 2050 under the GHG Scenario. The differences in the outputs of BIOME-3 at each of the grids were used for assessing the direction and extent of the expected change in the vegetation.

The analysis is primarily based on the HadCM2 model, and on the scenario corresponding to one per cent compounded annual increase in CO_2 concentration. This led to about 3.4 °C increase in the average annual temperature over the Indian region by 2050. However, when effects of aerosols/sulfates were included in the same scenario, HadCM2 showed a smaller increase, of 1.89 °C, for the same region for the same year. The other, milder scenario, with 0.5% annual increase of CO_2 showed an increase of 2.3 °C without sulfates and 2.0 °C with sulfates. Thus, all the three remaining scenarios are likely to lead to less severe changes in vegetation and in the shifts of forest boundaries than obtained in the present analysis. It is even more difficult to draw any inference based on the changes in the precipitation, since there does not seem to be any direct correlation between the changes in temperature and those in the precipitation for the Indian region—all the four cases show a small overall decrease in the rainfall.

It is possible that this is an artifact of the coarse grid of GCM, since the HadRM2 with a finer grid does show a slight increase in the rainfall expected over the Indian region by 2050. Further, HadCM2 is one of the several GCMs. There is a variation in the projections of climate parameters (such as temperature and precipitation) among GCMs, though all GCMs project warming and changes in precipitation patterns across all regions.

The expected distribution of biome types in India is shown in Figure 3.30 for the climate projected to prevail over India during 2041-2061 under the GHG scenario. The large-scale changes in the vegetation types are immediately evident from the figure (right panel of Figure 3.30 when compared to the vegetation types prevailing today (left panel of Figure 3.30). These changes are along the lines expected, on the basis of increase in CO_2, as well as the changes in rainfall and temperature described in the previous sections.

Shifts in major forest types considering all grids and potential vegetation

While Figure 3.31 brings out the spatial distribution of projected changes in forest biome types, the quantitative estimates can be obtained on the basis of the number of RCM grids (out of a total of about 1500) that change from one biome type into another. A very large proportion (about 70 per cent) of the grids (and concomitantly, existing forests) are likely to experience a change. It is worth emphasizing here that large changes are possible for some of the biomes, even though the total aggregate area under these does not show any change during this period. This is because the locations of the biome show conspicuous shifts due to the marked changes in the climatic conditions.

The biome type most seriously impacted is the Dry Savanna. About 62 per cent of it, mainly lying in the northern/central parts of India, is likely to be converted into Xeric Woodland (Dry Thorn Forest), while another 24 per cent, mainly in the north-western parts, is likely to change to Xeric Shrubland. In general, increased CO_2 is expected to lead to an

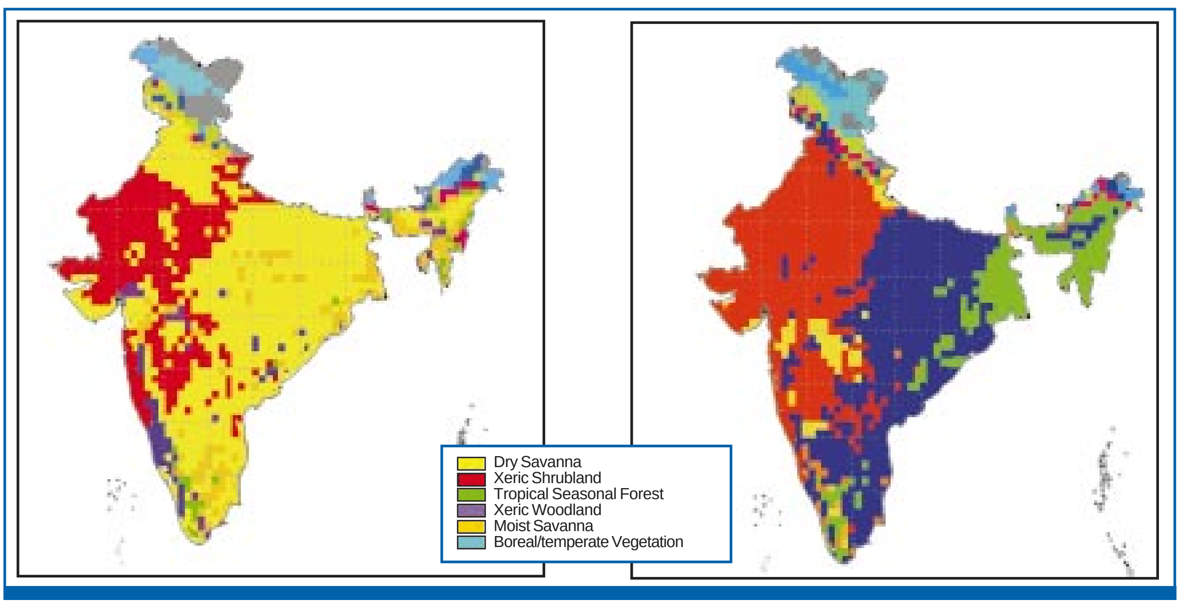


Figure 3.30. Vegetation map for year 2050, GHG run of HadRM2 considering all grids of India and potential vegetation (including grids without forests). The control run is shown in the left panel.

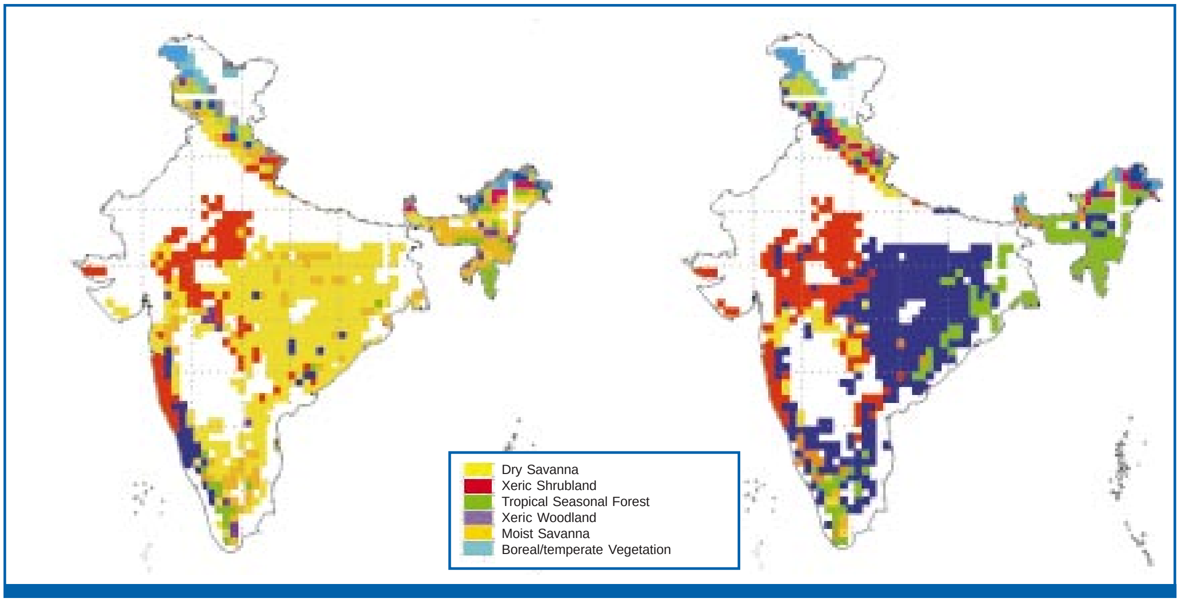


Figure 3.31: Vegetation map of India for 2050 including only the grids that have forests at present.

increase in the NPP (as will be discussed later). This has an effect of converting grassland into woodlands and woodlands into forests. Thus, in regions with a relatively large temperature increase, dry and moist savannas are likely to be replaced by xeric vegetation, while in the areas with a lower temperature increase and enhanced rainfall, the moist savannas seem to be transformed into Seasonal Tropical Forests. However, the northern part of the country has largely been transformed into agricultural land and thus the savannas occupy only a small geographical area.

The other biome type to be affected is the moist savanna located in the north-east and some parts of southern India. This is likely to be converted into Tropical Seasonal Forest (about 56 per cent), mostly in the north-east and Xeric woodland (Dry Thorn Forest) (about 32 per cent) mostly in southern India, depending on the change in the quantum of rainfall. The Tropical Seasonal Forest, especially in the north-east, is likely to change into Tropical Rain Forest due to a large increase in rainfall expected to take place in that region.

The changes expected in the colder regions are also along similar lines, with the Tundras likely to change to boreal evergreens, and boreal evergreens into temperate conifers.

Shifts in major forest types considering grids with forests: As mentioned earlier, the above results were based on the analysis of the potential forest cover. To make a more realistic assessment of the likely impact of projected climate change on forests, the analysis was repeated by confining it to actual locations of forests. This was made using the map provided by the Forest Survey of India. This map divides the Indian region into grids of 2.5 x 2.5 minutes and provides information on the type and density of forest in the grid. This is at a much finer scale than the RCM grid (about 26 X 26 minutes), and each of the RCM grids contains about 160 grids of the Forest Survey of India map. A detailed examination of this map showed the presence of forests in about 800 of the 1500 RCM grids.

The distribution of forest types obtained in these 800 grids under the control run is shown in the left panel of Figure 3.31, while that obtained for the GHG run (for the year 2050) is shown in the right panel of Figure 3.31. Interestingly, the results obtained from the analysis based on these 800 grids were very similar to the ones reported for the 1500 grids. Thus, changes in forest types were seen in about 600 out of the 800 forested grids (75 per cent), as compared to a figure of 70 per cent obtained for the analysis based on 1500 grids. The biome type likely to be most seriously impacted continues to be the Dry Savanna, and about

70 per cent of it is likely to be converted to Xeric Woodlands, and about 15 per cent to Xeric Shrubland. These estimates are similar to the 62 per cent and 24 per cent obtained earlier for the corresponding changes. The other forest type likely to be affected is Moist Savanna, with 56 per cent of grids likely to be converted into Tropical Seasonal Forest and 28 per cent into Xeric Woodlands, again very similar to the estimated changes of 56 per cent and 32 per cent obtained earlier.

In summary, more realistic estimates of impacts obtained by running the BIOME3 model only on the 800 grids corresponding to forested regions are seen to be qualitatively and quantitatively very similar to the ones obtained for the full Indian region (1500 grids), thus highlighting the robustness of the trends inferred from the analysis.

Implications for biodiversity: Independent of climate change, biodiversity is forecast to decrease in the future due to multiple pressures, in particular, increased land-use intensity and the associated destruction of natural or semi-natural habitats. While there is little evidence to suggest that climate change will slow species losses, there is evidence that it may increase species losses. Changes in phenology are expected to occur in many species. The general impact of climate change, is that the habitats of many species will move poleward or upward from their current locations. Species that make up a community are unlikely to shift together. Ecosystems dominated by long-lived species (for example, long-lived trees) will often be slow to show evidence of change and slow to recover from climate-related stresses.

Qualitative observations about the likely impact of climate change on wildlife species were made. If woody plants including exotic weeds invade montane grasslands of the Western Ghats, there would be serious consequences for the endemic Nilgiri *tahr*. Upward altitudinal migration of plants in the Himalayas could reduce the alpine meadows and related vegetation, thus impacting the habitats of several high altitude mammals including wild sheep, goat, antelope and cattle. An increase in precipitation over north-eastern India would lead to severe flooding in the Brahmaputra and place the wildlife of the Kaziranga National Park at risk. Any large-scale change in vegetation to drier types over central and north-western India would also have consequences for the fauna of these regions.

Implications for NPP, growing stock (biomass) and regeneration: At the global level, net biome productivity appears to be increasing. Modelling studies, inventory data and inverse analyses provide evidence that, over the past few decades, terrestrial ecosystems have been accumulating carbon. The mean NPP (grams of carbon per square metre per year) was about 338 in the control run, with a maximum value around 1,049. By 2050, as per the BIOME model, these values are likely to show a considerable increase. The mean value reaches about 435 (more than 25 per cent increase) while the maximum reaches about 1,400 (more than 30 per cent increase). In fact, more than 75 per cent of the grids show an increase in NPP. As expected, the grids showing a decrease in NPP lie in the northwestern region where a deficit in rainfall, and a large increase in temperature are expected. However, this region has a rather low value of NPP (about 230), and the projected decrease is also rather small (about 13 per cent).

Vulnerability of Forest Ecosystems in India and Socioeconomic Impacts

Thus, even in the relatively short span of about 50 years, most of the forest biomes in India seem to be highly vulnerable to the change in climate. As estimated earlier, about 70 per cent of the locations are expected to experience a change in the prevailing

Project tiger is a major initaitive of the Government of India for wildlife management, protection measures and site specific ecodevelopment.

biome type. In other words, about 70 per cent of the vegetation is likely to find itself less optimally adapted to its existing location, making it more vulnerable to the adverse climatic conditions as well as to the biotic stresses, which it is subjected to from time to time. As a result, during the process of take-over of one biome type by another, large-scale mortality might be expected.

The actual negative impact may be more than what is initially expected from the above description. This is because different species respond differently to the changes in climate. So, even in the region where there is no shift in the biome type, changes in the composition of the assemblages are certainly very likely. Thus, one expects that a few species may show a steep decline in population and perhaps result in local extinctions. This, in turn, will affect the other taxa dependent on the different species (i.e., a 'domino' effect) because of the interdependent nature of the many plant-animal-microbe communities that are known to exist in forest ecosystems. This could eventually lead to major changes in the biodiversity.

The north-western region of the country seems to be more vulnerable to climate change, since it is likely to experience the effect of two negative influences: a large temperature increase together with a decrease in precipitation. The vulnerability of the north-eastern region stems from a very different cause. The major increase in precipitation expected in this region is likely to shift the vegetation towards the wetter, more evergreen vegetation. Since these are rather slow growing, the replacement will take much longer, and increased mortality in the existing vegetation may lead to a decrease in the standing stock.

Uncertainty of projected impacts

GCMs are more robust in projecting global mean temperatures compared to their ability for making predictions at the regional levels. The uncertainty involved in projections of temperature and particularly precipitation at regional level is high. The vegetation response model BIOME-3 is an equilibrium model and does not project the transient phase responses. Also, the database on soil, water and plant physiological parameters as input to vegetation models such as BIOME-3, is poor. Thus, the findings

Reforestation programmes enhance the sequestration potential of forests.

of the present analysis should be viewed with caution. Though there is some uncertainty on the magnitudes of the projections of change, and though these may also vary with GCMs and RCMs used, the direction of change is unlikely to be different.

Socio-economic impacts: Nearly 200,000 villages in India are situated in or on the fringe of forests. Further, about 200 million people depend on forests for their livelihood, directly or indirectly. Forest ecosystems in India are already subjected to socio-economic pressures leading to forest degradation and loss, with adverse impacts on the livelihoods of forest dependent communities. Climate change will be an additional pressure on forests, affecting biodiversity as well as biomass production. According to the assessment of projected climate impacts on forests, significant changes in the forest boundary of different forest biomes as well as biodiversity are projected. However, during the transient phase, large-scale forest die-back may occur. This may affect the production and supply of non-timber forest products to the forest dependent communities, affecting their livelihoods. In the transient phase, there could be an increased supply of timber, due to forest die-back, depreciating timber prices.

Forest Policies and Programmes–Vulnerability of Forest Ecosystems

Forest policies in any country determine the status of forests; rates of deforestation and afforestation, levels of fragmentation, conservation and protection, and rates of timber and non-timber extraction. The vulnerability of forest ecosystems to climate change depends on the status of forests, biodiversity, fragmentation, afforestation practices, rates of extraction of timber, etc. For example, forest fragmentation may enhance vulnerability and decrease the adaptation capacity of forest ecosystems to climate change, whereas biodiversity conservation may reduce vulnerability.

India has formulated and implemented a large number of legislations, and forest conservation and reforestation programmes. These programmes have contributed towards: (a) stabilization of area under forests with marginal rates of deforestation, even though forest degradation may be continuing; (b) producing fuelwood and industrial wood, thereby reducing pressure on the forests; and (c) involvement of local communities in protection and management of forests, even though there is inadequate empowerment of community institutions.

Forest policies, programmes and practices that enhance vulnerability to climate change

Some of the policies, programmes and practices that potentially contribute to enhancing the vulnerability of forest ecosystems to climate change are as follows:

- Forest fragmentation leading to loss of biodiversity by hampering migration of species.
- Forest degradation leading to loss of biodiversity, affecting forest regeneration.
- Dominance of monoculture species under afforestation increase vulnerability to fire, pests, etc.
- Absence of fire protection and management practices enhance vulnerability to fire.
- Non-sustainable extraction of timber, fuelwood and NTFPs leading to degradation of forests, fragmentation of forests and affecting shift of forest boundaries and regeneration of plant species.
- Inadequate fuelwood conservation programmes increases pressure on forests, leading to degradation.
- Inadequate and less-effective implementation of the different conservation programmes leading to forest degradation.

There is a need for research studies to identify and assess the implications of policies and programmes to vulnerability of forest ecosystems.

Forest policies, programmes and practices reducing forest vulnerability

India has implemented a large number of forest conservation and development programmes that have the potential to reduce the vulnerability of forest ecosystems to impacts of climate change.

- The forest Conservation Act 1980, Wild Life Act, Protected Areas and other policies contribute to forest and biodiversity conservation and reduction of forest fragmentation.
- A large afforestation programme has reduced the pressure on forests for timber, industrial wood and fuelwood, leading to conservation of biodiversity and reduction of forest degradation.
- Involvement of local communities in forest protection and regeneration and creation of long-term stake in forest health, through the Joint Forest Management (JFM) programme.

The performance and impacts of these measures in quantitative terms are however not clear.

Adaptation Policies, Programmes and Practices

Why adaptation in forest sector?

The preliminary assessment of the impact of projected climate change, based on BIOME-3 outputs, indicates shifts in forest boundaries, replacement of current assemblage of species, leading to forest die-back. The need for adaptation measures to minimize the adverse impacts is strengthened due to the following reasons:

- The impacts such as loss of biodiversity are long-term and irreversible.
- There is inertia and a lag period between climate change and impacts.
- Long-term planning is necessary for forest conservation, afforestation and silvicultural practices to impact on forest regeneration and biodiversity.
- Large forest-dependent rural population and potential adverse impacts on their livelihood.

- Inadequate technical, institutional and financial capacity to adapt to climate change impacts in the forest departments, as well as at the forest dependent community level.

Policies, programmes and practices to promote adaptation

The current state of science has several limitations, particularly in projecting climate change at the regional level and assessing the response of diverse tropical forest vegetation to projected climate parameters. The vegetation models such as BIOME-3 do not incorporate the adaptation response component. Thus, at the current state of knowledge and the uncertainties involved, only 'no regret' or 'win-win' and a few 'precautionary' adaptation policies, programmes and practices could be considered. Some examples of such measures are listed here.

Forest policies: India has formulated a large number of innovative and progressive forest policies, which have the potential to reduce vulnerability. Some examples of policies, which need effective implementation, are as follows:

- Incorporate climate concern in along-term forest policy-making process.
- Incorporate climate concern in the forest 'working plan' process to enable incorporation of silvicultural practices to promote adaptation.
- Improve and ensure the effective implementation of existing policies/Acts/guidelines such as:
- Forest Conservation Act, 1980; Wildlife Protection Act, 1972 and 2002; enhance coverage and effectiveness of protected area; wildlife conservation programmes such as Project Tiger and Project Elephant.
- Link Protected Areas, Wildlife Reserves and Reserve Forests.
- Enhance support to afforestation and reforestation programmes and increase area covered to increase the production of timber and fuelwood to reduce pressure on primary forests.

Forestry and silvicultural practices: Current afforestation and silvicultural practices dominated by exotics and monocultures are enhancing the vulnerability of forests. Some of the potential silvicultural practices that could reduce vulnerability and enhance resilience are:

- The promotion of natural regeneration in degraded forest lands and mixed species forestry on degraded non-forest lands.
- The anticipatory planting of species along the latitudinal and altitudinal gradient.
- The *in-situ* and *ex-situ* conservation of plant and animal species.
- The implementation of fire prevention and management practices.
- The adoption of short rotation species and practices.
- The adoption of sustainable harvest practices for timber and non-timber products.

There is a growing need for research to identify the silvicultural practices which reduce vulnerability of forest ecosystems to changing climate parameters.

Institution and capacity building to address climate change in forest sector: India has institutions with significant infrastructure and technical capacity. However, these institutions have not focused on climate change research, which includes modelling, field ecological studies and laboratory experimentation. There is a need to create awareness and enhance technical and institutional capacity in the research institutions, forest department and NGOs. Forest dependent communities have poor financial, technical and institutional capacity to adapt to adverse impacts of climate change. Thus, it is necessary to enhance the capacity of those forest-dependent communities who are likely to be vulnerable to projected climate impacts.

Conclusions

A preliminary assessment using the BIOME-3 vegetation response model, based on regional climate model projections for India showed shifts in forest boundary, changes in species-assemblage or forest types, changes in NPP, possible forest die-back in the transient phase, and potential loss or change in biodiversity. These impacts on forests will have adverse socio-economic implications for forest-dependent communities and the national economy. The impacts of climate change on forest ecosystems are likely to be long term and irreversible.

There is a need for developing and implementing adaptation strategies to minimize the adverse impacts. Further, there is a need to study and identify the forest policies, programmes and silvicultural practices that contribute to vulnerability of forest ecosystems to climate change.

India needs to initiate studies to identify forest strategies, policies, silvicultural practices and institutional arrangements that enhance forest resilience and reduce vulnerability.

India should initiate long-term dedicated research, monitoring and modelling programmes to study vegetation responses to climate change, generate regional climate projections, improve dynamic vegetation models and their application, and conduct policy analysis to develop adaptation strategies.

CLIMATE CHANGE IMPACTS ON NATURAL ECOSYSTEMS

The large geographical area, varied topography and climatic regimes, long coastline and the possession of oceanic islands, have endowed India with a diversity of natural biomes from deserts to alpine meadows, from tropical rainforest to temperate pine forests, from mangroves to coral reefs, and from marshland to high-altitude lakes. The natural ecosystems have also been subject to exploitation and alteration by humans for several thousand years, and thus only a small fraction of these probably remain in a pristine state. Nevertheless, about one-fifth to one-fourth of the geographical area still comprises relatively 'natural' ecosystems; of this, forests occupy the major area. The non-forest ecosystems include mainly the wetlands (including mangrove forests and coral reefs) and the grasslands. The assessment of impacts of projected climate change on natural ecosystems is not based on modeling or field studies, but on current vulnerability and global-level projection of impacts from literature.

Wetlands

The natural wetland ecosystems of India include the marine ecosystems such as the coral reefs; coastal ecosystems such as the mangroves; and inland fresh-water ecosystems such as rivers, lakes and marshes. The most comprehensive wetland inventory of India that is available at present, is that prepared by the Space Application Centre (SAC) of the Indian Space Research Organization, using satellite imagery for the years 1991-1992. This inventory has listed 27,403 wetland units occupying a total area of 75,819 km^2, with the coastal wetlands comprising 53 per cent and the rest being inland wetlands.

Marine ecosystems (Mangroves and coral reefs)

The Indian coastline is over 7,500 km, and including the islands of Lakshadweep and the Andaman and Nicobars. As many as 3,959 coastal wetland sites, classified under 13 major wetland types, and covering a geographical area of 40,230 km^2 have been mapped by the Space Application Centre across nine states and four Union Territories. Of these, 426 sites (1,424 km^2) are man-made wetlands (salt pans and aquaculture ponds) and the rest are natural coastal wetlands. (Table 3.6).

The coastal wetlands play an important role in the economy of this region, especially in fisheries. The mangroves and the coral reefs in particular are important nurseries for several fishes, prawns and crabs. Of the annual fish catch of about 5.6 Mt, about half is from marine fisheries; the coral reefs and associated shelves and lagoons alone have the potential for about 10 per cent of the total marine fish yields. Climate change impacts on the coastal wetlands would thus have serious consequences for the livelihoods of people, as well as the integrity of the coastal environment.

Mangroves

Mangroves are mainly distributed along the east coast of the country and to a lesser extent along the west coast. The Sunderbans, covering an area of about 10,000 km^2 along the Ganges-Brahmaputra delta, constitute the largest mangrove wetland in the world; of this area, about 40 per cent is found in West Bengal and the rest in Bangladesh. Other important mangroves include the Mahanadi mangrove in Orissa, the Godavari and Krishna mangroves in Andhra Pradesh, the Pichavaram and Muthupet mangroves in the Cauvery delta of Tamil Nadu, the mangroves in the Gulf of Kutchh in Gujarat, and those in the Andaman and Nicobar islands.

Table 3.6: Area under various coastal and inland wetland types.

Types of Coastal Wetlands	Area (sq. km)	Inland Wetland Category	Number	Area (sq. km)
Tidal Mudflats	23, 621	Natural		
Mangroves	4,871	Lakes/Ponds	4646	6795
Estuaries	1,540	Ox-bow lakes	3197	1511
Lagoons	1,564	Waterlogged (Seasonal)	4921	2857
Sand Beaches	4,210	Playas	79	1185
Marshes	1,698	Swamps/Marshes	1814	1978
Other Vegetated Wetlands	1,391	Man-made		
Coral Reefs	841	Reservoirs	2208	14820
Creeks	192	Tanks	5549	5583
Backwaters	171	Waterlogged	892	773
Rocky Coasts	177	Abandoned Quarries (water)	105	58
Salt-Pans	655	Ash ponds/Cooling ponds	33	29
Aquaculture Ponds	769	Total Inland Wetlands	23444	35589

Source: Space Application Centre.

With the exception of the mangroves of the Andaman and Nicobars, the mangroves of the country are already considerably degraded. The development of agriculture in the deltas of the major rivers, the reclamation of the coastal wetland for settlement and the use of mangroves to supply products such as fuel-wood have resulted in considerable shrinkage of the mangrove areas. According to one estimate the mangrove cover of the country reduced by 35 per cent during the period 1987-1995 alone (estimate made by Sustainable Wetlands, Environmental Governance-2 in 1999).

The mangroves are at risk due to direct human activities as well as due to climate change.

Climate change impacts on the mangrove ecosystems would be governed by factors such as sea-level changes, storm surges, fresh-water flows in rivers both from precipitation in their catchments as well as from snow melt in the mountains, local precipitation, and temperature changes that would influence evapotranspiration. Sea-level rise would submerge the mangroves as well as increase the salinity of the wetland. This would favour mangrove plants that tolerate higher salinity. At the same time, increased snow melt in the western Himalayas could bring larger quantities of fresh water into the Gangetic delta. This would have significant consequences for the composition of the Sundarbans mangroves. Changes in local temperature and precipitation would also influence the salinity of the mangrove wetlands and have a bearing on plant composition. Any increase in freshwater flows would favour mangrove species that have the least tolerance to salinity.

It is therefore, necessary to model the specific scenarios for the various mangrove ecosystems using climate change projections, changes in freshwater and sediment flows, geomorphology, sea-level change and the land use of the coastal region.

Coral reefs

Coral reefs are distributed in six major regions along the Indian coastline. These are the Gulf of Kutchh in

Gujarat, the Malwan coast in Maharashtra, the Lakshadweep islands, Gulf of Mannar and Palk Bay in Tamil Nadu, and the Andaman and Nicobar islands. Built up during the Tertiary and the Quaternary Periods, the coral reefs in the Indian Ocean include sea level atolls (Lakshadweep archipelago), fringing reefs (Gulf of Mannar, Palk Bay, and Andaman and Nicobars), reef barriers (Andaman and Nicobars), elevated reefs and submerged reef platforms.

The biodiversity of the coral reefs includes a variety of marine organisms, including sea grasses, corals, several invertebrate groups, fishes, amphibians, birds (nesting on the reefs) and mammals. The reefs of the Andaman and Nicobar islands have the highest recorded diversity with 203 coral species, 120 algal species, and 70 sponges in addition to fishes, sea turtles, dugong and dolphins. About 1,200 species of fishes have been recorded in the seas around the islands, including 571 species of reef fish. The reefs of the Gulf of Mannar and Lakshaweep islands have intermediate levels of diversity, with 117 species and 95 species of hard corals respectively. The Gulf of Kutchh is the least diverse, with only 37 species of corals and the absence of ramose forms.

The coral reefs in the Indian region are already under threat from several anthropogenic and natural factors, including destructive fishing, mining, sedimentation, and invasion by alien species. To this we must add the possible impacts of future climate change.

It is well known that increased sea surface temperature (SST) results in 'bleaching' of corals. While bleaching

Coral bleaching due to warming.

is a normal event and is reversible, a prolonged increase in SSTs and/or intense bleaching may result in the death of the corals. In recent decades, the most widespread and intense bleaching of corals ('mass bleaching'), including in the Indian Ocean, occurred during the years 1997-1998 associated with *El Nino* when SSTs were enhanced by over 3° C, the warmest in modern record. While the coral reefs of India too were adversely affected, the precise extent of bleaching and mortality of corals is not clear in many regions.

The corals of the Lakshadweep islands were, however, significantly affected by this event with bleaching of over 80 per cent of coral cover and mortality of over 25 per cent of corals. The corals of the Gulf of Mannar were similarly affected. The most affected were shallow water corals, such as the branching *Acopora* and *Pocillopora* that were almost completely wiped out. Bleaching also affected the massive corals but these recovered and now dominate the reefs. The least affected coral reefs were those in the Gulf of Kutchh with an average of about 10 per cent bleaching and little mortality.

Inland or freshwater wetlands

The inland wetlands include a large number of natural lakes and swamps or marshes, as well as man-made reservoirs and tanks.

The SAC inventory lists 23,444 inland wetland units covering an area of 35,589 km^2 in total. Of these, the natural inland wetlands numbering 14,657 units cover an area of 14,326 km^2, are relevant to the discussion of climate change impacts. It must also be remembered that some of the man-made wetlands such as at Bharatpur in Rajasthan are exceptionally rich in bird species and should be considered as a natural wetland for the purpose of conservation in the face of climate change.

As in many other parts of the world, the inland wetlands of India have been transformed by draining for urban settlement, agricultural development, construction of roads, exploitation for their resources, and pollution from a variety of sources. A study by the Wildlife Institute of India showed that 70-80 per cent of freshwater marshes and lakes in the Gangetic floodplains have been lost over the past five decades.

Pollution of the wetlands is mainly from the discharge of sewage, industrial effluents, agricultural chemicals such as pesticides and fertilizers, and sedimentation from soil erosion.

Climate change impacts on the inland wetlands would be a complex issues dependent on several variables, including temperature increase, rate of evaporation, changes in precipitation of the catchment, changes in nutrient cycling and the responses of a variety of aquatic species. Although tropical lakes are less likely to be impacted by climate change as compared to temperate lakes, an increase in temperature would alter the thermal cycles of lakes, oxygen solubility and other compounds, and affect the ecosystem. In high-altitude lakes an increased temperature would result in the loss of winter ice cover; this would cause a major change in the seasonal cycle and species composition of the lake. Reduced oxygen concentration could alter community structure, characterized by fewer species, especially if exacerbated by eutrophication from surrounding land use. Lake-level changes from increased temperature and changes in precipitation would also alter community structure.

Shallow-water marshes and swamps would be even more vulnerable to increased temperatures and lower precipitation as projected for central and north-western India by the Hadley Centre's HADCM2. The increased evaporation of water and reduced inflow from rainfall could desiccate the marshes, swamps and shallow lakes.

Grasslands

There are five major grassland types recognized in India, on the basis of species associations, geographical location and climatic factors. These are: (a) alpine grasslands of the Himalayas; (b) moist fluvial grasslands of the Himalayan foothills; (c) arid grasslands of northwestern India; (d) semi-arid grasslands of central and peninsular India; and (e) montane grasslands of the Western Ghats

The same anthropogenic factors such as livestock grazing and fire that were responsible for creating many of the grassland types in the country are also involved in their degradation. While moderate levels of grazing could be sustainable and even promote plant species diversity, heavy grazing reduces the plant cover and eliminates palatable grasses and herbs while promoting the growth of unpalatable plants.

When considering the likely impact of future climate change on natural grasslands, we need to consider several factors including the direct response of grasses to enhanced atmospheric CO_2, as well as changes in temperature, precipitation and soil moisture. It is well known that plants with the C3 and the C4 pathways of photosynthesis respond differently to atmospheric CO_2 levels and also to temperature and soil moisture levels. The C3 plants include the cool, temperate grasses and practically all woody dicots, while the C4 plants include the warm, tropical grasses, many sedges and some dicots. The C4 plants that constitute much of the biomass of tropical grasslands, including the arid, semi-arid and moist grasslands in India, thrive well under conditions of lower atmospheric CO_2 levels, higher temperatures and lower soil moisture, while C3 plants exhibit the opposing traits. Increasing atmospheric CO_2 levels should, therefore, favour C3 plants over C4 grasses, but the projected increases in temperature would favour the C4 plants. The outcome of climate change would thus be region-specific and involve a complex interaction of factors.

GCM model projections (for example, the HADCM2) for India indicate an increase in precipitation by up to 30 per cent for the north-eastern region in addition to a relatively moderate increase in temperature of about 2° C by the period 2041-2060. This could increase the incidence of flooding in the Brahmaputra basin and thus favour the maintenance of the moist grasslands in the regions. The HADCM2 projections for the rest of the country (southern, central and north-western India are a steep increase in temperature of 3° C in the south (except along the coast) to over 4° C in the north-west, and a decrease in precipitation of over 30 per cent in the north-west though little change in parts of the south. This combination of temperature increase and rainfall decrease would cause major changes in the composition of present-day vegetation in these regions, with an overall shift to a more arid type. Increased atmospheric CO_2 levels and temperatures, resulting in lowered incidence of frost, would favour C3, plants including exotic weeds such as wattle (*Acacia spp.*) that could invade the montane grasslands of the Western Ghats. The cool, temperate grasslands of the Himalayas could also be impacted by rising temperatures that would promote the upward migration of woody plants from lower elevations.

An assessment of climate change impacts on natural ecosystems would require a systematic programme of documenting ecosystem processes, modelling climate change impacts and formulating strategies for adaptation.

CLIMATE CHANGE IMPACTS ON COASTAL ZONES

Indian Coastal Zones and climate change

The coastal zone is an important and critical region for India. This region is densely populated and stretches over 7,500 km, with the Arabian Sea on the west and the Bay of Bengal on the east. It is inhabited by more than a 100 million people in nine coastal states (West Bengal, Orissa, Andhra Pradesh and Tamil Nadu on the east coast, and Kerala, Karnataka, Goa, Maharashtra and Gujarat on the west coast), two UTs (Pondicherry and Daman and Diu) and two groups of islands (Andaman and Nicobars, and Lakshdweep). According to the census of 2001, there were about 65 coastal districts in these nine states. The total area occupied by the coastal districts is around 379,610 km^2, with an average population density of 455 persons per km^2, which is about 1.5 times the national average of 324 (Census, 2001). The Indian coastline can be categorized into three classes—coast of emergence, coast of submergence and neutral coast (Table 3.7).

The western coastline has a wide continental shelf with an area of about 0.31 million km^2, which is marked by backwaters and mud flats. East coast is flat, deltaic and rich in mangrove forests. Mangroves are located all along estuarine areas, deltas, tidal creeks, mud flats, salt marshes and extend to about 6740 km^2. Major estuarine areas located along the Indian coasts extend to about 2.6 million hectares. Coral reefs are predominant on small islands in Gulf of Kutchh, Gulf of Mannar in Tamil Nadu and on Lakshadweep and the Andaman and Nicobar islands. Ecosystems such as coral reefs, mangroves, estuaries and deltas are rich in biodiversity. These ecosystems play a crucial role in fishery production in addition to protecting the coastal zones from erosion by wave action. There are 11 major and 130 minor sea ports located in coastal zones that are economic engines of international and national trade and commerce in India.

Future climate change in the coastal zones is likely to be manifested through the worsening of some of the existing coastal zone problems. Some of the main climate-related problems in the context of the Indian coastal zones are erosion, flooding, subsidence, deterioration of coastal ecosystems, such as mangroves, and salinization. In many cases, these problems are either caused by or exacerbated by sea level-rise and tropical cyclones. The key climate-

Table 3.7: Physiographic characteristics of the Indian coastline.

Coastline part	Coastline type
North-east coast (West Bengal, Orissa and parts of Andhra Pradesh)	Emerging coastline with no offshore bar
Shoreline off the mouths of Ganga, Mahanadi, Krishna, Godavari and Cauvery Rivers	Neutral and highly dynamic (due to the large influx of sediments) coastline
Southeast coast (Tamil Nadu and parts of AP)	Emerging coastline with an offshore bar and lagoon
Southwest coast (Kerala)	Submerging coastline (highly-indented shoreline with an erosional tendency)
Mid-west coast (Karnataka, Goa Maharashtra)	Submerging coastline (network of coastal rivers, inland creeks, backwaters and rocky headlands)
North West coast (Gujarat)	Submerging coastline (creeks and inland waters)

Source: NIO

related risks in the coastal zone include tropical cyclones, sea-level rise, and changes in temperature and precipitation in the context of the Indian coastal zones.

A rise in sea level has significant implications on the coastal population and agricultural performance of India. A variety of impacts are expected which include:

- Land loss and population displacement.
- Increased flooding of low-lying coastal areas.
- Agricultural impacts (like, loss of yield and employment) resulting from inundation, salinization, and land loss.
- Impacts on coastal aquaculture.
- Impacts on coastal tourism, particularly the erosion of sandy beaches.

The extent of vulnerability, however, depends not just on the physical exposure to sea-level rise and population affected, but also on the extent of economic activity of the areas and capacity to cope with impacts. The coastal ecosystems sustain a higher density of human population. The pressure on coastal areas has been growing due to migration from inland to the coastal zone making it vulnerable to the increased frequency and intensity of natural and human interventions. The reason for this increased pressure is due to the greater employment opportunities, when compared to inland areas of the coastal states, as some of the major urban centres are located in this region. For instance, three of the four major Indian metropolitan areas are located in the coastal region (Mumbai, Kolkata and Chennai). Moreover, out of the 35 urban agglomerations (UA) with a million plus population identified for India in the census of 2001, 18 (*viz.*, Rajkot, Ahmedabad, Vadodara, Surat, Greater Mumbai, Pune, Nagpur, Nashik, Bangalore, Kochi, Hyderabad, Vishakhapatnam, Vijayawada, Chennai, Coimbatore, Madurai, Asansol, and Kolkata) are situated in the coastal states. From among these, eight lie on the coastline. The activities in many of these areas tend to exceed the capacity of the natural coastal ecosystem to absorb them, making these regions vulnerable to the increased frequency and intensity of natural and man-made hazards.

Methods and Models for Assessing Vulnerability

Vulnerability is considered as a composite of: (a) climate-related *hazards* that are relevant and significant in the coastal zone; (b) *exposure*—socio-economic components, including human and manufactured capital, as well as natural ecosystems that are exposed to climate risk; (c) *adaptive capacity*—the ability of the exposed units to perceive and formulate a response and implement to climate risk, with a view to reducing impacts.

Assessment of coastal zones to projected climate impacts and development of adaptation strategies include:

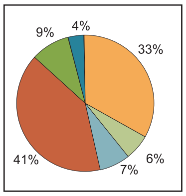
- a description and analysis of present vulnerability, including representative vulnerable groups (for instance, specific livelihoods at the risk of climatic hazards).
- descriptions of potential vulnerabilities in the future, including an analysis of pathways that relate the present to the future.
- comparison of vulnerability under different socio-economic conditions, climatic changes and adaptive responses.
- identification of points and options for intervention, which would lead to formulation of adaptation responses.
- relating the range of outputs to stakeholder decision making, public awareness and further assessments.

Greater emphasis is placed on the first two components, that is, hazard and exposure, and their combination, which are the actual climate impacts in coastal regions. While adaptive capacity is important, and key in determining *future*, as opposed to *current* vulnerability, there are a number of significant methodological and conceptual issues with regard to adaptive capacity.

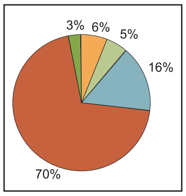
Climate-Related Coastal Hazards–Current Vulnerability

The characteristics of the key climate-related risks in the coastal zone, including sea-level rise and tropical cyclones and, are presented.

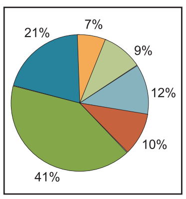
Table 3.8: Percent area for erosion and depositional segments of the coastline of the states along the West Coast of India (left panel) and East Coast of India (right panel).



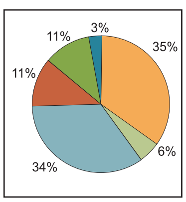
Gujarat has 'submerging type' of coastline, which is more prone to the effects of sea-level rise. The Gulf of Kutchh has a highly dynamic coastline. The Gulf of Khambhat is a potential site for shoal migration and vulnerable to large shoreline changes because of the prevalent macro-tidal regime. The southern coast of Gujarat has a highly dynamic coastline with erosion tendency.



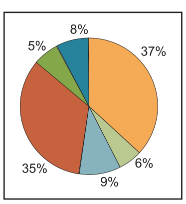
The northern coast of Maharashtra has an indented coastline with many creeks, inland waters, and pocket beaches. The coastline, though mostly rocky along the coast due to the presence of the Sahyadri Range, is under threat at many locations due to the reduced fluvial input. The west coast fault (a N-S trending regional tectonic feature) and the submergence characteristics add to the vulnerability of these regions.



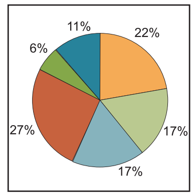
Goa has many pocket beaches. Owing to pressure from tourism-related anthropogenic activities, some of the beaches are destabilized and are vulnerable in the event of sea-level rise.



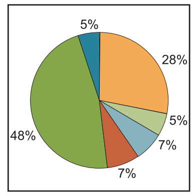
The shoreline of Karnataka is indented with hills, creeks, and small estuarine rivers, the mouths of which have dynamic shoaling. In the southern region, the shoreline is more dynamic compared to the north. The mouths of the small coastal rivers and backwaters at many places are undergoing erosion. The coastline at locations with dynamic and migrating shoaling activities is prone to destruction.



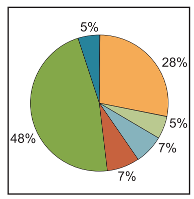
The shoreline of Kerala is, by and large, dynamic, with a high erosion tendency. The entire coastline of Kerala is vulnerable to sea-level rise, and needs special attention.



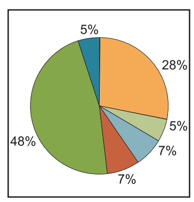
Pockets of high erosion all along the coast with high erosion in the Gulf of Mannar and the Tuticorin area. The southern part of Tamil Nadu is vulnerable due to localized segments of unstable shoreline.



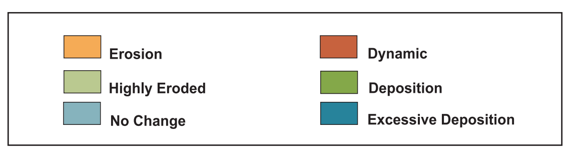
In Orissa the shoreline is dynamic due to the high fluvial input and is metastable in the creeks and backwaters. It is subjected to severe erosion during cyclones/depressions. The coastal area has numerous small and large rivers and their distributaries, which fan out into the coastal region, and are prone to salinity ingress, particularly in the event of sea-level rise.



The southern coast of Andhra Pradesh is more dynamic than the northern coast. The coasts along the mouths of all major rivers are highly dynamic, as the mouths of many perennial rivers are migratory. The area is also frequently affected by cyclones, and the shoreline is highly sensitive to such extreme natural processes



The fluvial flux from the Ganga and the Brahmaputra Rivers makes the shoreline of West Bengal is very dynamic due to the large. At many places, the shoreline is erosional (Digha Beach), and large changes in the island geomorphology have been observed. The delta region is also highly dynamic and the islands located in this region need special consideration. The Sunderban area and the Hooghly estuarine regions are the two other areas that are found to be the most vulnerable to the observed sea-level rise.

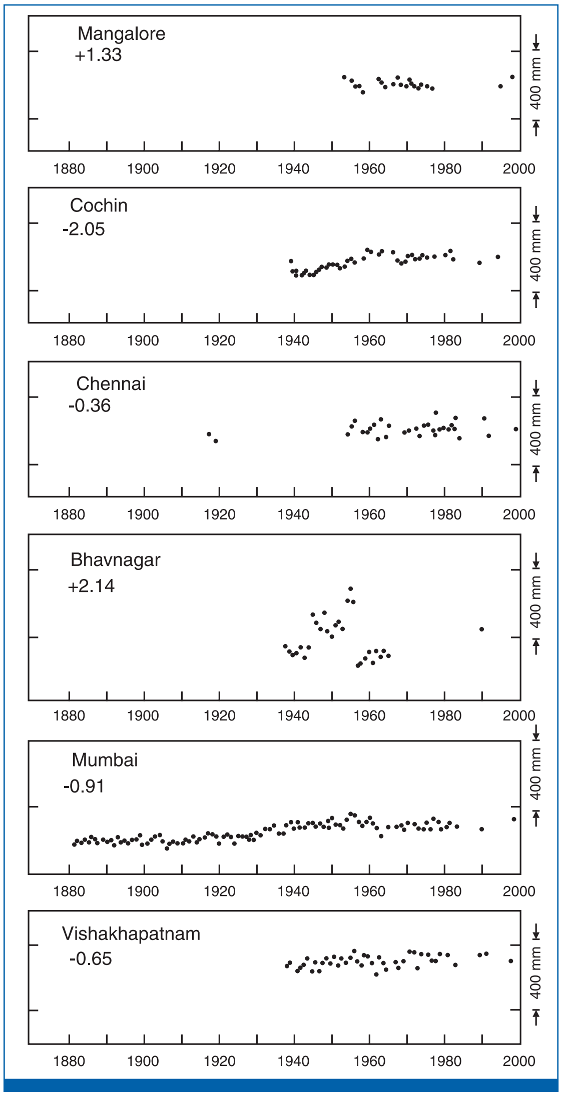


Sea-level Rise

This is based on available data shoreline changes over a short span of 10-15 years, along the Indian coastline. Using the available models, global sea-level rise of 10-25 cm per 100 years has been predicted due to the emission of GHGs. To separate the influences due to the global climatic changes the available mean sea-level historical data from 1920 to 1999 at 10 locations were evaluated. There is a large contrast in the observed sea level changes. The sea level rise along the Gulf of Kutchh and the coast of West Bengal is the highest. Along the Karnataka coast, however, there is a relative decrease in the sea level.

Shoreline morphologies respond to prevalent hydrography and the changes in the shoreline have been estimated and categorized broadly as erosive, dynamic, and depositional. Based on the comparisons of satellite data and hydrographic charts, the shoreline changes along the Indian coastline were examined for a 10-15 year span. The state-wise characteristics of the shoreline for the Indian coast are shown in Tables 3.8.

Figure 3.32: Estimated sea level rise at selected locations along the Indian Coastline.*



*The values on the left-side corner indicate sea-level variations per year. A minus figure indicates a relative increase in the mean sea level with respect to the land.

The magnitude of tides has been predicted for 121 stations and has a high correlation with observed tides. The most vulnerable areas of the Indian coastline, determined from the risk assessment, is identified from the integration of physiographic evaluation, site-specific sea-level changes, tidal environment and hydrography data. The physiographic settings and tidal regime are important parameters to determine the resilience of an area to the influence of sea-level rise. From the estimated tidal environment at 121 stations, it is observed that the mean spring tide ranges show a progressive increase towards north along the east coast (Figure 3.32). A similar trend is also observed along the West Coast. Some of the highest tidal ranges are measured at stations in the Gulf of Kutchh and in the Gulf of Khambhat. From the time series mean spring tide amplitude, it is deduced that the northern areas along the east, as well as west coasts have a higher tidal range and very wide intertidal and supratidal zone.

The areas along the Indian coastline that are likely to be vulnerable to the predicted sea-level rise based on predicted sea level changes, tectonics, prevalent hydrography, and physiography of the areas can be seen from the Figure 3.33. These vulnerable regions need special attention.

Tropical Cyclones

For the Indian region, the data on cyclonic events is available from 1877. The spatial, temporal patters of occurrence is presented in Box 3.8.

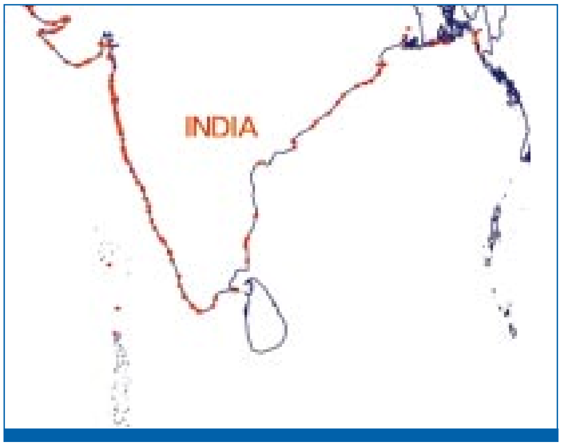


Figure 3.33: Likely vulnerable locations due to sea level rise.

Box 3.8: Cyclonic Events

The Spatial Pattern of Cyclone Incidences and the Facts (data from 1877 to 1990)

- 1,474 cyclones originated in the Bay of Bengal and the Arabian Sea during this period.
- 964 cyclones crossed the Indian coastline.
- Three districts of West Bengal (174 events).
- Seven districts of Orissa (422 events).
- Nine districts of Andhra Pradesh (203 events).
- 15 districts of Tamil Nadu (100 events)

The Temporal Pattern of Cyclone Incidences

- Depressions have a distinct peak in the month of August.
- Storms have two distinct peaks in June and October.
- Severe storms have distinct peaks in May and November.
- The total number of tropical cyclones seasonality follow the path of the depression.

Average based on the Facts:

- 8.45 cyclones cross the Indian coastline per year.
- 5.15 depressions cross the Indian coastline on an average per year.
- 1.93 storms occur on an average per year.
- 1.35 severe storms occur on an average per year.

Trends in Tropical Cyclone Incidence: Storms depict a decreasing trend (-0.017/year) significant at one per cent level. Severe Storms (SS) show an increasing trend (0.011/year) significant at one per cent level. Cyclone incidences show mixed trends spatially. West Bengal and Gujarat showed significant increasing trend, while Orissa showed a significant decreasing trend.

***Cyclone Hazard Indices*:** Indices were developed to represent the cyclone hazard and to identify the coastal districts that face the maximum cyclone occurrences. Three indices were computed. The first index is the frequency of events (by cyclone type, i.e., depressions, storms and severe storms) in a particular district. The second is by normalizing the number of events in a district by the coastline length of the districts; and the third is normalizing the number of events in a district by area of that coastal district. Table 3.9 presents the top 10 districts according to each of the indices for the severe storm category of cyclones.

The indices have been developed for the districts, rather than a continuous and a uniform metric like per 100 km of coastline length, since the impact data is reported for districts. Hence, there are differences in rankings for districts on the basis of different indices. Thus, Chennai ranks first when the number of cyclones is normalized by district area and Karikal ranks first when the number of cyclones is normalized by district coastline length, whereas South 24 Paraganas ranks first for other indices. This is because Chennai and Karaikal have much smaller area and coastline length respectively, when compared to other districts.

Table 3.9: Ranking of the districts based on different indices of cyclone hazard

Indices / Rank	Frequency of SS	SS normalized by coastline length	SS normalized by district area
1	South 24 Parganas (WB)	Karaikal (Pondicherry)	Chennai (TN)
2	North 24 Parganas (WB)	Nagapattinam (TN)	Nagapattinam (TN)
3	Nellore (AP)	Villupuram (TN)	North 24 Parganas (WB)
4	Srikakulam (AP)	Chennai (AP)	Jagatsinghpur (Orissa)
5	Nagapattinam (TN)	Jagatsinghpur (Orissa)	Kendrapara (Orissa)
6	Junagadh (Gujarat)	Pondicherry	Baleshwar (Orissa)
7	East Godavari (AP)	Cuddalore (Orissa)	Srikakulam (AP)
8	Baleshwar (Orissa)	North 24 Parganas (WB)	South 24 Parganas (WB)
9	Kendrapara (Orissa)	Nellore (AP)	Porbander (Gujarat)
10	Krishna (AP)	Baleshwar (Orissa)	Bhadrak (Orissa)

Exposure indices: Exposure refers to the extent to which the human systems are unprotected from climate-related natural hazards. Exposure can be understood of in two ways–physical and socio-economic. Historical record that spans three decades (census publications for the 1971, 1981, 1991 and 2001 census years) have been used to study the aspects of the population and construction of households at the coastal district level. Exposure indicators based on ***Housing Index*** (using the distribution of housing stock across the different categories of houses (based on the wall material) and the knowledge of susceptibility of a particular category of house to storm and flood damage); and ***Population index*** (the density of population has been considered the measure of population exposure to hazards).

Based on the rankings of 52 coastal districts belonging to eight states:

- The top five districts which had the maximum exposure in terms of housing were
  - o Valsad, Uttar Kannada, Ratnagiri, Ganjam and Kozikhode. Of these:
  - o four lie on the west coast (cyclone incidence is lesser on the west coast when compared to the east coast).
  - o This implies vulnerability of west coast (submergent type) to sea level rise.
- The top five districts with high exposure levels considering exposure in terms of density of population were:
  - o South 24 Paraganas, industrialized towns like Surat, place of tourist attraction Sindhudurg and towns in river floodplains and deltas West and East Godavari Krishna.
  - o Greater Bombay and Chennai have the highest exposure levels (urban).
- The exposure levels have increased over the years in terms of the absolute number of people, density of population and the size of the housing stock.

Data on human mortality, livestock mortality, damage to houses, damage to crop area, loss in monetary terms and population affected are used to measure impacts of climate-related extreme events. The approach followed for analyzing the impacts of the cyclones has been to rank the districts on the basis of an impact index, in order to obtain an idea about the districts that have historically suffered the maximum impacts.

The top five districts in the east coast, namely, Nagapattinam, Jagatsinghpur, Balasore, Bhadrak and Nellore and Porbandar and Junagadh, ranked the highest in terms of mortality due to the severe storms which occurred in the period 1971 to 1990.

Current Vulnerability of the Indian Coastal Zones: For assessing the vulnerability of the Indian coastal zones, three indices each for hazard, exposure and impacts were selected and computed. The impacts were represented by cumulative deaths, deaths per event and cumulative deaths per million of the population. Statistical correlations (Spearman's rank) between different indices were computed. The district ranks for the impact indices and hazard indices are correlated with each other. However, the district ranks for the exposure indices are not correlated, implying that the hazard, exposure and impacts interact in complex ways to define the vulnerability of a district. To capture this, a complex cluster analysis was performed. The cluster analysis grouped the 14 districts used in the analysis into two major clusters, classified as highly vulnerable and somewhat vulnerable. The rest were classified into less vulnerable cluster. Table 3.10 shows the classification of Indian coastal districts on the basis of vulnerability

Agricultural Development in Coastal Districts: The eastern coast districts are major producers of rice in India, and adverse effects of climate change may have an impact on production and availability of food grains in the country. The literature shows that these shortfalls have the potential to create market imbalances that can further lead to market and price fluctuations. Agricultural production in these coastal areas is heavily dependent on climatic conditions, despite the availability of irrigation facilities. In Tamil Nadu, the growth rate for the area irrigated is declining. In other states, a rise in area irrigated has given a thrust towards commercial crops, such as groundnut and sugarcane and, hence, extreme climatic shocks like storms and severe storms can have a negative affect on agriculture and the incomes of people. The settlements in coastal areas of India have a high percentage of people, whose income is derived from climate-sensitive sectors like agriculture, fisheries and forestry.

Table 3.10: Classification of Indian coastal districts on the vulnerability to cyclones

Vulnerability	Districts
Highly vulnerable	Cuttack (now Jagatsinghpur and Kendrapara) in Orissa; Nellore in Andhra Pradesh; Thanjavur (now Nagapattinam) in Tamil Nadu; Junagadh (now Junagadh and Porbander) in Gujarat.
Somewhat vulnerable	North 24 Parganas in West Bengal; South 24 Parganas in West Bengal; Baleshwar (now Baleshwar and Bhadrak) in Orissa; Srikakulam in Andhra Pradesh; East Godavari in Andhra Pradesh; Guntur in Andhra Pradesh; Krishna in Andhra Pradesh; Chengalpattu (now Thiruvallur) in Tamil Nadu; South Arcot (now Cuddalore) in Tamil Nadu; and Ramnathpuram in Tamil Nadu.
Less vulnerable	The rest of the coastal districts.

Climate-related Coastal Hazards—Future Scenario

The past observations on the mean sea level along the Indian coast show a long-term rising trend of about 1.0 mm/year. However, the recent data suggests a rising trend of 2.5 mm/year in the sea-level along Indian coastline. Model simulation studies, based on an ensemble of four AOGCM outputs, indicate that the oceanic region adjoining the Indian subcontinent is likely to warm at its surface by about 1.5-2.0°C by the middle of this century and by about 2.5-3.5°C by the end of the century. The corresponding thermal expansion, related sea-level rise is expected to be between 15 cm and 38 cm by the middle of this century and between 46 cm and 59 cm by the end of the century. A one-metre sea level rise is projected to displace approximately 7.1 million people in India, and about 5,764 km^2 of land area will be lost, along with 4,200 km of roads. An increase in the frequency of severe cyclonic storms is likely under the climate change scenario; this may enhance the vulnerability of those districts that are already ranked as vulnerable under the current climate scenario.

Adaptation Options

There are a number of adaptation options that could be adopted for reducing the vulnerability of a coastal system to climate-related hazards. These adaptation options could be classified into structural and non-structural interventions. Structural interventions basically attempt to change the physical conditions of the natural system and resource base through technological interventions. It involves putting up of artificial physical structures in the landscape, for example building dikes or seawalls or enhancing the natural setting or landscape in such a manner so as to provide protection from the climate-related coastal hazards. Planting of mangroves, beach nourishment, etc., are some examples of other interventions. Non-structural approaches employ land-use controls, information dissemination, and economic incentives to reduce or prevent disasters. The Coastal Regulation Zone, or using insurance to cover the risk related to impacts of climate-related hazards would fall under the non-structural measures. A coastal zone management plan should also include research and development activities for cost-effective methods for the protection of coastal lands. Rules and regulations must be framed and enforced to have a control over the developmental activities and to put restrictions on seaward extrusion.

CLIMATE CHANGE IMPACTS ON HEALTH

People have adapted to living in a wide variety of climates around the world—from the tropics to the arctic. Both climate and weather have a powerful impact on human life and health. Human physiology can handle most variations in weather, within certain limits. Certain health outcomes associated with the prevailing environmental conditions include illnesses and death associated with temperature extremes, storms and other heavy precipitation events, air pollution, water contamination, and diseases carried by mosquitoes, ticks, and rodents. As a result of the potential consequences of these stresses acting individually or in combination, it is possible that

Coastal areas and livelihoods at risk.

projected climate change will have measurable beneficial and adverse impacts on health.

In India, the overall susceptibility of the population to environmental health concerns has dropped dramatically during the past few years with the improvement in availability of the health infrastructure. However, the extent of access to and utilization of health care has varied substantially between states, districts and different segments of society; to a large extent this is responsible for substantial differences between states in health indices of the population. During the 1990s, the mortality rates reached a plateau and the country entered an era of dual disease burden. Communicable diseases have become more difficult to combat because of the emergence of insecticide-resistant strains of vectors and antibiotic-resistant strains of bacteria. Under-nutrition, micro-nutrient deficiencies and associated health problems coexist with obesity and non-communicable diseases in the country. The existing system suffers from inequitable distribution of institutions and access to nutrition and health care.

Current climate trends have shown an increase in maximum temperatures, heavy intense rainfall in some areas and emergence of intense cyclones. In the summer of 1994, western India experienced temperatures as high as 50°C, providing favourable conditions for disease-carrying vectors to breed. In 1994, as summer gave way to the monsoon and western India was flooded with rains for three months, the western state of Gujarat was hit by a malaria epidemic. Weather conditions determine malaria transmission to a considerable extent. Heavy rainfall results in puddles, which provide good breeding conditions for mosquitoes. In arid areas of western Rajasthan and Gujarat, malaria epidemics have often followed excessive rainfall. In very humid climates, drought may also turn rivers into puddles. Similarly, the super-cyclone in 1999 caused at least 10,000 deaths in Orissa and the total number of people affected was estimated at 10-15 million.

Changes in climate may alter the distribution of important vector species (for example, mosquitoes) and may increase the spread of disease to new areas that lack a strong public health infrastructure. High altitude populations that fall outside areas of stable endemic malaria transmission may be particularly vulnerable to increases in malaria, due to climate warming. The seasonal transmission and distribution of many other diseases transmitted by mosquitoes (dengue, yellow fever) and by ticks (Lyme disease, tick-borne encephalitis), may also be affected by climate change. Some of the key health impacts that might arise due to climate change are listed in Table 3.11.

Projections of the extent and direction of potential impacts of climate variability and change on health are extremely difficult to make with confidence because of the many confounding and poorly understood factors associated with potential health outcomes. These factors include the sensitivity of human health to elements of weather and climate, differing vulnerability of various demographic and geographic segments of the population, the movement of disease vectors, and how effectively prospective problems can be dealt with. In addition to uncertainties about health outcomes, it is very difficult to anticipate what future adaptive measures (for example, vaccines and the improved use of weather forecasting to further reduce exposure to severe conditions) might be taken to reduce the risks of adverse health outcomes. Therefore, in this scenario, carrying out improvements in environmental practices, preparing disaster management plans and improving the public health infrastructure in India, including disease surveillance and emergency response capabilities, will go a long way in coping with the impacts of climate change on human health.

Table 3.11: Known effects of weather /climate and potential health vulnerabilities due to climate change.

Health Concerns	Vulnerabilities due to climate change
Temperature-related morbidity	Heat- and cold-related illnesses.
	Cardiovascular illnesses.
Vector-borne diseases	Changed patterns of diseases.
	Malaria, filaria, kala-azar, Japanese encephalitis, and dengue caused by bacteria, viruses and other pathogens carried by mosquitoes, ticks, and other vectors.
Health effects of extreme weather	Diarrhea, cholera and poisoning caused by biological and chemical contaminants in the water (even today about 70% of the epidemic emergencies in India are water-borne).
	Damaged public health infrastructure due to cyclones/floods.
	Injuries and illnesses.
	Social and mental health stress due to disasters and displacement.
Health effects due to insecurity in food production	Malnutrition and hunger, especially in children.

Malaria is one of the important climate-change related diseases that has been extensively studied since the early 1960s in India. Records of incidences and mortality due to the same are inadequate. Malaria was chosen for an in-depth study to develop the relationship between climate parameters and disease incidence, and for studying its future spread in the climate change context.

The Present Scenario of Malaria

Malaria is caused by a species of parasites belonging to the genus *Plasmodium.* There are four species of the malaria parasite namely, *Plasmodium vivax* (or *P. vivax*), which is extensively spread geographically, and is present in many temperature zones, as well as the tropics and sub tropics, *P. falciparum* is the most common species in tropical areas and the most dangerous clinically, *P. ovale* resembles vivax and replaces it in West Africa and *P. malariae* is much less apparent, with low parasitaemia and is found mainly in tropical Africa.

Malaria is endemic in all parts of India, except at elevations above 1,800 metres and in some coastal areas. The principal malaria-prone areas are Orissa, Madhya Pradesh, Chattisgarh, and the north-eastern parts of the country. Periodic epidemics of malaria occur every five to seven years. According to the World Bank, in 1998 about 577,000 Disability-Adjusted Life Years (DALYs) were lost due to malaria. The principal malaria vectors are mosquitoes of the genus *Anopheles*. These include *A. culicifacies* (a rural vector), in most parts, *A. stephensi* (an urban vector) and *A. fluviatilis, A. minimus, A. dirus* and *A. sundaicus* in other parts of India.

Amongst these states, Orissa has the highest Annual Parasite Index (API) which is greater than 10, followed by Madhya Pradesh and Chattisgarh (API between 6-10). The occurrence is high in Jharkhand, which is mainly inhabited by a tribal population (Figure 3.34). Here, the incidence increased from 35,000 to more than 40,000 between 1995 and 2000.

In the early 1950s, malaria was not only the cause of morbidity and mortality, but also one of the major constraints in ongoing developmental efforts. The National Malaria Control Programme was spectacular successful initially in bringing down the incidence of malaria from 75 million cases with 0.8 million deaths, to 0.1 million cases with few deaths by 1965, even though there was no well-established health care infrastructure in the rural areas. Subsequently, however, there was a resurgence of malaria. In 1976, over 6.7 million cases were reported (Figure 3.35). From 1977, the National Malaria Eradication Programme (NMEP) began implementing a modified plan of operation for the control of malaria. Despite of these efforts, the number of reported cases of malaria has remained around two million in the 1990s.

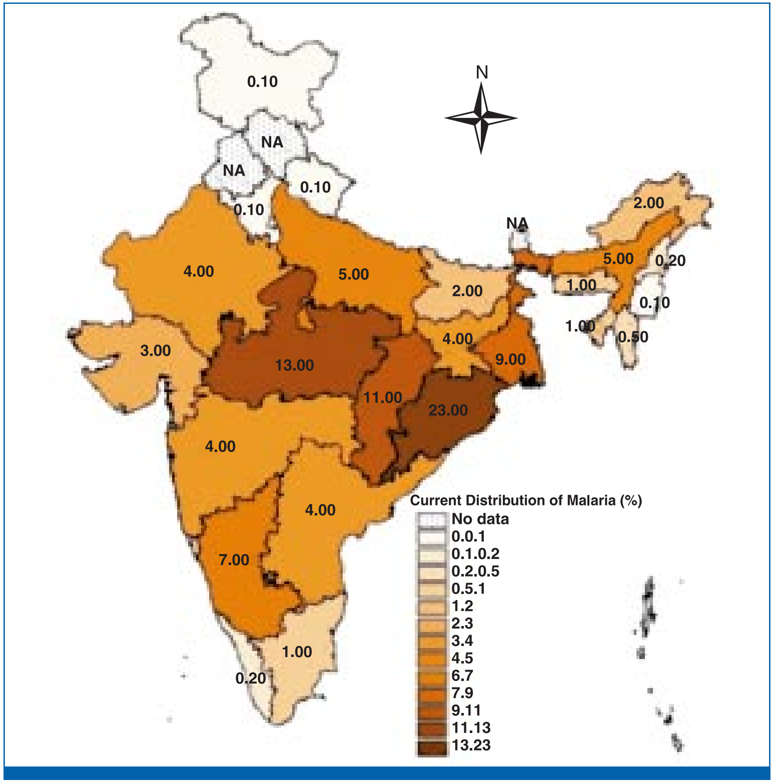


Figure 3.34: Distribution of malaria in India in 2001.
Source: National Malaria Eradication Programme, 2002.

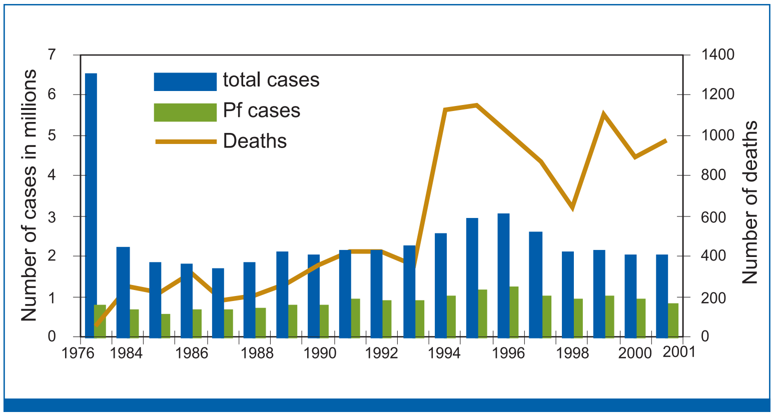


Figure 3.35: The malaria situation in India between 1976 and 2001.
Source: Ministry of Health and Family Welfare, 2003.

The increase in malaria incidences are attributed to the resistance of mosquitoes to pesticides, and the resistance of parasites to anti-malarial drugs, thus, limiting the effectiveness of malaria control attempts through the NMEP. The sudden jump in the number of deaths to 1100 in 1993 corresponding to the same number of incidences in the previous years may be explained by the improved reporting of the health workers of NMEP (now known as National Anti-Malaria Programme or NAMP).

Factors influencing malaria

Climate Parameters: For most vectors of malaria, the temperature range 20°C-30°C is optimal for development and transmission. Relative humidity higher than 55 Per cent is optimal for vector longevity, enabling the successful completion of sporogony. Malaria transmission requires a minimum average temperature higher than 15°C for *P. vivax* and 19°C for *P. falciparum*, and this temperature should sustain over a period of time for the completion of sporogony. For example, when average temperature, humidity, precipitation and incidences have been plotted for Gujarat (Figure 3.36), the maximum incidences are seen to occur in the months of June, July and August when relative humidity is highest i.e., greater than 60 per cent and less than 80 per cent, at temperatures ranging between 25°C to 30°C. This window shifts from state to state as we go from south to north, depending on the arrival of the monsoon. Hence, to represent this diversity, climate determinants are further classified into Class I, II and III cases, which are needed for the growth and effective transmission of malaria vectors (Table 3.12).

Table 3.12: Climate determinants for *P. vivax* development and transmission.

Type	Temperature range (°C)	Humidity (%)	No. of days to develop
Class I	15–20	>60%	*20±5*
Class II	20–25	>60%	15±5
Class III	25–30	>60%	8±5

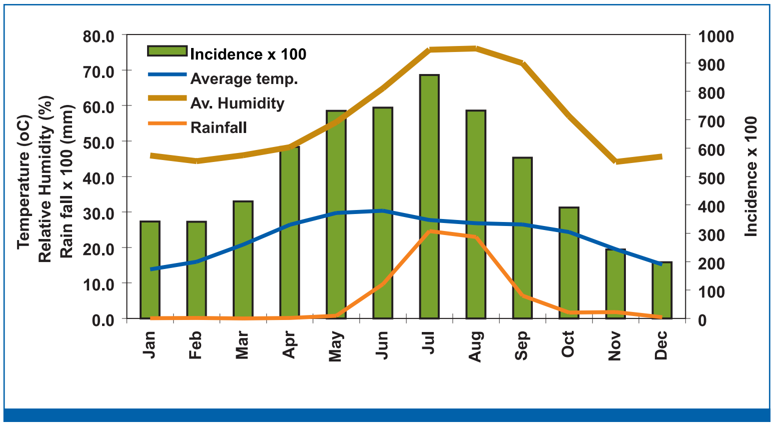


Figure 3.36: Dependence of malaria incidence on climate determinants.

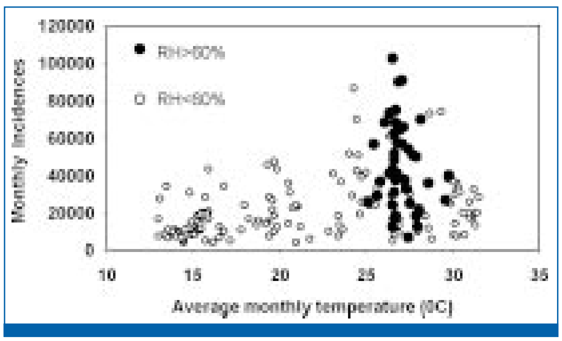


Figure 3.36: Variation of malaria incidences with temperature for relative humidity greater than and less than 60%.

These classifications are based on extensive climate data analysis at a daily level.

A analysis of temperature versus incidences for each state, for the days when humidity was less than 60 per cent and between 60 per cent to 80 per cent indicated that Class I conditions prevail in the northern regions of India and Class II and Class III conditions prevail in the southern states. For example, in Gujarat, the temperature window corresponded to 26°C -32°C (Figure 3.37), with peak incidence at 27°C, which correspond to Class III conditions. However, as regards the relative influence of temperature and precipitation for relative humidity greater than 60 per cent, it is observed that temperature has more influence over malaria transmission than does precipitation (Figure 3.38). Since the correlations are not strong (i.e. greater than 0.95), other non-climate parameters such as socio-economic conditions also influence vector generation and malaria transmission. Further in-depth data analysis for other states is required at the district level to conclusively establish the dominance of temperature with respect to precipitation on incidence for a given humidity condition. Other than temperature, precipitation and humidity controlling malaria at the local level, the link with global climate has also been observed in generating malaria in some years in India. (Box 3.9).

Urban settlements: Increasing urban population creates a large number of peri-urban areas on the outer limits of cities, which now account for 25-40 per cent of the Indian population. These areas are unplanned and poor people live here in unsanitary conditions. A suitable environment is thuscreated for epidemics to be caused by increases in *A. culicifacies* (which breeds in clean water on the ground due to rain) and *A. stephensi* (which breeds in wells and stored water). *A. stephensi* has extended its distribution in India over the past four decades by entering more towns and peri-urban areas. This spread in *A. stephensi* is related to the spread of piped water systems throughout the

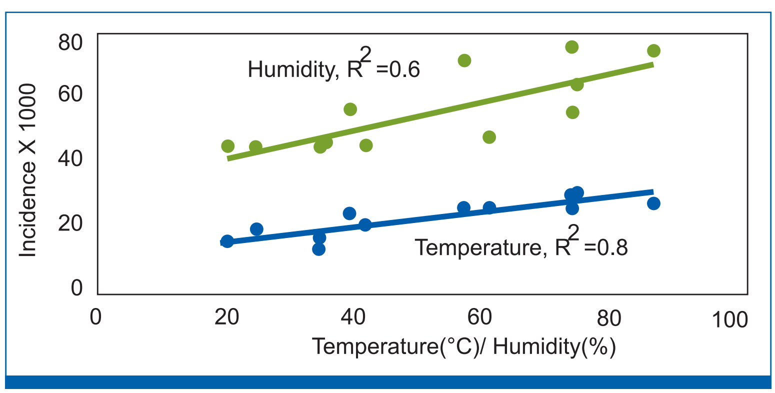


Figure 3.38: Relative importance of temperature and humidity in malaria incidence.

Box 3.9: The Influence of *El Niño* Southern Oscillation (ENSO) events

An increased risk of malaria and excessive rainfall can be expected in the years following the onset of La Nina and the opposite during *El Niño* events. Most of the *El Niño*/La Nina years in India have resulted in below or above normal incidences of malaria, respectively. Although there is a general tendency for the malaria incidences to be below or above normal during drought/flood monsoon seasonal rainfall years, the separation is not as good as that observed in the case of *El Niño*/La Nina events.

Malaria incidences during 1961–1995.

El Niño years	Incidence	La Nina Years	Incidence	Excess years	Incidence	Deficit years	Incidence
1965	–5327	1964	8740	1970	–3102	1965	–5327
1969	10503	1966	13455	1975	252329	1966	13455
1972	–6506	1970	–3102	1983	49907	1968	30730
1976	24462	1973	122977	**1988**	**66833**	1972	–6506
1982	–38534	1975	252329	1994	137745	1974	211768
1987	**–19702**	1978	87133			1979	9856
1991	166370	1983	49907			1982	–38534
1992	–42242	**1988**	**66833**			1985	–110449
						1986	93271
Drought/flood years						1987	19702

country. Peri-urban malaria is a new malaria phenomenon, because migrants often have chronic malaria and the poor environmental conditions in their temporary settlements foster mosquito breeding and malaria transmission.

Poverty : Malaria is declining in states in India that have performed well in economic terms over the last decade and has increased where the performance is below average. The ever-increasing population, widespread poverty and illiteracy, malnutrition and anaemia and the low socio-economic status creates an immense pressure on the environment, and provision of safe drinking water and basic sanitation for millions. Poverty is multidimensional. It deprives the poor from access to the basic health benefits.

Irrigation: Irrigated area has increased in India from 26.8 Mha in 1950 to more than 90 Mha in 1995. It was introduced in some areas for increasing agricultural productivity by building a large number of dams and canals. The seepage from canals and a rise in the water tables create a source of still water for malaria breeding. Examples of such regions can be found in the Thar desert, where mismanagement of the widespread developmental activities of canal-based irrigation have led to malaria becoming endemic. No malaria incidences were recorded here earlier. In Uttar Pradesh. *A. culicifacies* which is resistant to DDT and HCH pesticidestook over from *A. fluviatilis*, when irrigation was implemented in the state. Also, the Sardar Sarovar dam, an irrigation project on the Narmada river, though not fully implemented yet, has already lead to the invasion of *A. culicifacies* and *A. fluviatilis*, extending the malaria season, changing the area into an endemic malaria region and causing a 10-15 fold increase in malaria.

Agricultural practices: Agricultural practices, such as rice farming, create large areas of stagnant water that are suitable breeding grounds for malaria vectors. Rice fields in India provide breeding habitats for 20 *Anopheles* species. However, there are differing opinions about whether increases in area under rice cultivation correlate with increases in malaria.

Land-use change: Forests, where a majority of the tribal population resides, are a reservoir of high levels of malaria in India. Currently, malaria in the forests accounts for 30 per cent of all malaria in the country and it is stable with high transmission rates. Most incidences in these areas are caused by *P. falciparum*, which is increasingly becoming more resistant to chloroquin and, in certain locations, to other anti-malarial drugs. Deforestation, mainly carried out for development projects and due to economic pressures, allows new vectors to invade the forest fringes, producing epidemics, especially in the non-tribal non-immune people who move to these areas for jobs. Some forest areas in India also experience moderate levels of chloroquin resistant *P. falciparum.*

Malaria scenario under climate change

Presently, the transmission window (based on minimum required conditions for ensuing malaria transmission) is open for 12 months in eight states (Andhra Pradesh, Chhatisgarh, Karnataka, Kerala, Maharashtra, Orissa, Tamil Nadu and West Bengal), nine to 11 months in the north-eastern states (Gujarat, Haryana, Madhya Pradesh, Punjab, Rajasthan, Uttar Pradesh and Uttaranchal). The states of Himachal Pradesh and Jammu and Kashmir have transmission windows open for five to seven months, respectively. When the temperature and relative humidity are considered together for determining the transmission window, it is observed that for less than 60 per cent relative humidity, the transmission window is reduced by one to five months. For example, in Madhya Pradesh, the transmission window is open only for four months if both temperature and relative humidity are considered, while it is open for eight months if only temperature is considered. Therefore, it appears that transmission may take place at less than 60 per cent relative humidity.

Considering a 3.8°C increase in temperature and a seven per cent increase in relative humidity by the 2050s (with reference to the present), nine states of India may have transmission windows open for all 12 months. The transmission windows in the states of Jammu and Kashmir and Rajasthan may increase by three to five months as compared to the base year. States like Orissa and some southern states, where the mean temperature is more than 32°C in four to five months, a further increase in temperature is likely to cut the transmission window by two to three months (Figure 3.39). Since there exists climate as well as geographical diversity within a state, district-wise projections are desirable.

The above approach is a preliminary attempt to project

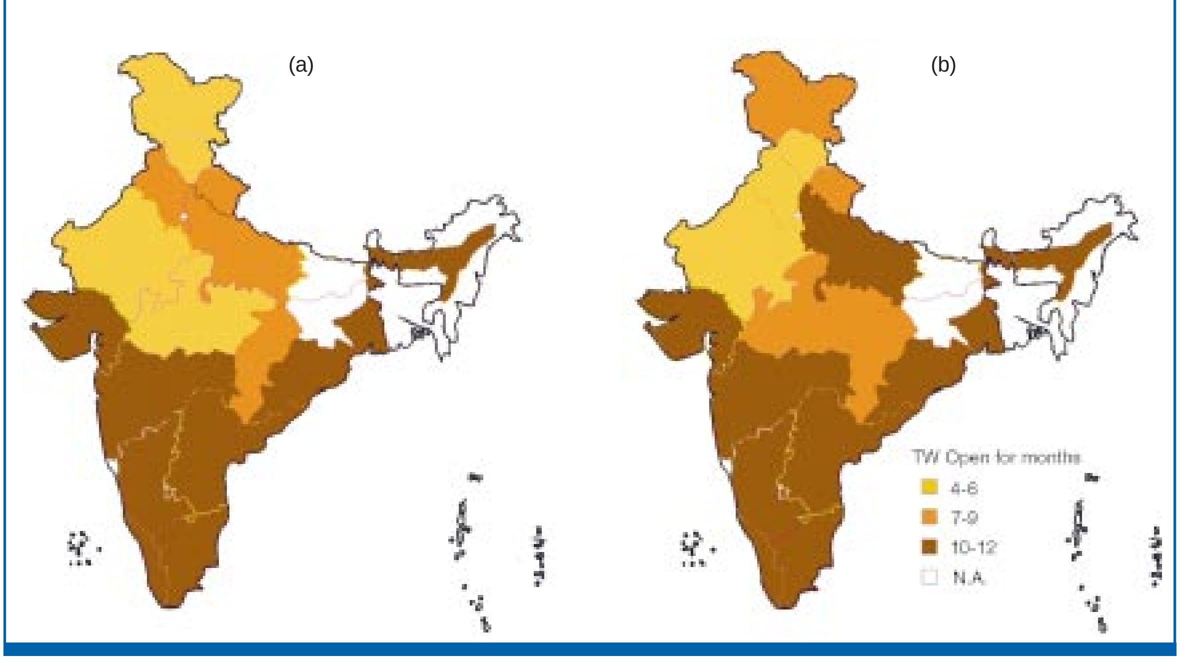


Figure 3.39: Transmission window of malaria in different states of India: (a) for base case (year 2000); and (b) under projected climate change scenario (2050s).

climate change impacts. An integrated approach is required to evaluate the impacts of climate change on malaria in India, that will include not only the future climate and land-use pattern parameters but also would integrate the projected socio-economics which need to include access to medical intervention in the region/state/district. This is further corroborated by the fact that in the northern Indian states, the winter months are usually not suitable for transmission of malaria but some cases do occur through all the months. It may be due to relapsed cases, which is a common phenomenon in *P. vivax* parasite. Therefore, the projections of malaria in 2080 based on present projections of temperature and relative humidity, may not be accurate.

Adaptation Strategies

The Government of India since the late 1940s has been implementing various programmes to control malaria in the country. Initially, as a result of these programmes, the disease subsided in the 1960s, but since the late 1970s it has become resistant to the interventions. These measures will also be relevant as potential adaptation strategies in the climate change regime. Indeed, improved malaria drugs, potential immunization and enhanced economic welfare of the people may reduce the incidence of malaria.

Existing Government policies

India started using the pesticide DDT to control malaria beginning in 1946 (see Box 3.10). In 1953, when 70 million cases and 0.8 million deaths occurred due to malaria (NMEP, 1996), the National Malaria Control Programme was started. This programme was renamed the National Malaria Eradication Program (NMEP) in 1958 due to the success of DDT and the commitment to malaria eradication in India at that time. It was believed that it could eradicate malaria in seven to nine years, but the disease began to re-emerge in 1965. After 1965, malaria rates in India rose gradually and consistently, with a peak of 6.47 million cases in 1976 (NMEP, 1996). This resurgence of malaria caused India to begin an attempt to control rather than eradicate malaria in 1977 with a Modified Plan of Operation (MPO), which also comprised the *P. falciparum* Containment Programme (P_f CP). The P_f CP aimed to contain the spread of falciparum malaria, which is the most commonly resistant and deadly strain of malaria. During MPO, chloroquin distribution was extended through Fever Treatment Deport and Drug Distribution Centres, in addition to other means through which malaria drugs had already been distributed. MPO also only used residual insecticides in areas with an API index greater than two. This method still relied mainly on spraying pesticides and distributing anti-malarial drugs, although there was also an attempt to get more local officials involved in anti-malarial activities and an increase in research. By 1985, it seemed as though the NMEP would succeed in controlling malaria, because there were only two million cases of malaria and the incidence rate had stabilized. India has, however, experienced more epidemics and deaths from malaria in the 1990s, along with the creation of a new malaria phenomenon. In 1994, there were large-scale epidemics of malaria throughout the country, and since then malaria mortality has increased.

Box 3.10: Malaria control in India

Year	Action
1946	India started using DDT
1953	NMCP is started
1958	NMCP becomes the NNMEP
1959	The first-time vector resistance is detected in India (in Gujarat)
1965	Malaria begins to re-emerge
1976	The peak of malaria cases in the re-emergence period
1977	India starts MPO and P_f CP
1985	Only 2 million annual cases of malaria in India
1991	The peak of P. falciparum cases
1994	Large-scale epidemics, particularly in the Eastern and Western parts of India
1997	NMEP to NMAP (focus shifts from malaria eradication to malaria control)

According to the Planning Commission, despite extensive malaria eradication efforts, the number of reported cases of malaria has remained around two million in the 1990s. Financial assistance also has been received from the World Bank for the Enhanced Malaria Control Programme (EMCP) to cover a 100 predominantly *P. falciparum* malaria endemic tribal-dominated districts in Andhra Pradesh, Bihar, Jharkhand, Gujarat, Madhya Pradesh, Chattisgarh, Maharashtra, Orissa and Rajasthan and 19 other cities. The project also has the flexibility to divert resources to any area in case of a malaria outbreak. In other areas, the NMAP continues to be implemented as a centrally sponsored scheme on a 50:50 cost-sharing basis between the centre and states in urban and rural areas. The central government provides drugs, insecticides and larvicides and also technical assistance/guidance as and when the state governments require. The state governments meet the operational cost, including salaries. In view of the high incidence of malaria (particularly of falciparum malaria) and high mortality, a 100% central assistance under the NAMP is being provided to the north-eastern states since 1994.

Although there has been an enhanced amount allocated for malaria eradication in the Ninth Plan, the decline in cases in this period was not commensurate with the substantial increase in funding. The rising proportion of *P. falciparum* malaria, increased vector resistance to insecticides and the growing parasite resistance to chloroquin, will render malaria containment and control more difficult in the Tenth Plan period. Since the Ninth Plan goal for reduction in API and morbidity has not been achieved, the Tenth Plan aims to achieve a morbidity and mortality rate reduction by 25 per cent in 2007 and 50 per cent in 2010 (Box 3.11).

Box 3.11: Goals of the Tenth Plan

Parameter	To achieve
Annual Blood Examination Rate (ABER)	Over 10%
API	1.3 or less
Moribidity and Mortality	Reduce by 25% by 2007 and 50% by 2010

Source: Tenth Five year plan, Planning Commission, Government of India, 2002.

Adaptation options in the climate change regime

It is essential that adaptation policies are designed in such a way that they take into account the uncertainties associated with the impacts of climate change, the specific anticipated changes in the existing disease conditions, including the expected improvement in the socio-economic conditions of the people in the future. Thus, in addition to disease specific measures, the following actions might be taken to develop adaptation strategies for the future:

- Improved surveillance and monitoring systems.
- Develop vector specific regional maps.
- Technological engineering strategies.
- Improved infrastructure to avoid artificial breeding.
- Medical interventions.
- Develop predictive models linking climate and incidence.
- Develop integrated environmental management plans.
- Public education.

A combination of these options can be used in addition to the ongoing efforts of the government to control malaria. The appropriateness of these measures will of course be decided by the local experts according to the health care needs of the public in the region and some of them may be temporary in their effectiveness.

Future Research Needs

The research results presented here, vis-a-vis the relationship between malaria and its determinants, and the likely spread of malaria to other regions are not conclusive by themselves. Since India has a diverse climate and socio-economic pockets, conditions conducive to malarial vector growth and its transmission vary at small spatial scales. Therefore, more research is required for a better assessment of malaria transmission under the additional climate change scenario. Further research needs to include:

- A study of the effect of different combinations of temperature and relative humidity on the development of malaria vectors infected with *P. vivax* and *P. falciparum*, the common parasites of malaria.
- A study of the impact of rainfall on creation of breeding habitats of malaria vectors/or flushing off the breeding habitats, in different malaria paradigms.
- District-wise prospective studies in different eco-

epidemiological types of epidemic prone areas to evaluate the role of temperature, rainfall and RH on mosquito vectors and malaria so as to develop an early warning system for proactive adaptation measures.

- For determining the transmission windows more definitively in the climate change scenario, an integrated assessment approach is required. This will link the outputs of the regional climate change models with the anticipated socio-economic trends, soil moisture, surface water run-off, vegetation cover, and the biogenic characteristics of malaria.

Key Findings

The transmission windows of opportunity conducive to malarial vector growth and transmission are unique to India and are defined in terms of climate parameters as Class I, Class II and Class III which correspond to different temperature ranges and durations when the humidity persists between 60 per cent to 80 per cent. This differs from state to state as the topography and land use have high variability. Temperature plays a greater role with respect to precipitation in the transmission of malaria.

Malaria has not yet penetrated elevations above 1,800 metres and some coastal areas. However, some of these areas may be penetrated by malaria in future due to climate change. It is projected that during the 2080s, 10 per cent more states may offer climatic opportunities for malaria vector breeding throughout the year with respect to the year 2000. These opportunities are projected to increase by three to five months in Jammu and Kashmir, and western Rajasthan, while they may reduce by two to three months in the southern states as temperatures increase.

The disease potential, i.e., the risk of contracting malaria by a population is the result of a combination of parameters such as climate change, public and private health capabilities, and man-made conditions conducive to malaria, such as unhygienic surroundings with accumulated water pools. Development associated with improved access to health systems, housing conditions, better infrastructure for waste disposal, better sanitary systems and new technological interventions vis-a-vis medication for malaria will play a key role in checking the spread of malaria in the future.

CLIMATE CHANGE IMPACTS ON ENERGY AND INFRASTRUCTURE

Infrastructure is an engine for economic development. It may be broadly defined as a system of linkages that facilitate and enable the flow of goods and services. These linkages include road, rail and airways; river systems, electric power systems, and all the different types of communication and service lines. It also includes the built and engineered entities, the factories, buildings, dams, and all that comprise the cities and towns. Huge investments are being committed in new infrastructure projects in developing countries. Development of infrastructure enhances the scope of utilizing underemployed resources, besides creating new investment opportunities. Infrastructures are long-life assets and are designed to withstand normal variability in climate regime. However, climate change can affect both average conditions and the probability of extreme events, temperatures, precipitation patterns, water availability, flooding and water logging, vegetation growth, land slides and land erosion in the medium and long run which may have serious impacts for the infrastructure. Infrastructure displays some special characteristics that have a strong bearing for the adaptation policies for protecting it against the likely impacts.

Infrastructure – Special Characteristics

The word 'infra' means below and 'infrastructure' means the support services below the real economic

Infrastructure is at risk due to climate change.

structure. Though the concept of infrastructure has been extensively used in the literature of economic development, it has not been explicitly defined in a precise and generally accepted manner. A number of interchangeable terms such as social overhead, economic overhead and basic economic facility have been used to denote services, which are generally identified with infrastructure.

Some of the basic characteristics of infrastructure facilities can thus be defined as:

- *Essential but not directly productive:* Infrastructure facilities are universally required for carrying out any kind of production, yet they themselves do not produce goods for final use. They provide support to the directly productive activities and are, thus, in the nature of overhead costs.
- *Pre-requisites of development:* Infrastructure facilities are normally created ahead of demand. Due to their universal requirement they are often considered as necessary pre-requisites of development. The expansion of production activities is unlikely to take place, beyond a level, without these services.
- *Non-importable:* More often than not, the technical nature of these facilities is such that necessitates their creation and supply at the very place of their use. Electricity can be cited as an exception, which can be transported but requires specialized infrastructure in place.
- *Lumpiness:* Infrastructure cannot be built in bits and pieces and has to be provided in a minimum size. This feature emanates from what can be described as technical indivisibility. In general, a minimum quantum of investment, which is often large, is required for the creation of infrastructure. A corollary of indivisibility and lumpy investment is that the per unit cost of services generated by infrastructure declines over a very large range of production.
- *External Economies:* Another distinguishing feature of infrastructure is that it generates external economies, i.e., 'services rendered free'. The benefits from infrastructure are sometimes so widespread that it is difficult to identify each and every beneficiary. Hence, it is said that investment in infrastructure is profitable for society as a whole.
- *Provision by state:* Due to very high investment involved and inability to generate attractive return to the investor, infrastructure facilities generally require investment by the government. Historically the world over, most of the services have been developed with the initiative of the states.

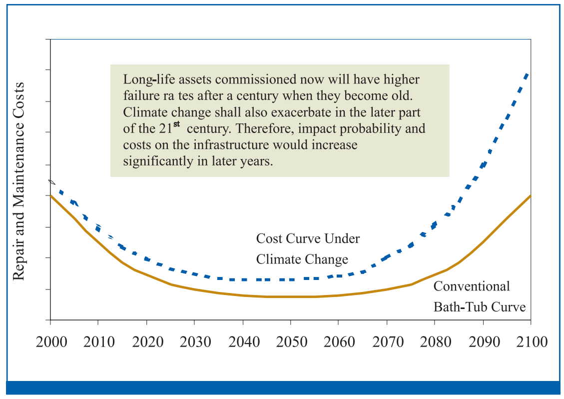


Figure 3.40: Infrastructure maintenance and impact costs.

In addition to the above characteristics, infrastructure projects have a long gestation period and a comparatively long life span. Any asset like infrastructure, that has a long life, has a tub-shaped cost curve for repair and maintenance. In the initial stabilization period, it may require frequent maintenance. The maintenance requirement decreases once the system has stabilized (Figure 3.40). It increases again due to wear and tear, as the asset reaches the end of its useful life. Attention to climate change impacts becomes important, since these may be more pronounced in the later part of the 21st century (IPCC, 2001b). These two effects coupled together, would increase the economic impact on infrastructures. Thus, developing countries need to take the investment decisions for infrastructure development very carefully, because these decisions result in long-term irreversible commitment of resources.

Infrastructure development in India

Economic growth in India demands development of its infrastructure. In the light of the continued need for development of infrastructure in India, successive five-year plans have devoted a large and increasing volume of outlays for the development of economic, social and institutional infrastructure. The following broad generalization can be made about the trend of investment in infrastructure items over the planning period.

The major share of plan outlay has gone for the development of a few infrastructure items that reflects the high priority given to some sectors. In the first two five-year plans, nearly two-thirds of the total plan outlays were devoted to social and economic infrastructure. In the later plans, this declined to about three-fifths of the outlay. Economic infrastructure (transport, power, irrigation and communication) has claimed a lion's share—around 45 per cent of the plan outlays. Within the economic infrastructure, power and transport have received the largest share. Social infrastructure has received relatively less attention, claiming less than one-sixth of the plan outlays. The pattern of plan outlays on infrastructure in the 1950s is distinctly different from that of the later plans. However, there is stability in the pattern of plan outlays, though certain marginal shifts have occurred from one plan to the other.

The Ninth Plan Working Group on Housing had estimated the investment requirement for housing in urban areas at Rs 526 billion (US$ 11.5 billion). The India Infrastructure Report estimates the annual investment need for urban water supply, sanitation and roads at about Rs 280 billion (US$ 6.15 billion) for the next 10 years. The Central Public Health Engineering (CPHEEO) has estimated the requirement of funds for a 100 per cent coverage of the urban population under safe water supply and sanitation services by the year 2021 at Rs 1,729 billion (US$ 37.9 billion). Estimates by Rail India Technical and Economic Services (RITES) indicate that the amount required for urban transport infrastructure investment in cities with population 100,000 or more during the next 20 years, would be of the order of Rs. 2,070 billion (US$ 45.4 billion).

Obviously, these massive investments cannot be located from within the budgetary resources of central, State and local governments. Private sector participation and access to international finances are, therefore, required for infrastructure development projects. As a result, investment opportunities are arising in the infrastructure sector, especially in roads, ports, energy, telecommunications and urban services. India may require Rs 9,800 billion during 2001-2006 to meet the projected growth in demand for infrastructure (India Infrastructure Report, 1996).

Some recent initiatives of large-scale infrastructure development in India include the development of the national highways network. Such infrastructure projects require huge investments. The national highways development project for four/ six-laning of around 13,146 km of road network, with another 1,000 km of port and other connectivity, is expected to cost Rs 540 billion (US$ 11.8 billion). More than 2,100 km has already been completed over the last three years and another 5,000 km are under various stages of completion. More than US$ 3.5 billion have been spent and/or committed. The river linking project is estimated to require a Rs. 5,560 billion (US$ 122 billion) investment over next the 10 years. This project has been envisaged in the current climatic regime and assumes the availability of water in the perennial Himalayan rivers. If the climatic changes predicted by international scientific assessment (IPCC, 2001b) were to be realized over the present century, the monsoon and rainfall patterns would alter and the glaciers would recede, thus changing the annual water flow patterns in the sub-continental rivers. This would alter the project's assumptions and the costs and benefits assessment.

Huge investments in infrastructure, having a long life span, are presently being planned without any conscious analysis of climate change-related impacts on them. It is indisputable that long-term climate changes are likely to have impacts on infrastructure. All over the world, extreme weather events are a major cause of damage to infrastructure. In developing countries, governments have to bear the losses arising from this damage to infrastructure, since currently 95 per cent of infrastructure is government-owned and it bears the responsibility for repair and maintenance. Even for privatized infrastructure, the *force majeure* provisions largely allocate financial responsibility for catastrophe risk to governments. An inevitable result of the increased damages to infrastructure from climate change will be a dramatic increase in resources needed to restore infrastructure. A developing economy like India has to take these issues into consideration while formulating appropriate policies.

Methods and models

The present assessment of climate change impacts on infrastructure has been analyzed by developing an impact matrix. The matrix approach facilitates the identification of indicators which may have impacts for a particular case study. A matrix approach with indicator analysis is also preferable, because indices make it possible to compare two or more complex, multifaceted systems at one time by analyzing the interactions among the systems and converting the information related to varied impacts in a single observable outcome. While this process of reductionism enhances the understanding about the phenomenon, it works contrary to both the complex behaviour of the system and potentially disparate nature of impacts. However, modelling requires this simplification of complex realities and the matrix approach provides the required simplification mechanism.

The stages involved in the design of the matrix include:

- Defining existing conditions/components.
- Projecting and estimating likely future changes.
- Taking each component one by one and applying change (as a ‘thought experiment’).
- Recording the extent of interactions.
- Identifying major problem areas.

Traditionally, the impact matrix approach used for environmental assessment carries out an analysis of the impacts of economic activities on the environment. A conventional impact matrix explores a one-way relationship of the effect of human activities on the environment. The reverse link is most often ignored. For the present assessment, a reversed matrix has been developed, which links the impacts of change in environmental variables to the project activities. A schematic diagram of the matrix is given in Figure 3.41.

The first quadrant in the above matrix indicates the conventional impact matrix, where the impact of project components on the environment is analyzed. The first and second quadrant show the interrelationships of the environmental variables and project components. The fourth quadrant shows the impacts of changes in the environmental variables on the project components.

Impact on Transport sector

Climate change impact on transportation infrastructure and the operation of transportation systems may be divided into three categories: the effects of climate on operations; the effects of sea-level rise on coastal facilities; and the effects of climate on infrastructure.

A future climate with an increased number of rainy days, rainstorms and higher rainfall intensity may increase vehicular accidents and injuries in accidents, and result in longer travel time and increased delays. The effect of climate change on transport is not very clear. However, transportation by air is known to be sensitive to adverse weather conditions; major system-wide effects sometimes follow from flight cancellations, rerouting, or rescheduling. There is a high level of confidence that sea-level rise will increase the cost of protecting infrastructure located in the coastal regions.

Dependent Variables / Forcing Variables	Environmental Variables	Project Components
Environmental Variables	2	4
Projects Components	1	3

Figure 3.41: Reverse impact matrix.

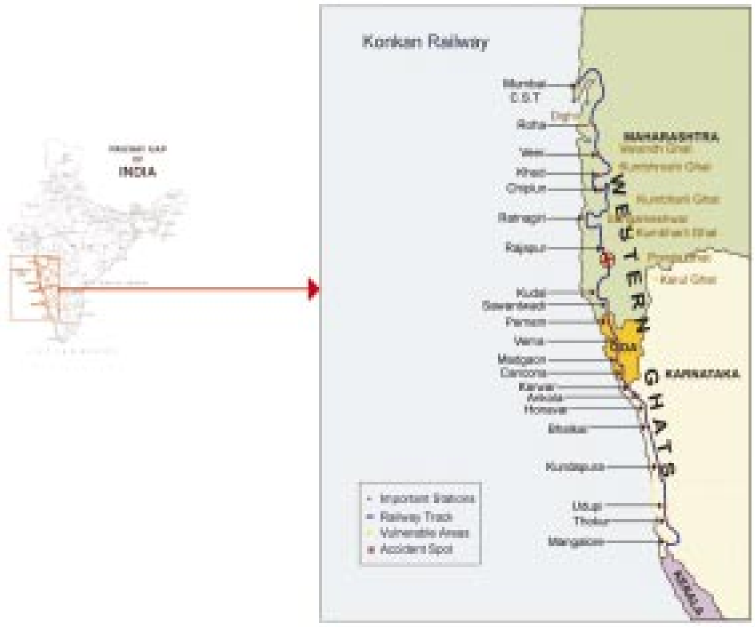
Transportation operations are sensitive to local weather conditions. Fog, rain and snow slow down transport movements and increase risks of accidents. In addition, maintenance costs and durability of infrastructure are also dependent on weather events. Changes in frequency and intensity of extreme events such as hurricanes, floods, high-speed winds and cloudbursts may have significant impacts on the safety and reliability of transportation. All these impacts are location-specific and the infrastructure located in different regions will experience different intensity of impacts.

In the following section, a case study of climate change impacts for the Konkan Railway has been presented. This work has been carried out applying the proposed reversed impact matrix. An analysis of the currents conditions, lessons from the past climate variability, potential climate change impacts, knowledge and information gaps, and the point of view of the stakeholders have also been presented.

Impacts on Konkan Railway

Konkan is a coastal strip of land bounded by the Sahyadri hills to the east and the Arabian Sea to the west in the states of Karnataka, Goa and Maharashtra. It is a region with rich mineral resources, dense forest cover, and a landscape fringed with paddy, coconut and mango trees. This railway project was conceived with the objective of bridging the 'Konkan gap' and reducing the distance and travel time between Mumbai, and coastal Karnataka and Kerala (Figure 3.42).

Konkan Railway: The Layout and Vulnerable Spots



The 760 km long Konkan Railway on the western coastal ghats of India is an engineering marvel with 179 main and 1,819 minor bridges, 92 tunnels (covering 12% of the total route) and over 1,000 cuttings (224 deeper than 12 metres). The longest tunnel is 6.5 Km long and the longest bridge is over 2 km. The pillars of the tallest viaduct bridge are more than 64 metres high, taller than Qutab Minar.

Presently 20% of repair and maintenance expenses on tracks, tunnels and bridges are due to climatic reasons.

A recent accident on 21[st] June 2003 night (see ⊕ on the map), resulting in over 50 deaths, was caused by landslide at a deep cutting due to incessant heavy rains, presumably higher than the system's adaptive capacity. Consequent to the accident, maximum permissible speed of trains has been reduced from 120 Km/h to 75 Km/h.

200 mm rainfall within 24 hours increases vulnerability (Nagrajan et al., 2000) (see ■ present vulnerable regions around the northern corridors as on the map). Future rainfall pattern shows that such events are likely to occur more frequently and with higher intensity (chapter 3 of this book).

Adaptation measures should also consider vulnerable spot identification based on future climate change projections.

Figure 3.42: Konkan Railway: Layout and vulnerable spots.

The Konkan Railway is a broad gauge (1,676 mm) single line, between Roha (about 150 km south of Mumbai) and Thokur (22 km north of Mangalore), a distance of 760 km, built at a cost of about Rs 34 billion (US$ 745 million). It has 59 stations, 179 major bridges (total linear waterway 20.50 km) and 1,819 minor bridges (total linear waterway 5.73 km). This is for the first time that Indian Railways have constructed tunnels longer than 2.2 km and there are nine such tunnels in the project (KRCL, 1999). The Konkan Railway Corporation Limited (KRCL) track passes through more than 1,000 cuttings[4], with 224 being deeper than 12 metres. All these deep cuttings have been declared as vulnerable spots by KRCL after the June 2003 accident.

Impact analysis

The Western Ghats, through which the Konkan Railway passes, experience moderate to heavy rainfall and its marine ecosystems are sensitive to climate

Table 3.13: Climate Change Impacts on Konkan Railway.

Climatic Parameter	Impact Parameter	Intervening Parameter	Impact on KRC
Temperature Increase	High evaporation rate	Stability and strength of the building materials	Buildings get weakened. Frequent repair and maintenance
	Surface and ground water loss	Crop productivity in the region may be affected	Agricultural freight traffic
	Need for air-conditioning	Passenger traffic may shift to air-conditioned class	Affects efficiency, carrying capacity and composition.
Rainfall Increase	Ground and surface water-level change	Flooding and water logging, erosion reduces the quality of land cover	Buildings affected, structural damages may take place. Increased maintenance and other related costs
	Improved water availability in the region	Agricultural production	Changes in agricultural freight traffic
	Humidity increase	Uncomfortable climatic conditions, vegetation growth along the track	Passenger traffic affected, increased maintenance cost
Sea-level Change	Land erosion	Tracks tunnels and bridges may be affected	Increased maintenance,
	Flooding	Land instability and land slides	Damage to infrastructure, reconstruction and relocation
	Water logging		Risk of delays increase
Extreme Events	Cyclone and high-velocity winds and storms	Damage to buildings, communication lines, etc	Disruption of services, repair and reconstruction costs
	Cloudbursts	Land erosion, floods, and landslides	Extensive damage to infrastructure, high cost of repair and reconstruction

[4] Small hillocks are cut through to construct passage for the railway track duly maintaining reasonable slope for the track. These passages are called cuttings. Cuttings are like top-open tunnels, with spread-out slopes on either side. Some cuttings are deeper than 12 to 15 metres. Such deep cuttings pose higher safety hazards due to higher possibilities of water logging and landslides. Cuttings cave in mostly due to excessive rains. Unstable cutting-slope and geological characteristics of the soil determine its sensitivity to rains. Adaptation measures include regular monitoring during the rainy season, temporary speed restrictions on the trains passing through these cuttings, nylon-net erection and retaining wall construction to trap sliding boulders, removing precariously placed boulders in anticipation, appropriate drainage construction and maintenance, further easing out and consolidation of the cutting-slopes, paving and sowing of grass on the cutting-slopes.

changes. Although many studies were carried out to analyze the impacts of the Konkan Railway project on the surrounding ecosystems and environment, none of these have analyzed the environmental impacts on the Konkan Railway. The present assessment explores the potential impacts of climate change on the Konkan Railway infrastructure by identifying the relationship of the various climate change parameters with the likely impacts on the Konkan Railway, through a series of impact and intervening parameters (Table 3.13).

Cause-effect analysis

The cause-effect analysis was carried out through a reverse causal matrix, where various identified indices were assessed for their capacity to force changes in the other elements, through a qualitative approach. Table 3.14 shows the causal analysis for Konkan Railway for 10 identified indices. The table shows a two-way matrix, where 'L' denotes a weak link, 'M' a moderate link and 'H' a strong link. Rows show the forcing variables and the columns dependent variables. The strength of the causal link was determined in consultation with the officials of Konkan Railway. A total of eight senior officials were interviewed. A two-stage process of interviewing was adopted for this purpose. In the first stage, relevant causal variables were identified, and in the second, the strength of the link was determined. The analysis matrix presented here shows the perceptive importance assigned by the people working in the field and therefore no quantification of the relative strengths of the linkages has been attempted.

The analysis carried out with the help of the impact matrix shows that low dependence and high-forcing factors such as rainfall are the major climatic drivers having impacts on Konkan Railway. This factor is influenced by elements external to the Konkan Railway and is beyond the control of the system. Other factors such as temperature, sea-level rise and extreme events have complex feedback loops and result in high forcing. Further research may be needed to improve the understanding of these linkages. On the contrary, factors such as landslides have a high-forcing effect, but are also highly influenced by other elements within and outside the system, such as precipitation patterns, geological characteristics of the soil, stabilization and prevention mechanisms in place. Factors, such as traffic volume, which have a high dependence on all other factors, are very important for Konkan Railway.

	Dependent variables → Forcing Variables ↓	Environmental Variables							Project Components		
		Temperature	Rainfall	Sea level rise	Extreme events	Water logging	Vegetation growth	Land slide	Safety/Efficiency	Maintenance	Traffic volume
Environmental Variables	Temperature		L	M	L	--	L	--	--	--	L
	Rainfall	L		--	M	M	M	H	L	L	M
	Sea level rise	--	--		--	M	L	M	L	--	L
	Extreme events	--	L	--		M	--	M	L	--	M
	Water logging	--	--	--	--		--	L	L	--	M
	Vegetation growth	L	L	--	--	--		L	--	L	--
	Land slide	--	--	--	--	M	L		M	L	H
Project Components	Safety/Efficiency	--	--	--	--	L	--	L		M	M
	Maintenance	--	--	--	--	M	L	H	H		M
	Traffic volume	--	--	--	--	--	--	--	L	M	

Table 3.14: Causal matrix for impact analysis for Konkan Railway

From the matrix it is clear that the most relevant factor for measurement of potential impacts is rainfall, which has a strong negative influence, and preventive maintenance, which is a strong positive influence. Rainfall is highly influenced by external factors and cannot be forced by the factors internal to the system, whereas preventive maintenance is internal to the system and can help in minimizing the extent of impacts.

After identifying the forcing variables, the next step is to explore critical thresholds to determine when the risk of a climate change impact becomes ‘dangerous’. These thresholds are case and climate change scenario-specific. These indicate decision points where additional preventive measures become imperative. For the Konkan Railway case, rainfall has been identified as the main forcing variable. Based on the studies carried out in the past, the rainfall threshold for landslides in the Konkan region has been identified as more than 200 mm precipitation in 24 hours. However, rainfall alone is not sufficient for causing landslides, which can be influenced by many other factors such as geology, soil structure, vegetation cover and slope.

Every year during the monsoon, train operations are disrupted due to water logging and landslides. There are numerous instances of trains running late due to preventive speed restrictions and disruptions during the rainy season every year. An analysis of the past data indicates that on an average, the operations are suspended for about a week during the monsoons because of such problems along the track. One of the major traffic suspensions was for 14 continuous days between 11-25 July 2000, due to landslides at 36 locations caused by more than 300 mm rainfall on a single day. The expected losses were estimated to be about Rs 100 million (US$ 2.2 million). There were a total of 140 reported incidences of landslides during the entire monsoon season in 2000.

Konkan Railway authorities annually identify vulnerable locations where preventive maintenance is carried out before the onset of monsoon, to deal with any such calamity. Based on experiences over the years, the number of identified vulnerable locations has varied between 60 and 120 every year. In the year 2002-2003 more than 200 vulnerable spots have been identified. Several preventive adaptation activities[5] have been undertaken at these vulnerable locations to minimize adverse impacts. The purpose is to reduce the number of such locations gradually and stabilize the track over the years for trouble-free train operations.

Climate change Impacts on Energy

The energy sector is highly dependent on temperature conditions and this is probably, where climate change could have very strong direct impacts. The regional temperature would change significantly, thus affecting the future energy consumption behaviour. In the residential and building sector, a major energy demand is expected to be for space cooling and heating. Air-conditioning and refrigeration load is closely related to the ambient air temperature and will thus have a direct relation to temperature increase. Temperature increase in the northern mountainous region, where space heating in winter is required, might result in some saving in heating energy. This will be more than compensated by increased energy requirement for space cooling in the plains, thus resulting in a net increase.

Higher income levels will further increase demands for air-conditioning. There are many energy sources for space heating, including coal, biomass and electricity. However, the main source of energy for cooling is electricity. A higher demand for air-conditioning will thus result in an increased electricity demand. Similar to the residential sector, the commercial and industrial sector will also experience an increased load for air-conditioning and refrigeration due to temperature rise.

Many sectors affected by climate change will have indirect impacts on the energy sector. A major sector that causes indirect impact on energy is agriculture. Agriculture is very sensitive to any type of climate changes. Climate change in India will result in temperature rise and a changing precipitation pattern. The evaporation rate is also expected to rise because

[5] These include regular monitoring during rainy season, temporary speed restrictions on the trains, nylon-net erection and retaining wall construction to trap sliding boulders, removing precariously placed boulders on cutting-tops in anticipation, appropriate drainage construction and maintenance, further easing out and consolidation of the cutting-slopes, paving and sowing of grass on the cutting-slopes.

of the temperature increase. This may be countered by increase in rainfall and humidity in some regions. All these put together will affect the water requirement for agriculture which will be greater, resulting in a higher demand of energy for irrigation. The residential water demand is also expected to increase, which would in turn affect the energy required for the water supply system.

Additional electricity generation due to climate change, over and above the electricity generation in 2100, is estimated to be 64 TWh, which is 1.5 per cent of the reference scenario generation for the same year. The domination of coal-based generation continues due to the reliance on domestic resources for energy supply and a major share of this added generation requirement is taken up by the coal-based generation. The economic linkages with coal are also very strong due to the large infrastructure associated with the mining industry, coal transportation network, generation equipment manufacturers, etc., and coal remains competitive in the long run.

As renewable technologies including hydro, wind, cogeneration, other biomass technologies, solar and geothermal, are expected to reach plateau by this time, fuel-mix changes in the energy sector would largely depend on development of nuclear power and new sources of energy such as fuel cells, fusion etc. over a period of time.

Risk and Insurance

The insurance sector has participated in covering the risks of the large-scale infrastructure projects against future uncertainties. Climate change increases risks for the insurance sector, but the effect on profitability is not likely to be severe, because insurance companies are capable of shifting changed risks to the insured, provided that they are 'properly and timely informed' on the consequences of climate change. For example, in the event of a catastrophic event, the insurance sector reacts to increased risk and large losses by restricting coverage and raising premiums. It has been shown by various authors that the increased climatic variability necessitates higher insurance premiums to account for the higher probability of damages.

Despite the costs, there has been a great deal of excitement about the potential of insurance and other forms of risk transfer for hedging the risks of extreme weather-related and other disasters facing developing countries. Governments carry a large and highly dependent portfolio of infrastructure assets, some of which are critical for restoring economic growth, and for the same reason, as firms, they may wish to reduce the variance of their disaster losses by diversifying with insurance and other risk-transfer instruments.

Lacking more attractive financing alternatives, the government benefits from risk transfer, since it reduces the variability of its disaster losses, but risk transfer requires resources that could otherwise be invested in the economy. In terms of economic growth, there is thus an inherent trade-off: a reduction in funds spent on current growth permits a government to protect itself against extreme future losses.

Conclusions

There is a need for building awareness about the potential impacts among the concerned people, and developing good quality databases. Systematic efforts are required to study the impact assessments of different climatic parameters. Studies about future projections of changing regional climate provide insights for methodological developments, including models for integrated assessment and GIS-based computer algorithms for supporting policy assessments at regional levels.

The climate change impact analysis on energy infrastructure indicates that a rise in average temperature increases the need for space cooling for buildings and transport sectors. The variability in precipitation can also impact the irrigation needs and consequent demand for energy. These would increase electricity demand, and consequently result in the need for higher power capacity. The demand for air-conditioned transport and their increased use may result in lower fuel efficiency, increasing petroleum product consumption. The increased energy demand will result in higher emissions. The assessment for India suggests an increase of around one per cent annually, which though not substantial, is still significant for examining the reverse links and feedback with climate change.

The infrastructure sector is a vital sector, where huge investments are being committed in developing countries. The sector creates long-life and open-to-weather assets that will face increasing impacts from the changing climate. It would be prudent for developing country policy-makers to pay attention to protecting these assets, which may otherwise cause significant welfare losses to future generations. Myriad adaptation strategies are needed. These would include the incorporation of future climate extremes in the project design parameters in the immediate term; improved operational and maintenance practices in the near term; and improved climate predictions and creation of insurance markets in the long term.