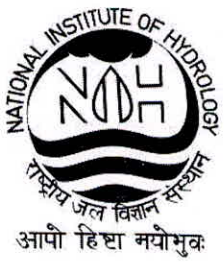
CLIMATE CHANGE AND ITS IMPACTS ON WATER RESOURCES WITH FOCUS ON INDIA



National Institute of Hydrology
(Ministry of Jal Shakti)
Roorke-247667, India
July 2019

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CLIMATE CHANGE AND ITS IMPACTS ON WATER RESOURCES WITH FOCUS ON INDIA

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3	Climate Change and Temperature	P. K. Singh
4	Climate Change and Precipitation	Manohar Arora and Sunil Gurrapu
5	Impact of Climate Change on Evaporation and Evapotranspiration	Suhas D. Khobragade
6	Impact of Climate Change on Himalayan Cryosphere	Sanjay K. Jain and Vishal Singh
7	Climate Change and Riverflow	Swapnali Barman and M.K. Goel
8	Climate Change and Groundwater	C P Kumar, Anupma Sharma, K. V. Sruthi, B. K. Purandara, and S. Kumar
9	Impact of Climate Change on Water Quality	Rajesh Singh and Sumant Kumar
10	Impact of Climate Change on Floods	Rakesh Kumar, P.C. Nayak, J.P. Patra, and Pankaj Mani
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PREFACE

Based on analysis of data and a large number of studies, there is a near unanimity among scientists that the climate of earth is rapidly changing due to anthropogenic activities. Projections show that impact of this change is going to be significant and adverse at many places. These changes will alter the temporal and spatial pattern of rainfall with consequences for runoff, surface and ground water storage, water quality and destructive potential. Therefore, it would be necessary to initiate actions in time so that the adverse impacts are mitigated and the damage to the infrastructure and population is minimized.

Among the countries of the world, India is highly vulnerable to the adverse impacts of climate change due to a number of reasons. Himalayas are the largest storehouse of snow and glaciers outside Polar Regions and are the source of three major Indian Rivers, namely, Indus, Ganga and Brahmaputra. More than 60 crore people of India depend on waters of these rivers and their tributaries. Hydrological response of Himalayan rivers is likely to be significantly impacted due to climate, land use and other changes. India also has 7500 km long coastline and about 171 million people are residing in the coastal zones. Besides, many key infrastructure projects including sea-ports are located in the coastal districts. All these are also likely to be impacted by changes induced by global warming and climate. In addition, climate change will likely to have adverse impacts on other areas in the country especially the areas having frequent floods and drought.

The main objective behind the present report is to compile the likely impacts of climate change on various processes and components of hydrological cycle. Its focus is on the impacts of climate change on water resources in India. After introducing the subject, the topic of downscaling has been discussed which is an essential feature of impact assessment studies in water sector. This is followed by individual chapters to discuss impacts of climate change on temperature, precipitation, evapotranspiration, snow and glaciers, river flows and ground water. As a result of global warming, quality of water in rivers and aquifers is also likely to be impacted. Climate change would also impact the occurrence of extreme events as floods and droughts as well as soil erosion and transport. These aspects have also been dealt in separate chapters. Since the focus here is on future events, uncertainties naturally come into picture. A chapter describes the uncertainty that are expected and how to handle them. In the end, suggestions for adaptation and research in the water sector have been given.

It is hoped that the report would be useful for academicians, planners and decisions makers in the water sector in India and elsewhere. A number of NIH scientists have contributed to the various chapters of the report. I compliment the NIH team for bringing out a useful and timely report. I also thank the reviewers for their useful suggestions which helped in improving the report.

Roorkee, July 16, 2019

(Sharad K Jain)
Director, NIH

CHAPTER 1

CLIMATE CHANGE: AN OVERVIEW

Vishal Singh and A. K. Lohani

1.0 Weather & Climate: A Brief Understanding about the Climatic Phenomenon

Weather can be defined by the specific event or condition or situation that happened or may happen over a period of hours or days. Weather can change from hour to hour, day to day, and season to season. Climate refers to the average weather conditions in a given place or region over many years. For example, climate of Rajasthan is usually hot and dry in summer and cold during the winters, while the eastern Himalayas have a wet and cold climate. Some typical features of the weather are humidity, atmospheric pressure, wind, temperature, precipitation, and cloudiness. The World's average climate is usually referred to global climate. The basic difference between weather and climate is that weather reflects short-term conditions of the atmosphere while climate is the average daily weather for an extended period of time at a certain location. When we talk about issues like climate change, that means we are talking about long term changes in the pattern of the natural climate system around the world. Climate studies showed that the temperature induced changes are mainly responsible to cause global climate change. Rising of the global average temperature of the earth leading to other changes related to short term changes such as weather patterns (e.g. daily and seasonal variations in rainfall intensity and amount) and long-term changes related to climate (e.g. melting glaciers). Climate-associated changes can be estimated by utilizing a minimum of 30 years of time series data (e.g. daily temperature and precipitation). Understanding of climatic indicators is important to assess the climate change because any significant change in climate may directly or indirectly affect people around the world. Increasing global temperature is expected to raise sea levels, and change precipitation and other local climate conditions. Changing regional climate might alter crop yields, forests, and water ecosystems. It could also affect human health, animals and many types of ecosystems.

1.1 Climate Change: Definition

As per IPCC (2007) "*Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer*" (Stocker et al., 2013). As per the UNFCCC (United Nations Framework Convention on Climate Change) climate change is defined as "*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*" (Kagawa et al., 2015).

In a warming world, we are witnessing many adverse impacts of different weather phenomenon on the Earth caused by "Climate Change". The climate change phenomenon refers to long-term alteration of temperature and normal weather patterns in a place over a long period with respect to the growing accumulation of greenhouse gases in the atmosphere. Intergovernmental Panel on Climate Change (IPCC) clearly stated that recent anthropogenic emissions which are causing global warming were maximum in history and had shown widespread impacts on human and natural systems. The concentration of carbon dioxide (CO_2) in the atmosphere recorded as 145%, of pre-industrial period, from about 280 parts per million (ppm) in the pre-industrial period, to 402 ppm in 2016, which in turn

has led to the global warming. The IPCC was formed in the year 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to facilitate an authoritative statement on climate change – its causes, impacts and possible response strategies. Based on the IPCC, the period from 1983 to 2012 was recorded as the warmest period in the last 1400 years in the Northern Hemisphere (Pachauri et al., 2014). Changes in the atmospheric abundance of greenhouse gases and aerosols, in solar radiation and in land surface properties alter the energy balance of the climate system (Kumar et al., 2005).

1.2 Climate Change: Causes

Many climate scientists around the World agree that human induced anthropogenic actions such as the burning of fossil fuels (coal, oil & gases), industrial development and agricultural expansions are mainly leading to climate change. An atmospheric 'greenhouse' - a layer of gasses such as CO_2, methane (CH_4), primarily water vapour, in the lower atmosphere that trap heat from the sun as it's reflected back from the earth, radiating it back and keeping our earth at a temperature capable of supporting life. In the last few decades, anthropogenic human activities have significantly enhanced the greenhouse gases (GHGs) concentrations in the atmosphere and increasing the global average temperature, which is disturbing the natural climate system around the world. The acceleration of anthropogenic activities enhancing the global mean temperature of the planet Earth and causing "global warming". The weather stations have recorded higher levels of water vapor in the air and when it is hot out, it feels even hotter (Couto et al., 2015). When the surface temperature warms (both land and sea surface), it tends to increase more evaporation, and consequently an increase in atmospheric humidity. Water vapour is one of the greenhouse gases which traps heat very rapidly. Therefore, any increase in the humidity will cause additional warming. The cooling in the upper atmosphere and heating or warming of lower atmosphere gives us key insights into the primary causes of climate change.

Several climate change studies reported that land cover/land use (LULC) changes driven by human activities are also influencing Earth's climate (IPCC 2014). Deforestation or cutting of plants and trees is the second leading cause of global warming and produces about 24% of global greenhouse gas emissions. It has been reported by various researchers that the deforestation in tropical rainforests adds more CO_2 into the atmosphere than the fossil fuels consumptions. Deforestation results an increase in CO_2 and which increases the Earth's temperature. Other causes include the variations in the Sun's energy and Earth's rotations. Sun provides the primary source of energy driving the Earth's climate. Changes in the shape of Earth's orbit as well as the tilt and position of Earth's axis can also affect the amount of sunlight reaching Earth's surface. Although, few studies reported that variations in the Sun's energy are responsible for increasing Earth's surface temperature. Further discussions have been made to explore the fundamental causes of climate change in detail.

1.2.1 Increase of Greenhouse Gases Concentration

In the early 1820s, many scientists began to appreciate the importance of the presence of certain gases into the atmosphere in regulating the temperature of the Earth. The 'greenhouse effect' is a natural phenomenon that is essential for keeping the Earth's surface warm. Like a greenhouse window, GHGs allow sunlight to enter and then prevent heat from leaving the atmosphere. Gases, which are regulating and maintaining the Earth's temperature, are called greenhouse gases. The greenhouse gases regulating heat in the lower atmosphere and balance the Earth's temperature. Overall, this terminology is referred to "atmospheric greenhouse gas effect". The GHG effect was proposed by Joseph Fourier in 1824,

discovered in 1860 by John Tyndall, was first investigated quantitatively by Svante Arrhenius in 1896, and was developed in the 1930s through 1960s by Guy Stewart Callendar (IPCC, 2014). The amounts of GHGs which occur naturally have a mean warming effect of about 33 °C (59 °F). Without the Earth's atmosphere, the Earth's average temperature would be well below the freezing temperature of water. The major GHGs, which causes about 36–70% of the greenhouse effect; CO_2 causes 9–26%; CH_4 causes 4–9%; ozone (O3), which causes 3–7% and other atmospheric pollutants such as water vapour and aerosols (<3%). Clouds also affect the radiation balance through cloud forcing similar to GHGs. The greenhouse gases emissions accelerated around 1.3%/year from 1970 to 2000 (around 38 Gt), while in recent decades (from 2000-2010), the rate of change is recorded around 2.2%/y (49 Gt).

The global average atmospheric CO_2 in 2017 was 405.0 ppm, with a range of uncertainty of plus or minus 0.1 ppm. CO_2 levels today are higher than at any point in at least the past 400,000 years. Atmospheric carbon dioxide concentrations in ppm for the past 400,000 years, based on EPICA (ice core) data (IPCC 2014). The peaks and valleys in CO_2 levels track the coming and going of ice ages (low CO_2) and warmer interglacials (higher levels). During these cycles, atmospheric CO_2 was always lesser than 300 ppm; in 2017, it reached 405.0 ppm as shown in Figure 1.1. In reality, the last time the atmospheric CO_2 amounts were this high was more than 3 million years ago, when temperature was 2°–3°C (3.6°–5.4°F) higher than during the pre-industrial era, and sea level was 15–25 meters (50–80 feet) higher than today. Natural increases in CO_2 concentrations have periodically warmed Earth's temperature during ice age cycles over the past million years or more. The warm episodes (interglacials) began with a small increase in sunlight due to a tiny wobble in Earth's axis of rotation or in the path of its orbit around the Sun.

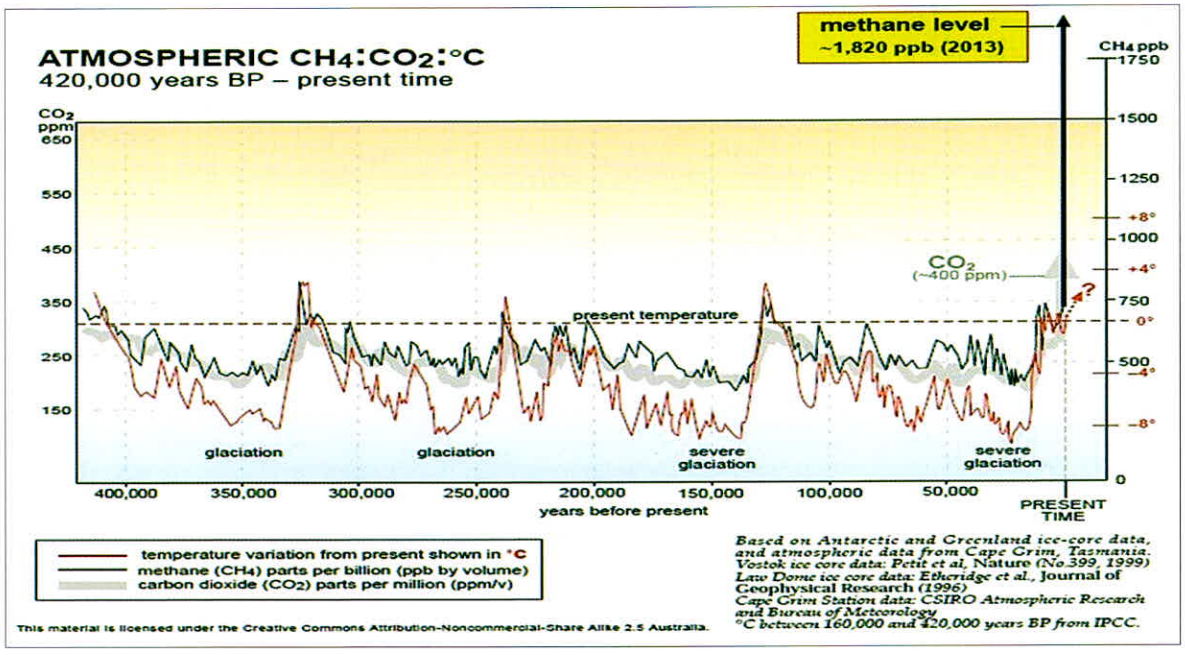


***Figure 1.1**: CO2 concentration since 4,20,000 year BP (Source: IPCC 2014; Etheridge et al., 1999).*

Figure 1.2 shows the trend of GHG emission and global anthropogenic CO_2 emissions during the latest-historical time 1850 to 2011. Figure 1.1 clearly shows that concentration of greenhouse gases has been significantly increased from 1950. Figure 1.1 also showed that the anthropogenic acceleration of CO_2 has been significantly enhanced after the 1950s. The CO_2 concentration was around 260 ppm in

1950 and at present it has been reached up to 400 ppm (Figure 1.1). As per Figure 1.1, it can be seen that total anthropogenic GHG emissions have continued to increase over 1950 to 2010 with larger absolute increases between 1980 and 2010, despite a growing number of climate change mitigation policies (Pachauri et al., 2014). The anthropogenic GHG emissions in 2010 have reached 49 ± 4.5 GtCO2-eq/yr[3]. As per calculations, it was predicted that if human activities increased the CO_2 level in the atmosphere, a warming trend will be obtained. About 78% of the total GHG emissions contributed from CO_2 burning of fossil fuels and industrial processes which increase from 1970 to 2010, with a similar percentage contribution to the increase during the period 2000 to 2010.

As per the IPCC (2014), concentrations of CO_2 and CH_4 have increased by 36% and 148%, respectively, since the 1850s (IPCC 2014). These concentration levels are much higher than at any time during the last 800,000 years, the time period for which consistent data have been generated from ice cores. The burning of fossil fuels has produced about three-quarters of the additional CO_2 from human activity in the last 20 years. A very few direct geological evidences indicate that CO_2 values higher than this were last found around 20 million years ago.

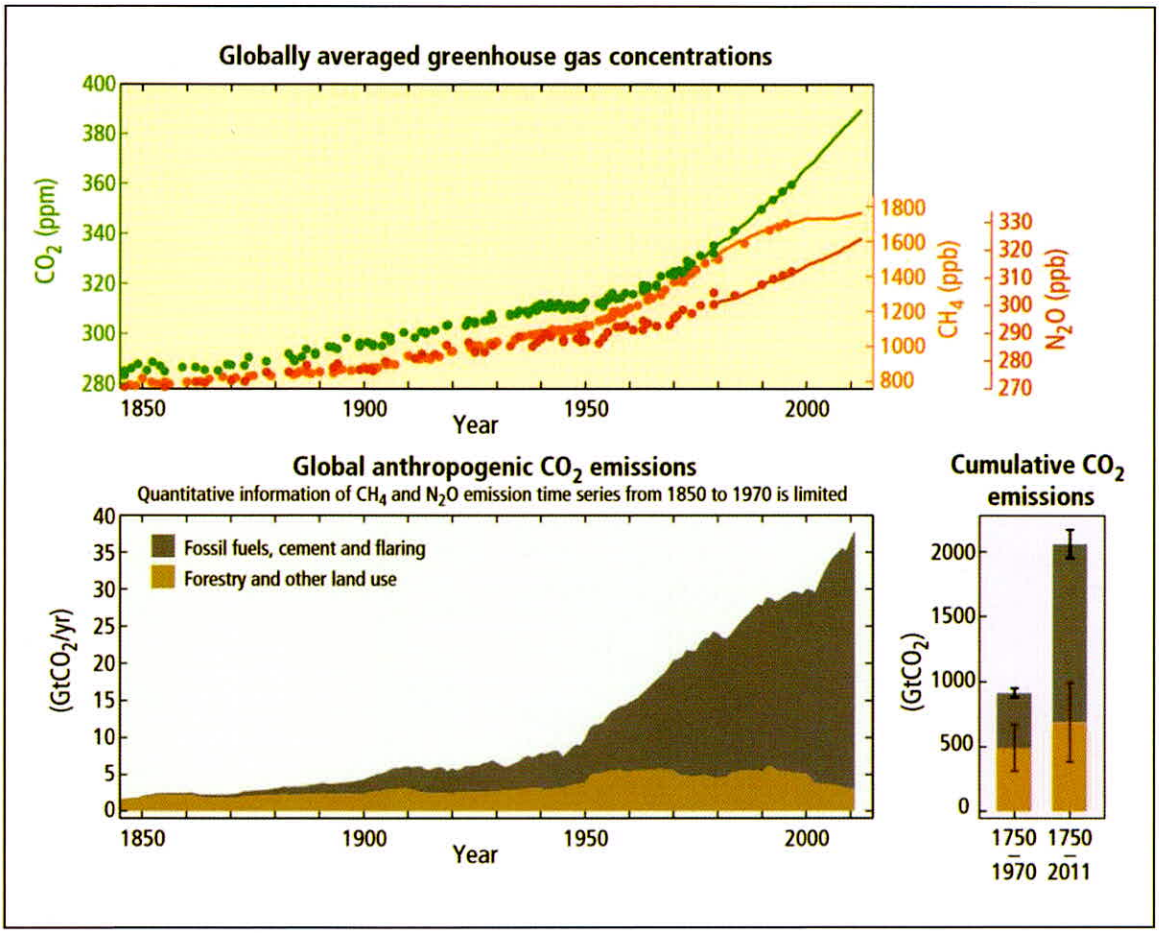


***Figure 1.2**: Total annual anthropogenic GHG emissions scenarios for the period 1850 to 2011 (Source: IPCC, 2014).*

Figure 1.3 shows how average annual global mean concentration of CO_2 is significantly increasing in the 21st century. In Figure 1.3, the CO_2 concentration (ppm) data have been downloaded

from the IPCC CMIP5 climate data web portal. The annual average global mean CO_2 concentration levels have been plotted under the CMIP5 based multiple representative concentration pathway (RCP) experiments. As per the RCP8.5, in the 21st century, the expected CO_2 concentration will be around 900 ppm, while RCP4.5 corresponded with 400-500 ppm showing the actual current level of CO_2 concentration into the atmosphere. In addition to direct measurements of CO_2 concentrations in the atmosphere, scientists have combined detailed records of how much coal, oil, and natural gas is burned each year. They also estimate how much CO_2 is being absorbed, on average, by the oceans and the land surface. However, CO_2 emissions are not going to stop and the level of change depends on the amount of greenhouse gases (Pachauri et al., 2014).

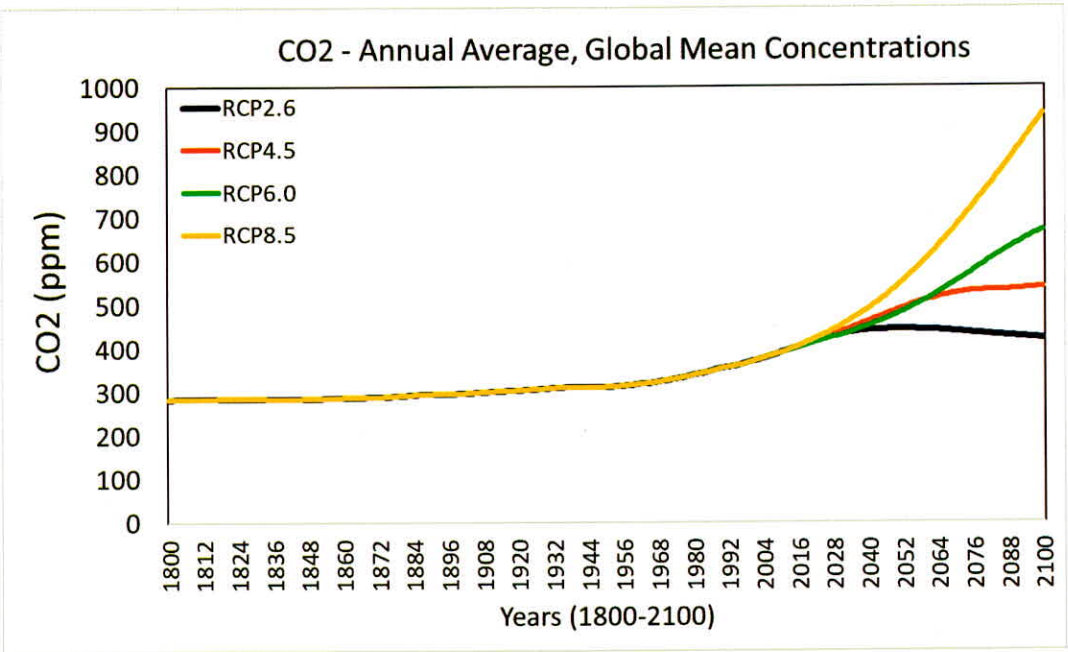


Figure 1.3: *Average annual global mean concentration of CO_2 is increasing from 1800 to 2100.*

1.2.2 Global Warming: The Rising of Earth's Temperature

As per the IPCC AR5 (2014), scientists were more than 95% certain that global warming has generally been caused by increasing concentrations of greenhouse gases and anthropogenic activities (IPCC 2014). Terms such as 'global warming' has been used for the observed century-scale rise in the average temperature of the Earth's climate system and its related effects (IPCC 2014). Global warming is mainly caused by the greenhouse gas effect. Usually, heat from the sun warms the Earth and then escapes back into space. But CO_2 and other GHGs in the atmosphere trap the sun's heat, and this is slowly making the Earth warmer. Global warming mainly occurs when the GHGs and other air pollutants like aerosols collect in the atmosphere and absorb sunlight and solar radiation that have bounced off the Earth's surface. CO_2 gas is recognized as one the most significant GHGs. The concentration of CO_2 gas is usually higher than any other gas and therefore, this gas is the major contributor to the warming of the Earth and its atmosphere. Other GHGs are CH_4, nitrous oxide, fluorinated gases - hydrofluorocarbons, perfluorocarbons, etc. are equally responsible for the global warming.

The effect of these gases on climate change depends on the amount of gas and their global warming potential (GWP). The GWP is computed to reflect how long a gas particle remains in the

atmosphere, on average, and how strongly it absorbs energy (IPCC 2014). It is observed that gases with a higher GWP absorb more heat and thus contribute more to warming Earth. Many anthropogenic activities such as the burning of fossil fuels like coal and oil, industrial development and agricultural expansions have significantly increased the concentration of atmospheric CO_2 and other gases. Cutting of forests for cultivation has also significantly increased concentrations of greenhouse gases. The share of changes in land use patterns in the total emissions is in the range of 5-10% of the total emissions.

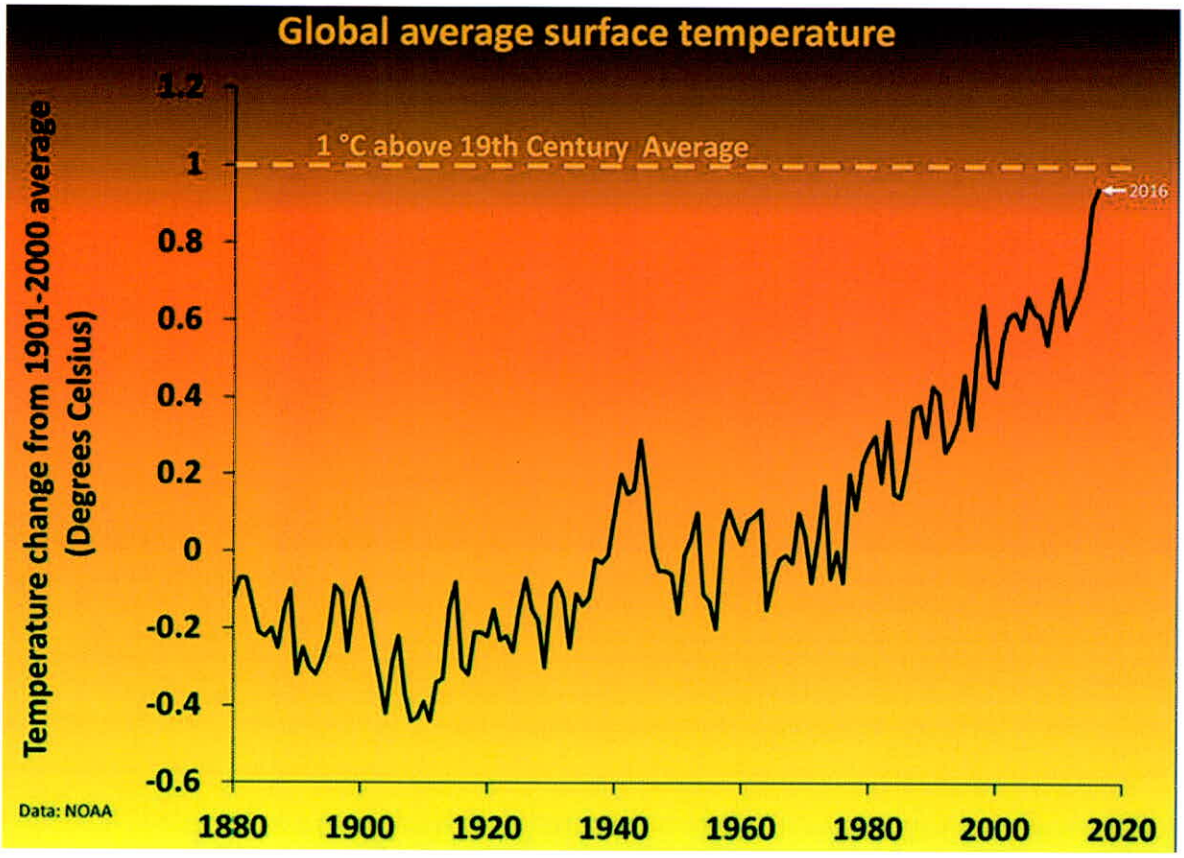


Figure 1.4: *Global average temperature change from 1880-2016 based on NOAA temperature data. (Source: NOAA 2016)*

Due to global warming, the global mean surface temperature has been changed from 1880 to 2015, relative to the 1951–1980 mean. The global climate system is warming; however, an increase of near-surface atmospheric temperature due to accelerated global warming often reported in many scientific studies (Kagawa et al., 2015; Stocker et al., 2013). Scientific evidences reported that Earth's surface temperatures rose by about 0.6°C to 1.2°C up the mid-21st century. The IPCC AR5 (2014) based forecasts or predictions showed that the average global surface temperature will continue to rise and might potentially reach around 6.4°C above 1990 levels by 2100 if instant action is not taken.

IPCC AR5 (2014) indicated that during the 21st century the global surface temperature is likely to rise a further 0.3 to 1.7 °C (e.g. RCP2.6 scenarios) and 2.6 to 4.8 °C for their highest (under RCP8.5 scenarios). These findings have been standardized by the National Science Academies (NSAs) of the major industrialized nations and are not disputed by any scientific body of national or international standing. In Figure 1.4, one can clearly see how the global average temperature has risen from the year 1880 to 2016. Anomalies of mean temperature from the CMIP5 multi-model GCMs with their RCP

scenarios also showed a significant increase in temperature from 1850 to 2300 (Figures 1.5). Figure 1.5 shows the temperature increments in India under the effect of low to high emission scenarios.

The RCP2.6 shows around 1°C change (or increase in temperature) and other RCPs such as RCP4.5, RCP6.0 and RCP8.5 show around 2°C, 3°C and 4-5°C change, respectively (Figure 1.5). Temperature trends plotted for the world and India (Figures 1.4 and 1.5) clearly show that the global warming is taking place while all RCP trends show a significant increase in temperature anomaly since 1950.

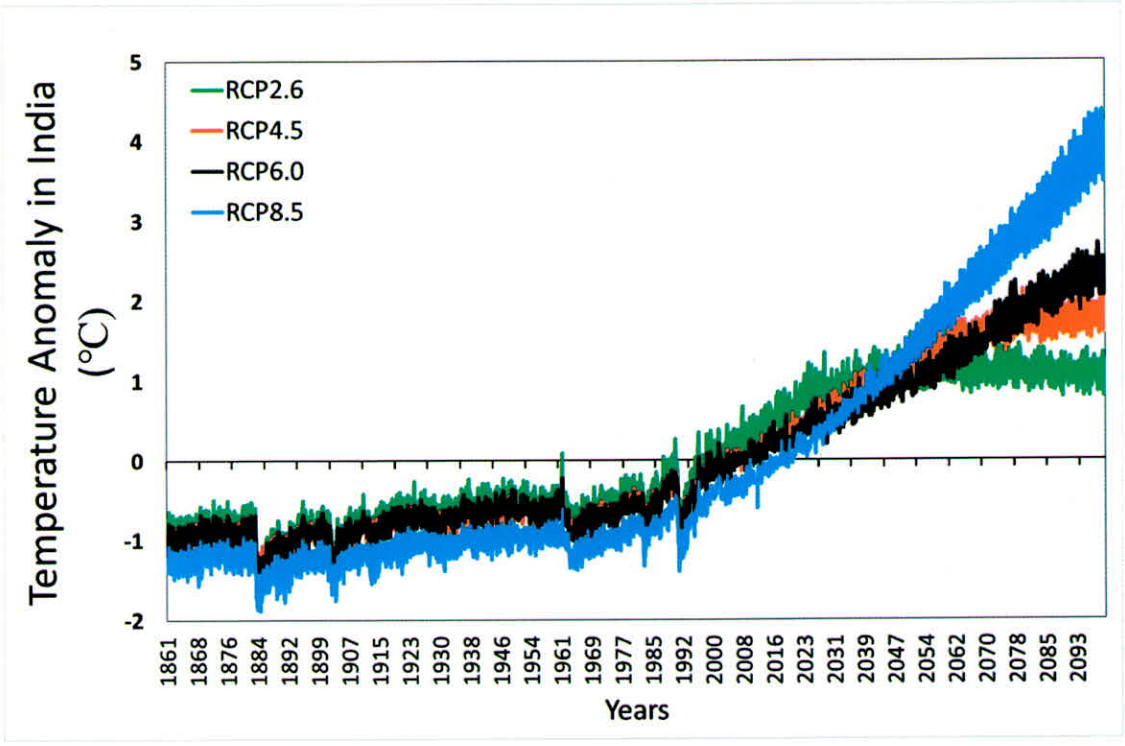


Figure 1.5: *Anomalies of mean temperature from CMIP5 multi-model RCP scenarios [low (RCP2.6) to High emission scenarios (RCP8.5)].*

Temperature trends (Figures 1.4 and 1.5) have shown significant similarities between greenhouse gas emission scenario and CO_2 concentration scenario (Figures 1.2 and 1.3). In both cases, the change year is detected as 1950. Every one of the past 40 years has been warmer than the 20th century average. Based on IPCC data center, the year 2018 was recorded the hottest year. The twelve (12) warmest years on record have all occurred since 1998.

1.2.3 Rising of Sea Surface Temperature

Global warming has shown significant impact on ocean surface temperature (Stocker et al., 2013). Recent climate studies revealed that the amount of heat absorbed by the oceans has increased significantly in the last two decades (Figure 1.6). The warm ocean water may damage marine ecosystems and disrupts global fisheries. A change in ocean heat content may also alter patterns of ocean circulation, which can have far-reaching effects on global climate conditions, including changes to the outcome and pattern of meteorological events such as tropical storms. The temperatures in the northern Atlantic region may be affected which are strongly influenced by currents that may be substantially reduced with CO_2 increase in the atmosphere (McCarthy et al., 2015). The surface of the ocean is getting warmer. The presence of

warmer air near the ocean surface is leading to increase in evaporation and adding more water vapor content in the air. The increased amount of water vapor not only contributing to extra warming, but may feed heavy precipitation events and act as fuel for potential hurricanes (McCarthy et al., 2015).

1.3 Climate Change: Impact & Assessment

In the last few decades, the adverse impacts of climate change caused by anthropogenic greenhouse gas emissions affected both natural and human systems on all continents and across the oceans. Because of the effect of climate change, many marine, freshwater and terrestrial species have been shifted geographically (Pachauri et al., 2014). The globally averaged land and ocean surface temperature data analyzed by a linear trend analysis showed a warming rise of 0.85 (0.65 to 1.06) °C, over the period 1880 to 2012 (Mishra et al., 2015).

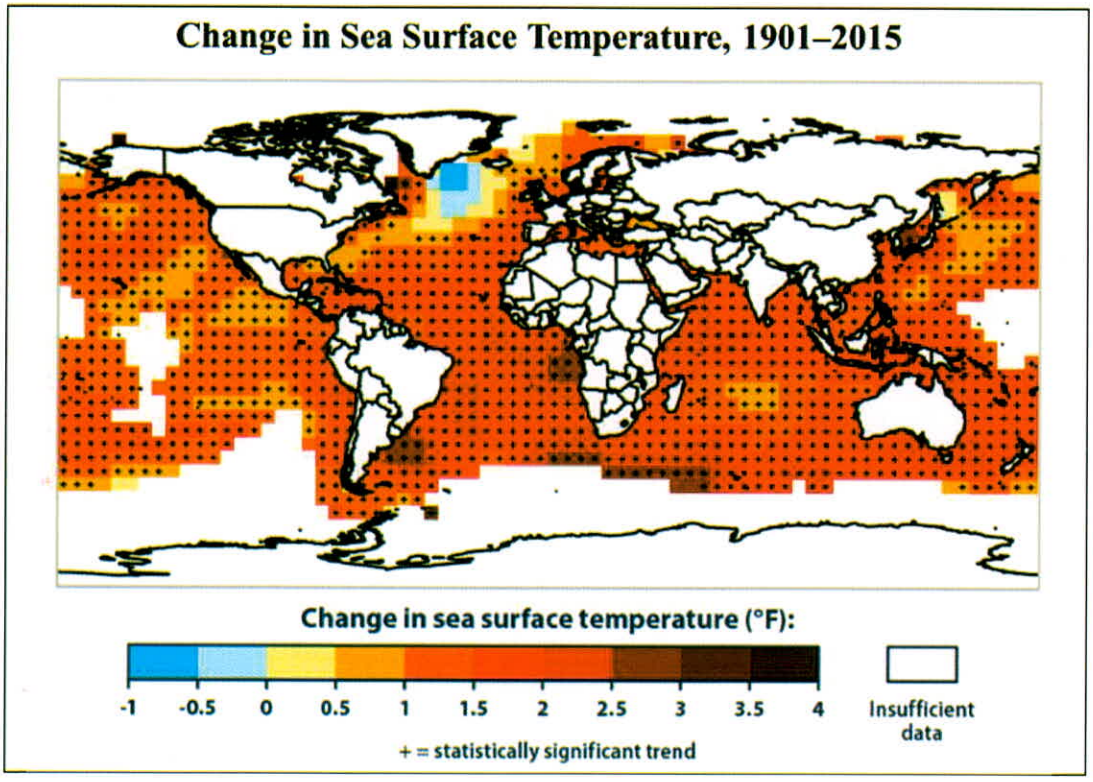


Figure 1.6: *Change in Sea Surface Temperature (SST) during 1901 to 2015 (Source: www.epa.gov).*

In another study done by Stocker et al. (2013), it has been observed that the total increase in temperature between the average of the 1850-1900 period and the average of the 2003-2012 period is calculated as 0.78 (0.72 to 0.85) °C. Many studies have been focused on the change in mean climate and addressed the impact of climate change in terms of increasing global annual average air temperature (Stocker et al., 2013; Vaughan et al., 2013). There is a continuous increase observed in the radiative forcing (RF) due to the continuous growth in GHG concentrations, indicating a frailer net cooling effect (Vieli, 2015; Stocker et al., 2013). The atmospheric RF is recorded around 43% higher than the records from 2005 (IPCC, 2007). The combined effect of alterations between atmospheric and surface warming, and fluctuations in water vapour, is exceptionally likely positive and thus intensifies changes in climate have been observed (Change I.C., 2013; Stocker et al., 2013; Vaughan et al., 2013). For an example; since last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover

have continued to decrease in extent (Vieli, 2015; Bolch et al., 2012). Climate change studies performed in Himalayas also showed that the Himalayan glaciers are retreating faster in the present time than before the 1950s and the rate of melting snow is also increasing (Azmat et al., 2017).

Changes in the severity of extreme events and climatic variabilities related to weather and climate patterns will have significant impacts on the natural as well as human systems. In the recent time, climate extremes, warming air temperature, droughts, floods, cyclones, and Glacial Lake Outburst Flood (GLOF) have revealed significant vulnerabilities and exposures on several ecosystems and many human systems (Azmat et al., 2017; Shrestha et al., 2012). Evidences of climate change impacts are strongest and most comprehensive for water resource systems (Mishra et al., 2015; Shrestha et al., 2012). At the present time, significant evidences of global climate change have been discussed by the IPCC (Palazzi et al., 2014; Change, 2013). Scientists notified that the severity of extreme precipitation events will increase in the 21st century (Azmat et al., 2017; Singh and Goyal, 2016). The extreme events related to weather and climate such as droughts and floods are increasing (Pachauri et al., 2014, Stocker et al., 2013; Vaughan et al., 2013).

Cloudburst and flash floods are treated as the most damage causing disasters in the world (Rao et al., 2014), and they can be more frequent in the 21st century, especially over the western and eastern Himalayas (Pramanik et al., 2010). In the last two decades, several extreme events have been observed in the Himalayas. A major challenge has been associated with extreme events such as the quantitative character of the forecast. Thus, the proper forecasting and accurate prediction of extreme events can be done by the advancement of the basic simulation methods (Rao et al., 2014).

A foremost challenge in observing human vulnerability as the result of manifold and dynamic factors is the need to take an artificial approach to understand the sectoral impacts of changes in climate and climate variability into consequences for people. The vulnerability and severity of climate change in living beings are highly distinguished across geography in terms of food security and other necessities (Stocker et al., 2013; Vaughan et al., 2013).

1.4 IPCC Reports and Evolution of GCMs

The formation of the IPCC was recommended by the United Nations General Assembly in 1988. Its initial task was to prepare a comprehensive review and recommendations with respect to the state of knowledge of the science of climate change; the social and economic impact of climate change, and potential response strategies and elements for inclusion in a possible future international convention on climate. Since 1988, the IPCC has completed five assessment cycles and delivered five assessment reports (ARs). The most comprehensive scientific reports about climate change produced worldwide. The IPCC report provides a comprehensive assessment of climate change issues, their impacts and response strategies through the evaluation of scientific approaches (Figure 1.7). In 1990, the First IPCC AR (FAR) was introduced that underlined the importance of climate change as a challenge with global consequences and to analyze the scientific understandings and related uncertainties. The Second AR (SAR) (1995) provided important material for governments to draw from in the run-up to the adoption of the Kyoto Protocol in 1997.

The Third AR (TAR) (2001) highlighted the impacts of climate change and the need for adaptation. The Fourth AR (AR4) (2007) laid the groundwork for a post-Kyoto agreement, concentrating on limiting warming to 2°C. The IPCC AR5 came in 2014 which provides the literature on the scientific, technological, economic and social aspects of mitigation of climate change (Change, 2014). It was found

that freshwater related risks of climate change increase significantly with increasing greenhouse gas concentration in the atmosphere (Field, 2014).

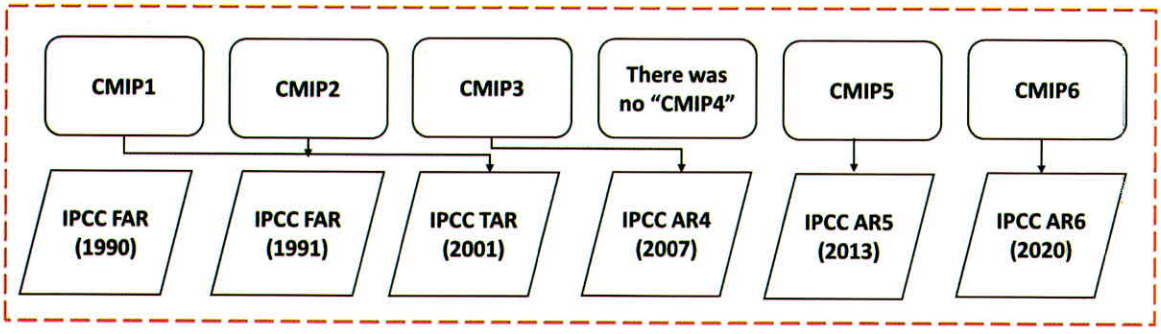


***Figure 1.7**: Progress of the IPCC Scenarios.*

A number of GCMs have been developed since IPCC AR3 to enhance the hydro-climatologic projections at larger and smaller scales to analyze the real impact of climate change on the earth's environment. GCMs have generated under different IPCC assessments, are the primary source to investigate the global and regional changes which are caused due to climate change. The evolution of GCMs in different time periods has been shown in Figure 1.8. The CMIP5 and CMIP6 (presently under the development) build after the accomplishments of earlier phases of CMIPs (Taylor et al., 2012; Meehl et al., 2005). The CMIP5 models include two types of experiment, (1) long term and (2) near-term scenarios (10-30 years). Both experiments are coupled with ocean-atmosphere GCMs (Taylor et al., 2012; Meehl et al., 2009). The GCMs accuracy reduces with the finer spatial scales (Singh and Goyal, 2016). The precision of the projected scenarios reduces when the scale of assessment is fine, because GCMs are typically available at 2° to 4° resolution, which may be consisted different kind of uncertainty and therefore, several times they are found highly erroneous. The construction of GCMs under various developmental stages has shown in Figure 1.8.

The CMIP5 GCM scenarios of climate change are determined by emission scenarios reliable with the RCP experiments, which explores an estimate of the radiative forcing of 21st century. (Taylor et al., 2012; Moss et al., 2010). The CMIP5 GCMs are considered as more accurate climate models than earlier versions (Taylor et al., 2012). There are four emission scenarios based on radiative forcing (RF) such as RCP2.6. RCP4.5, RCP6.0 and RCP8.5. The RCP8.5 experiment represents the extreme emission scenario with higher level RF and likewise, RCP2.6, RCP4.5 and RCP6.0 corresponded with low, moderate and high emission scenarios. RF is defined as the change in the net, downward minus upward, radiative flux (expressed in Watts per square metre; Wm^{-2}) at top of the atmosphere due to a change in an external driver of climate change such as change in the concentration of CO_2 gas (Taylor et al., 2012). For RCP2.6, the RF peaks at approximately 3 Wm^{-2} before 2100 and then declines. Similarly, for RCP4.5, RCP6.0 and RCP8.5, the RF is stabilised at approximately 4.5 Wm^{-2}, 6.0 Wm^{-2} and 8.5 Wm^{-2} and it will continue till 2100, approximately (Taylor et al., 2012).

The Earth System Models (ESMs) have been developed based on the atmospheric component comprises physical parameters such as cloud physics, aerosols, and precipitation. ESMs represent terrestrial and topographical factors such as precipitation, evaporation, streams, lakes, and streamflows to simulate dynamic reservoirs of carbon and other tracers (Arora et al., 2013; Dunn and Son et al., 2013). In order to generate climate projections at a defined scale that decision makers desire, a process termed "downscaling" has been evolved. Many downscaling techniques have been developed and can be applied

to improve the scaling and resolution of coarser GCMs (Singh and Goyal, 2016; Mishra et al., 2014; Ghosh and Mujumdar, 2008). Downscaling of GCMs may consist of a variety of methods such as statistical and dynamic downscaling, each with their own merits and limitations.

Therefore, the main focus should be to explore the applicability and capabilities of different downscaling approaches in the simulation, projections and forecasting of coupled hydro-climatic system. Several studies addressed the scope of different downscaling approaches as per the characteristics of climate model dataset such as the resolution of the data, time series availability and the physical relevance (Singh and Goyal, 2016; Ghosh and Mujumdar, 2008). Recently, dynamic downscaled regional climate models (RCMs) have been produced at a finer scale (~10-50^{0}), which can be applied for regional/local scale climate evaluations.

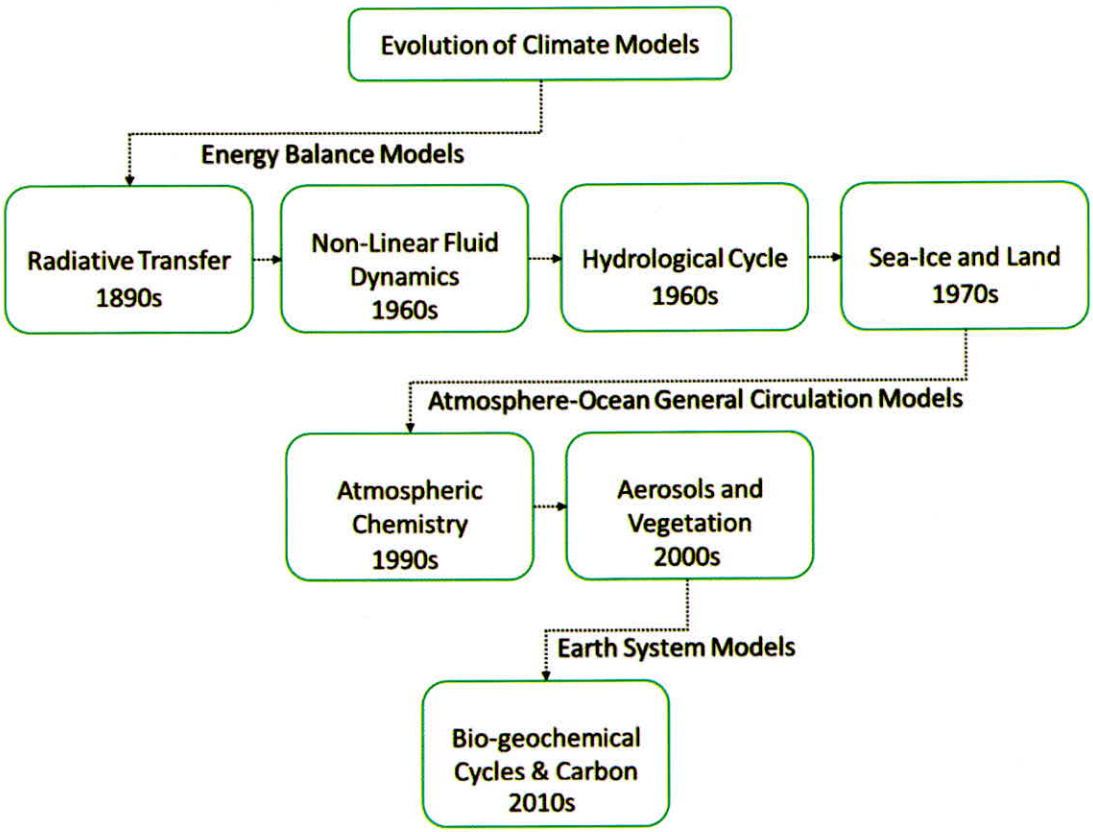


Figure 1.8: *Evolution of GCMs in different decades.*

1.5 Climate Change: Impact on Hydrological Processes

In this section, the impact of climate change on hydrological processes has been discussed in brief. The detail has been provided in the coming chapters. The frequency and intensity of meteorological factors will be enhanced in 21st century (IPCC 2014). Several studies reported that droughts will be more severe in lower rainfall regions (Wong et al., 2014) and the intensity and amount of the precipitation, the extreme event will be enhanced in higher rainfall regions around the world (IPCC 2014). The negatively altered climate change will affect the freshwater ecosystems through changing streamflows. Climate change will impact the vegetation density and species diversity which influence the water use and rate of

evapotranspiration (ET). Thus, the effective land use strategies and management practices will be helpful to mitigate the adverse impact of climate on water resources (Arnell and Hughes, 2013; Arnell, 1999).

Changes in the hydrological cycle, which are associated with the negative impacts of climate, will lead to diverse impacts and risks. Temperature and precipitation variability will enhance in the 21st century (Whitehead et al., 2015; IPCC 2014). The negative consequences of climate change such as warmer water, more intense precipitation and longer periods of low flow in the rainfall-dependent catchment could be greater during 21st century (IPCC 2014). Climate change can certainly alter the probability of a specific extreme event such as floods. The probability of such an event can be estimated by analyzing the magnitude and fraction of events (Whitehead et al., 2015; Field, 2012; Jones et al., 2007). Potential ET and precipitation events are considered as the main climate drivers that control the watershed hydrology on any region (IPCC 2014). Several observations on water resources have been projected under the CMIP5 simulations which are given below (Whitehead et al., 2015; IPCC 2014):

- Surface temperature is increasing due to accelerated global warming, thus, the vapor carrying capacity of the atmosphere is affecting; and the variability and the ratio of precipitation to snowfall and precipitation to rainfall are increasing non-uniformly (Figures 1.4 and 1.5).
- In high mountains like the Himalayas, the warming over high elevation areas is affecting the snowmelt and glacier mass budgets.
- The critical range of temperature responsible for Precipitation-to-Rain and Precipitation-to-Snow is affected and therefore, the precipitation as snowfall is decreasing and the extent of snow cover is reducing by earlier melting.
- Precipitation intensities and frequencies are changing; wet regions and seasons are becoming wetter and dry regions are becoming drier.
- Global average precipitation has increased in the warmer world and the variability from region to region is also increasing (Figure 1.9).
- Variations in evaporation are recorded similar patterns to precipitation with the increase.

In Figure 1.9, monthly precipitation anomalies averaged over India have been plotted under different RCP experiments. As RCP6.0 and RCP8.5 experiments stand for high to extreme level changes, the precipitation scenarios corresponded with RCP6.0 and RCP8.5 showed maximum variability and increase during 1850-2100 (Figure 1.9). As per the SREX (Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation), the flood frequency and intensity are projected to increase, and the regional changes by the implications of temperature and precipitation will also be increased (Kharin et al., 2013; Seneviratne et al., 2012). In the 21stcentury, the quality of fresh water lakes and availability of clean water will also be affected due to climate change.

Relating to the adverse impacts of climate change on water resources, a long-term planning and conservation-management practices are needed, which are highly uncertain at the present time. Several adaptive procedures that may demonstrate predominantly operative include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees in steeply sloping fields, mini-terracing for soil and moisture conservation, improved pasture management, water reuse, desalination, and more efficient soil and irrigation water management (Seneviratne et al., 2012). These adaptation policies and measurement techniques could be useful for the conservation of water resources under extreme climate condition.

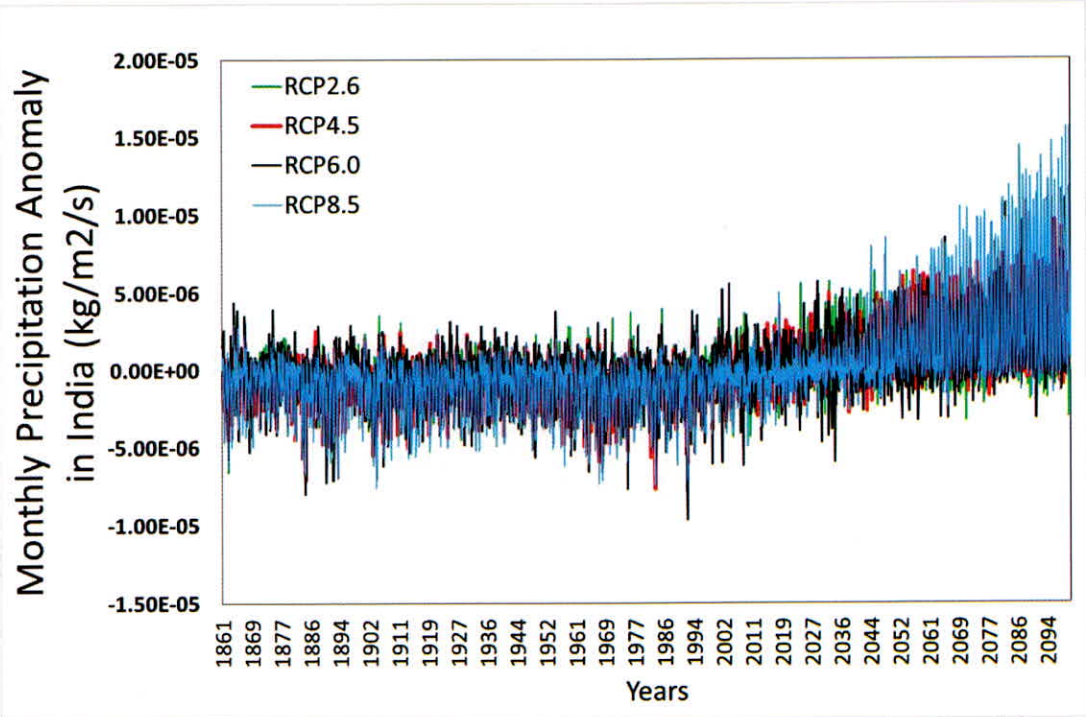


Figure 1.9: *Precipitation anomalies (mean of all CMIP5 GCMs computed under different RCP experiments) showing precipitation changes (1850-2100) in India.*

The severity of climate change on water resources utilizing coarser resolutions GCMs and dynamically downscaled higher resolution RCMs has been addressed around the World (Pushpadas et al., 2015; Vicente-Serrano et al., 2015; Whitehead et al., 2015; Harding et al., 2014; Kharin et al., 2013; Arnell and Hughes, 2014). GCMs are mainly utilized to highlight the large-scale changes and RCMs are generally used to analyze the regional/local scale changes in water resources system. Several studies suggested advanced probability distribution methods for the futuristic assessment of water resources by combining outcomes from multiple climate projection and emission scenarios (Liu et al., 2013; Christierson et al., 2012). The probability-based methods may be useful to account uncertainty involved in the climate projections. Effects of climate change on groundwater and aquifer recharge utilizing GCMs and RCMs have also been evaluated (Hua et al., 2015; Jena et al., 2015; Portmann et al., 2013; Crosbie et al., 2013; Jackson et al., 2011). Studies concluded that groundwater has been significantly affected by the direct/indirect influence of climate change around the World.

1.6 Climate Change & Water Resources of India

In this section, the impact of climate change on the water resources of India has been discussed. The detail aspect has been covered in the next chapters. Indian water resources are grouped into six major water resource regions and further divided into 25 major river basins (India-WRIS). In India, around 55% area of the country belong to Indian Himalayan river basins such as Indus, Ganga and Brahmaputra including their tributaries. Runoffs form the Himalayan watersheds are the combination of rainfall-runoff and snowmelt runoff. Runoffs (or streamflows) of these Himalayan river basins mostly depend on southwest monsoon (June-September) and melting of snow-glaciers (Azmat et al., 2017; Jain et al., 2007). The inland river basins cover around 45% total area of the country and their flows also depend on the Southwest monsoon (Jain et al., 2007). In India, the rainfall patterns show high spatial and temporal variability as demonstrated in many climate change-based studies (Mishra et al., 2018; Singh and Goyal,

2016). The average annual rainfall in India varies from 20 cm (Thar Desert region) to 250 cm (Meghalaya) (Fujinami et al., 2017). The north eastern parts of India belong to the high rainfall regions (e.g. >6000 mm/year) and the Rajasthan state of India characterized by the lowest rainfall region (~250-500 mm/year) (Jain et al., 2007). Due to increasing population, changes in landuse/landcover pattern and incremental trend of urbanization are other causes of the disruption in the watershed hydrology in India (Bolch et al., 2012; Kulkarni et al., 2010). An assessment of the availability of water resources in 21st century and expected impacts of changing climate can be reviewed critically for making the relevant national and regional long-term development strategies in a sustainable manner (Sharma and Goyal, 2018).

1.7 Evidence of Climate Change in India

Several observations related to climate change and its impact of water resources of India have been demonstrated by various researchers through a number of studies performed in different parts of India. India has experienced several vast climate extremes during past few decades. For example, the drought event happened in 2016 in India covered about 10 states and about 330 million people were affected, causing an economic loss of $100 billion (Goyal and Surampalli, 2018; Gosain et al., 2011). Ali and Mishra (2018) demonstrated that climate warming seems to be more pronounced over the northern parts of India resulting an increase in the severity of droughts in dry regions of India and an increase in the intensity of floods in various parts of the country analyzed by multi-model climate datasets. As per Planning Commission (2011), about 13.78% of India's geographical area is subjected to flood disasters and about 33 million people were affected by flooding from 1953 to 2000. In northern India, groundwater reserves decreased at the rate of 2 cm/year, while groundwater storage in southern India increased at the rate of 1 to 2 cm/year between 2002 and 2013 because of changes in pumping and precipitation patterns analyzed using Gravity Recovery Climate Experiment (GRACE) data (Asoka et al. 2017).

Another northern India based study by Singh et al. (2014) showed a declining trend of daily streamflow records in Sutlej River at three discharge gauging stations (e.g. Kasol, Sunni, and Rampur) in 41 years (1970–2010). The Satluj River basin has high potential for hydroelectricity power generation and agricultural practices. As per the study by Masood et al. (2015) over Ganga-Brahmaputra-Meghna (GBM) basins, a long-term mean runoff is projected to increase by 33.1%, 16.2%, and 39.7% in the Ganges, Brahmaputra, and Meghna basins, respectively, by the end of the 21st century. Sharma and Goyal (2018) performed a study over India at a district level to assess the ecohydrological resilience to the hydro-climatic disturbances and concluded that out of 634 districts only 241 (~38%) districts were found resilient to dry conditions. Sinha et al. (2018) analyzed the impact of anthropogenic human interactions and climate variability on rivers basins of India and revealed that only 34.17% anthropogenic dominated watersheds were found to be resilient and 58.82% climate dominated watersheds had resilience attributes.

The weather pattern and monsoon climatology of South Asia and Southeast Asia maximally affect due to climate change (Ali and Mishra, 2018). These changes have observed at both broader (at continental) scale and regional or local scale (Paiva, 2009). However, the precipitation extremity found more severe in South Asia and Southeast Asia regions (Mishra et al., 2018; Guhathakurta et al., 2015). Studies utilizing GCM scenarios and different rainfall datasets showed different patterns of rainfall over Indian continents, therefore it is difficult to predict how rainfall might change within India (Ali and Mishra, 2018). The severity of rainfall on shorter time scales will have the biggest impacts (Sharma and Goyal, 2018). Intense heavy rainfall events lead to flooding in the flood plain areas of high discharge

river basins. Floods and droughts are a normal occurrence in India. CMIP5 multi-model GCM scenarios of rainfall showed that the extremity of high rainfall events will be enhanced in the future (5-10%) (Mishra et al., 2015), which will cause more flooding in the flood plain areas. In previous decades, several high intensity rainfall events have been recorded across the India such as the Kedarnath, Uttarakhand flash floods (2013), Jammu and Kashmir floods (2014), Chennai Flood (2015) and Kerala Flood (2018) (Mishra et al., 2015, Rao et al., 2014). In another study, Sonali and Nagesh (2013) performed the spatial and temporal trend analysis on monthly and seasonal scales utilizing maximum and minimum temperatures by applying various parametric and non-parametric tests to evaluate the precipitation over India and their results showed a significant variability in precipitation, especially in extremes, across the India. Study over Karakoram-Himalaya utilizing CMIP5 GCMs by Palazzi et al. (2014) showed gradual increments in the summer precipitation throughout the 21st century scenarios. Though, proper simulation of seasonal precipitation and its spatial and temporal distribution using GCMs has demonstrated many difficulties.

The Himalayan rivers such as Indus, Ganga and Brahmaputra are perennial river channels. Several inland major river basins such as Godavari, Krishna and Narmada are also perennial in nature. During summer, they maintain their flows from the groundwater and subsurface flows (Jain et al., 2007). As per the geographical area of the river basins, the inland and Himalayan river basins vary their flows from around 1,000 m3/sec (average monthly during monsoon period) to 80,000 m3/sec (average monthly during monsoon period), respectively. In India, at present, changes in agricultural cropping pattern, over-exploitation of groundwater, mismanagement of surface water resources, changing land-use pattern and rapid industrial revolution, including the global consequences of climate change are significantly affecting the hydrological processes of many Himalayan and In-land river basins (Mishra et al., 2018; Roxy et al., 2015; Paiva, 2009). Several consequences of climate change such as water scarcity, glacier retreat, earlier snowmelt, faster snowmelt, less precipitation as snowfall, increasing global mean precipitation, decreasing runoff in rainfall dependent inland based catchments and increasing winter runoff in snow glaciated regions have been noticed in many climate change studies carried out in India (Ali and Mishra, 2008; Mishra et al., 2018; Roxy et al., 2015).

The Indian Himalayan topography is consisted with moderate (1000 meters) to extreme hilly terrains (8000 meters) (Singh et al., 2017) and thus it reflects significant hydro-climatological variations even at smaller scales. The temperature lapse rate and precipitation lapse rate have been found highly variable in Himalayas and their variability will be enhanced in 21st century as projected by CMIP5 GCMs (Singh and Goyal, 2016). Due to steep slopes, the streamflow velocity of Himalayan rivers is generally high during monsoon season. Therefore, occurrences of extreme high precipitation events, which may be possible due to projected climate change, will create severe flash flood conditions also reported in India (Azmat et al., 2017). In Himalayas, many small glaciers and temporary snow packs are receding due to the warming trend of the lower atmosphere, which could be a significant cause of decreasing snow depth and snowpack duration over the snow-glacier induced Himalayan watersheds (Srivastava et al., 2014; Bolch et al., 2012; Rangwala and Miller, 2012). Overall, it has been observed that the water resources of India are at present under the threat of climate change. The availability of surface and groundwater is significantly affected by the impact of global climate warming or climate change.

1.8 Concluding Remarks

In this chapter, the brief description of climate change impacts, their causes and the adverse impacts of climate change have been presented. Climate change is real and it's happening around the world. Many

studies have provided sufficient evidences to that end. Climate change is causing a significant threat to the natural resources and environment of the world. Due to the acceleration of anthropogenic activities, the global average temperature is increasing. The un-natural enhancement in temperature is significantly affecting the natural climate system of the world. The water resources infrastructure is likely to be affected by climate change and this will increase in the future if mitigation measures and policies are not put in place.

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CHAPTER 2

DOWNSCALING OF CLIMATE DATA

Vishal Singh

2.0 Role of Climate Models in Hydrological Studies

Weather conditions can be explained over a certain area in a certain time-span. In a natural hydrological cycle, water continuously interchanges between oceans and atmosphere through multiple processes such as precipitation, evaporation and percolation in various spatial and temporal scales. Climate change is a complex issue involving interactions between ocean, atmosphere, and land (Jiang et al., 2007). However, under the influence of anthropogenic climate change, this continuum is changing due to changes in energy and mass balance of the associated processes (Bhuvandas et al., 2014). The accurate computation of complex hydrological processes has been critical in the present and 21st century due to the acceleration of climate change conditions. At smaller scales, hydro-climatological processes are more dynamic which may further increase uncertainty in the present and 21st century simulations and projections, especially when climate is changing. A comprehensive review of hydrological trends under changing climate conditions is widely available that showed a significant variability in the global hydro-climatology from 1951 to 2100 (Karmalkar, 2018; Sharma et al., 2018; Gupta and Jain, 2018; Mishra et al., 2014). In India, the severity of climate change has been increased and it highlighted in various hydro-climatological studies (Sharma et al., 2018; Gupta and Jain, 2018; Mishra et al., 2014). The use of advanced hydrological models including numerical weather predictors (Sun et al., 2016), numerical methods for hydrological analysis (Tiwari et al., 2014), statistical and artificial intelligence approaches (Goyal and Ojha, 2012) coupled with General Circulation Models (GCMs) and Regional Climate Models (RCMs) provide a great asset in simulating and projecting the long-term hydro-climatological changes (Seiler et al., 2018; Sun et al., 2016; Tiwari et al., 2014; Mishra et al., 2014; Vu et al., 2015); however, they are significantly varied at global, regional and smaller scales.

GCMs are basically numerical coupled models that represent various earth systems, including the oceans, atmosphere, land surface and sea-ice. Therefore, the applicability of GCMs variables in simulating and projecting impacts of climate change depends on various factors, including topography, climatology, weather pattern and geography of the region (Sun et al., 2016). GCMs are considered to be the most comprehensive models for investigating the physical and dynamic processes of the earth's surface-atmosphere system and they provide plausible patterns of global climate change (Andrews et al., 2012). Studies utilizing GCMs conclude that the large-scale assessment of hydro-climatological changes can be done and GCMs have been found able to capture the large-scale changes in various climate scenarios (Karmalkar, 2018; Singh et al., 2017; Andrews et al., 2012). However, the small-scale studies utilizing coarser resolution GCMs are less predictive and erroneous (Karmalkar, 2018). Since 2013, the accuracy of GCMs has been improved (Andrews et al., 2012). The development of the last Couple Model Inter-Comparison Phase Five (CMIP5) based GCMs and Regional Climate Models (RCMs) along with low to extreme high Representative Concentration Pathway (RCP 2.6 to 8.5) scenarios have improved the accuracy of climatic projections and forecasted scenarios (Gupta and Jain, 2018; Seiler et al., 2018; Vu et al., 2016; Sarr et al., 2015). The large scale GCMs are re-gridded at a much finer scale through the dynamic downscaling and the resultant product is called the RCM, which supposed to be enhanced the accuracy of climate projections at the regional as well as smaller scale (Fenta Mekonnen and Disse,

2018). The main purpose was to generate finer resolution RCM, minimizing uncertainties in climate projections (Karmalkar, 2018; Singh et al., 2017). The scope of GCM versus RCMs has been analyzed in numerous climate change studies and it has been seen that RCMs performed superior than GCMs (Gupta and Jain, 2018; Seiler et al., 2018; Karmalkar, 2018; Singh et al., 2017).

A large number of hydrological and hydrodynamic models have been developed and performed in various applications such as flood routing, flood forecasting, water balance analysis, water quality modeling, hydro-climatological projections and extreme event analysis (Singh et al., 2017; Sun et al., 2016; Apurv et al., 2015). In case of projecting long-term hydrological variables, the coarse resolution GCMs cannot be directly coupled to hydrological models, because of the complexities involved in the coarse resolution GCMs and the simplification of the hydrological cycle. However, the downscaled GCM variables can be utilized as inputs to the hydrological and hydrodynamic models. Different downscaling methods have been developed to enhance the applicability of GCMs, which are able to highlight smaller scale climatic variations. (Singh et al., 2017; Sun et al., 2016; Humphrey et al., 2016). While coupling GCMs and hydrological models, the undergone processes should be properly understood. Because, each model has their own limit in terms of data-inputs, model structure, governing equations, capability to handle time-space variations, ability to generate scenarios at the desired time steps, calibration strategies to control model uncertainties and forecasting (Singh et al., 2017; Humphrey et al., 2016; Tiwari et al., 2014).

The scope of downscaled GCM and RCM variables and their coupling with hydrological/ hydrodynamic models have been evaluated worldwide (Tiwari et al., 2018; Singh et al., 2017; Jiang et al., 2007). For example, the deterministic hydrology models such as SWAT, VIC, MODFLOW etc. are easy to couple with GCMs and RCMs for the real time forecasting and projection of hydro-climatological variables (Singh et al., 2017; Rasmussen et al., 2012). A physically-based distributed-parameter models have been found complex in nature, because they require large amount of data-inputs; however, they have been successfully applied to provide satisfactory results for a wide range of climate change applications utilizing RCMs and GCMs (Sun et al., 2016; Jiang et al., 2007). The downscaled GCMs/RCMs with reference to observational datasets and their couplings with advanced modeling tools are flexible in recognizing and selecting the most suitable method and also to evaluate the applicability of GCMs/RCMs at any specific region (Karmalkar, 2018; Singh and Goyal, 2016; Goyal and Ojha, 2012).

2.1 General Circulation Models (GCMs)

Various types of climate models have been developed to investigate the Land, Ocean and Atmospheric (L-O-A) interactions across the World. GCMs represent various physical processes which are related to atmosphere, ocean, cryosphere and land surface. GCMs have been frequently used for modeling and analyzing the atmospheric variability and climatic diversity and changes related to the Earth's environment (Azmat et al., 2018; Tiwari et al., 2018; Mishra et al., 2014; Andrews et al., 2012). GCMs portray the climate using a three-dimensional grid over the globe (Figure 2.1), typically having a horizontal resolution between 250 and 600 km, vertical layers (10 to 20) in the atmosphere and around 30 layers in the oceans (Carter et al., 2007). GCMs resolutions are thus quite coarse relative to the scale of exposure units in most impact assessments. GCMs known properties must be averaged over the large scale in a technique known as 'parameterization'. This is one scene of uncertainty in GCMs based simulations of future climate.

Intergovernmental Panel on Climate Change (IPCC) Data Distribution Center (DDC) generated different GCM versions and their simulations involving various agencies around the World. Numbers of atmosphere-ocean-geophysical variables have been produced at different spatio-temporal scales (*https://cmip.llnl.gov/cmip5/data_portal.html*).

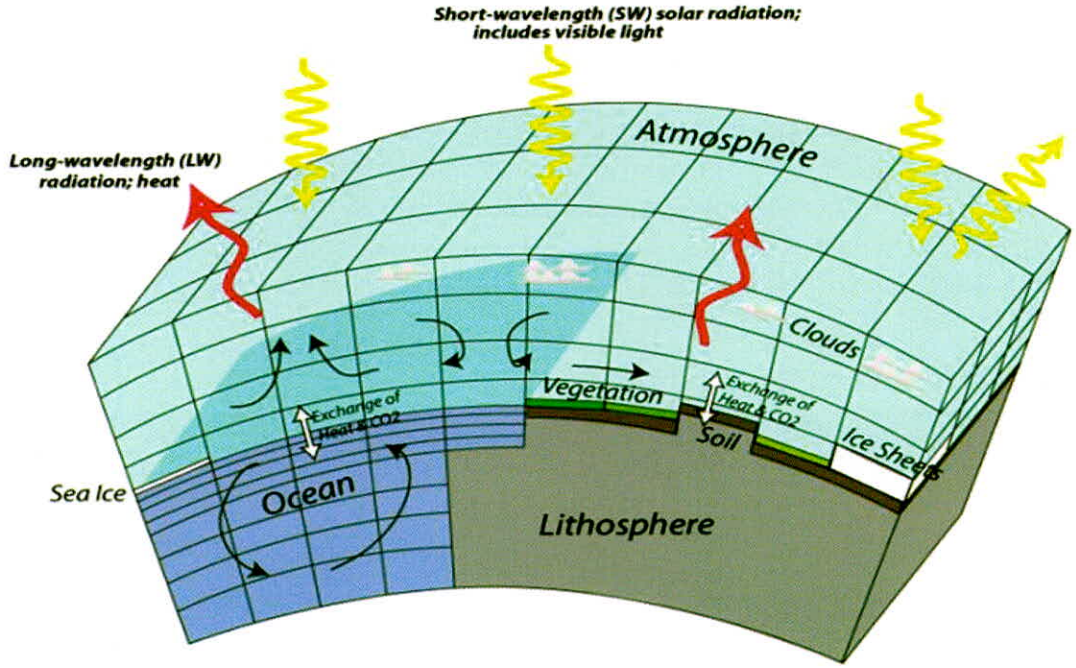


Figure 2.1: *Complex structure of a GCM grid and associated processes (Source: http://www.climate.be/textbook/chapter3)*

There are GCMs that model just the atmosphere (AGCMs), just the oceans (OGCMs) and those that include both (AOGCMs). GCMs characteristically include representations of surface hydrology, sea-ice, cloudiness, atmospheric radiation, convection and other pertinent processes (Azmat et al., 2018; Andrews et al., 2012). GCMs have coarse resolutions and therefore they cannot directly utilize for the analysis of smaller scale climate variations. Different versions of GCMs such as CMIP2 (Goyal and Ojha, 2012; Ghosh and Mujumdar, 2008), CMIP3 (Ghosh and Mujumdar, 2008), CMIP4 (Singh et al., 2017) and CMIP5 (Tiwari et al., 2018; Azamat et al., 2018; Gupta and Jain, 2018; Andrews et al., 2012) have been widely used to analyze atmospheric, terrestrial and climatic variations across the world, but many climatic observations based on GCMs are found reliable, mostly at the global scale (Gupta and Jain, 2018; Xue et al., 2014).

Hydrological models are generally complex in nature and mostly govern by the small-scale parameterizations. Therefore, the coupling of GCMs with complex hydrological tools may produce erroneous results while analyzing the impact of climate change in various hydro-climatological applications, especially at smaller and regional (Tiwari et al., 2018; Mishra et al., 2014; Xue et al., 2014). The global scale variables cannot directly couple with the local scale variables (Xue et al., 2014). The resolution of the climate model's dataset has a strong influence on the outputs of regional and small-scale processes. Thus, climate change studies performed utilizing coarser resolution GCMs sometimes may be failing in providing an accurate information (Xue et al., 2014; Mishra et al., 2014). Furthermore, GCMs are usually dependable at temporal scales of monthly means and longer.

Sometimes, the accuracy of projected and forecasting a climatic variable is a big challenge and we want to know how weather forecasts are so accurate? How climatic predictions have made over days and weeks? How cyclones or hurricanes have forecasted? GCMs and some large-scale climate indices (e.g. EL-Nino, ENSO, SOI etc.) are significantly involved in weather forecasting and they are extremely detailed grid-based simulations of weather that use atmospheric physics to predict events over hours, days and even further into the future. Therefore, GCMs can be utilized to predict or project climate changes in a long term like seasonal, annual, intra-annual and intra-decadal time series durations. GCMs may become more and more accurate as the physics of the atmosphere has become better understood. In a basic sense, the process of GCMs can be thought of in a few straightforward steps. In summary, GCMs provide quantitative estimates of future climate change that are valid in the global and continental scale and over long periods. GCM models are in a continuing state of development and evolution, so in the future, they will be more complex and realistic. The characteristics of GCM have been shown in Table 2.1.

Table 2.1: General features of GCM.

Contrasts	GCM
Goal	to predict climate
Spatial coverage	global
Temporal range	Years (1850-2300)
Spatial resolution	usually coarse (>100 km^2 to 500 km^2 grid)
Relevance of initial conditions	low
Relevance of clouds, radiation	high
Relevance of surface (land, ice, ocean)	high
Relevance of ocean dynamics	high
Relevance of model stability	high
Time dimension	ignored
Physics	equations of motion (plus radiative transfer equations and water conservation equations)
Method	Finite difference expression of continuous equations, or spectral representation; run prognostically
Output	state variables and motion of the atmosphere in 3 dimensions
Maximum time step	controlled by spatial resolution (CFL condition)

2.1.1 Model Scenarios

The IPCC has developed a whole set of scenarios that demonstrate the possible carbon emissions history for the next 100 years. The carbon emission is used as a key variable in driving climate modeling for each scenario (Taylor et al., 2012). Each scenario has been produced based on a group of assumptions about economic growth, population growth, and adoptions we might make regarding steps to minimize carbon emissions. A number of emission scenarios have been generated and their details are provided in the IPCC assessment reports (IPCC 2014, 2007). In this chapter, a few latest scenarios have been discussed. The projections corresponded to CMIP3 and CMIP5 have been utilized frequently and World-wide (Taylor et al., 2012). IPCC emission scenarios such as SRESA2, SRESA1B and SRESB1 generated under the CMIP3 assessment (2007). SRES A2 leads to a continuation of increased annual carbon emissions that follows the recent history. SRES A1B scenario envisions an integrated world characterized by rapid economic growth, a population growth and the rapid development of alternative energy sources that facilitate increased economic growth, while limiting and ultimately reducing carbon emissions. A SRES A1B scenario also assumes that there will be faster development and sharing of technologies which help us reduce our energy consumption. SRES B1 illustrates an even more integrated, more ecologically friendly world, but one in which there is still steady and strong economic growth. As in scenario SRES A1B, the population in this scenario peaks at 9 billion in 2050 and then declines. Each IPCC emission scenario shows emissions of carbon to the atmosphere (mainly from fossil fuel burning) (Gt C/yr; a GT is a billion tons!), so this is an annual rate. This highlights a flow into the atmosphere. Approximately, half of the carbon emitted will remain in the atmosphere and lead to a stronger greenhouse effect, which will, in turn, increase global temperature and change the climate in a variety of ways.

Under CMIP5 and earlier phases of IPCC model development, a few GCMs which have been frequently used in many climate change studies worldwide presented in Table 2.2. These GCMs have been developed by various agencies from the world. Under CMIP5 projection scenarios (2013), four representative concentration pathways (RCPs) were produced and defined by their total radiative forcing (RF) (cumulative measure of human emissions of GHGs from all sources expressed in Watts per square meter) pathway and level by 2100. The RCPs were chosen to represent a broad range of climate outcomes. The four RCPs used a common set of historical emissions data to initialize the integrated assessment models. The RCPs descriptions have been provided in Table 2.3.

Table 2.2: CMIP5 GCMs, their model components, resolution and sources (Source: IPCC 2014).

GCM	Model	Resolution (Lat × Lon)	Source
BCC-CSM and BCC-CSM 1.1 (m)	Atmospheric component, Ocean component, Land component, and Sea ice component are fully coupled. Information between the atmosphere and the ocean is exchanged once per simulated day. The exchange of atmospheric carbon with the land biosphere is	64 × 128 160 × 320	Beijing Climate Center, China Meteorological Administration, China

	calculated at each model time step (20 min).		
BNU-ESM	An earth system model is based on several widely evaluated climate model components and is used to study mechanisms of ocean-atmosphere interactions, natural climate variability, and carbon-climate feedbacks at interannual to interdecadal timescales	64 × 128	Beijing Normal University, China
CanESM2	It is the fourth-generation atmosphere-ocean general circulation model. Horizontal coordinates are spherical with grid spacing ~ 1.41 degrees in longitude and 0.94 degrees in latitude	64 × 128	National Center for Atmospheric Research (NCAR), United States
CCSM4	The Community Climate System Model (CCSM) is a coupled climate model for simulating the earth's climate system, composed of four separate models simultaneously simulating the earth's atmosphere, ocean, land surface, sea ice, and one central coupler component	192 × 288	National Center for Atmospheric Research (NCAR), United States
CNRM-CM5	CNRM-CM5 is an Earth system model designed to run climate simulations. It consists of several existing models designed independently and coupled through the OASIS software	128 × 256	CERFACS (Centre National de Recherches Meteorologiques, France)
CSIRO-Mk 3.6.0	Australian Commonwealth Scientific and Industrial Research Organisation	96 × 192	

FGOALS-g 2	Flexible Global Ocean-Atmosphere-Land System (FGOALS) model includes four individual components (an atmosphere component, an ocean component, a land component, and a sea-ice component) that are driven by a flux coupler module	108 × 128	GFDL& Institute of Atmospheric Physics (LASG-IAP), Chinese Academy of Sciences, Beijing, China
FIO-ESM	Earth system model, which is named as the First Institute of Oceanography-Earth System Model (FIO-ESM), is composed of a coupled physical climate model and a coupled carbon cycle model.	64 × 128	The First Institute of Oceanography, SOA, China
GFDL CM3	GFDL has constructed NOAA's first Earth system models (ESMs). The atmospheric component of the ESMs includes physical features such as aerosols (both natural and anthropogenic), cloud physics, and precipitation. The land component includes precipitation, evaporation, streams, lakes, rivers, runoff, and a terrestrial ecology component to simulate dynamic reservoirs of carbon and other tracers. The oceanic component includes features such as free surface to capture wave processes; water fluxes, or flow; currents; sea-ice dynamics; iceberg transport of freshwater	90 × 144	Geophysical Fluid Dynamics Laboratory, United States
HadGEM2-ES	HadGEM2-ES is Earth system model that was used by the Met Office Hadley Centre for the CMIP5 centennial simulations. Earth system components included are the terrestrial and ocean carbon	145 × 192	Met Office Hadley Center, Unites Kingdom

	cycle and tropospheric chemistry. Ocean biology and carbonate chemistry are represented by diat-HadOCC, which includes limitation of plankton growth by macro- and micronutrients and also simulates emissions of DMS to the atmosphere		
MPI-ESM-LR and MPI-ESMR	MPI-ESM (MPG) is a comprehensive Earth system model and are coupled through the exchange of energy, momentum, water, and important trace gases such as carbon dioxide. The model is developed by the MPI for Meteorology (MPI-M) and based on its predecessors.	96 × 192	Max Planck Institute for Meteorology (MPI-M), Germany

Table 2.3: RCPs and their description (Source: IPCC 2014).

RCP	Description	Emission Level
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m2 in 2100.	Extreme emission scenario
RCP6.0	Stabilization without overshoot pathway to 6 W/m2 at stabilization after 2100	High emission scenario
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m2 at stabilization after 2100	Moderate emission scenario
RCP2.6	Peak in radiative forcing at ~ 3 W/m2 before 2100 and decline	Mitigation/low emission scenario

2.2 Regional Climate Models (RCMs)

It is concluded that coarser resolution GCMs are not suitable for the local scale or regional scale studies, for example: to analyze the impact of climate change in a particular river basin or may be at district level requires more precise information than GCMs currently provide. GCMs determine a very large-scale effect of changing global climate system. The climatic parameters computed by the GCM can be effectively utilized as inputs to RCM for example: temperature and wind. Numerous RCMs have been

developed, applied, inter-compared, and demonstrating important downscaling skills, but also model deficiencies are still yet to be resolved. RCM is a numerical climate prediction model forced by specified lateral and ocean conditions from a GCM or observation-based dataset (reanalysis) that simulates atmospheric and land surface processes, while accounting for high-resolution topographic data, land-sea contrasts, surface characteristics, and other components of the Earth-system. RCMs are initialized with the initial conditions and driven along its lateral-atmospheric-boundaries and lower-surface boundaries with time-variable conditions. Therefore, RCMs utilize to downscale global reanalysis or GCM runs to simulate climate variability with regional refinements.

RCMs enhances the spatial resolution as compared to GCMs, because RCMs have been produced at finer mesoscale grids (grids belong to 10 km^2 – 50 km^2) (Singh et al., 2017; McCarthy et al., 2012; Van Meijgaard et al., 2008; Mailhot et al., 2007). The spatial resolution-based comparison between GCMs and RCMs has shown in Figure 2.2. RCMs can then resolve the local impacts by giving the small-scale information about orography (land height), land use, weather and climate information at a resolution of 50 km^2 or 25 km^2 (Karmalkar 2018; McCarthy et al., 2012) while GCMs may fail to do this. RCMs can be applied over a given area or limited area driven by GCMs can provide information at much smaller scales, which are capable to support more detailed impact and adaptation assessment studies (Bhuvandas et al., 2014). Studies have shown that RCMs are able to analyze the effect of climate change and geophysical environment better than GCMs (Karmalkar 2018; Singh et al., 2017). However, it should be noted that solutions from the RCM may be inconsistent with those from the global model, which could be problematic in some applications.

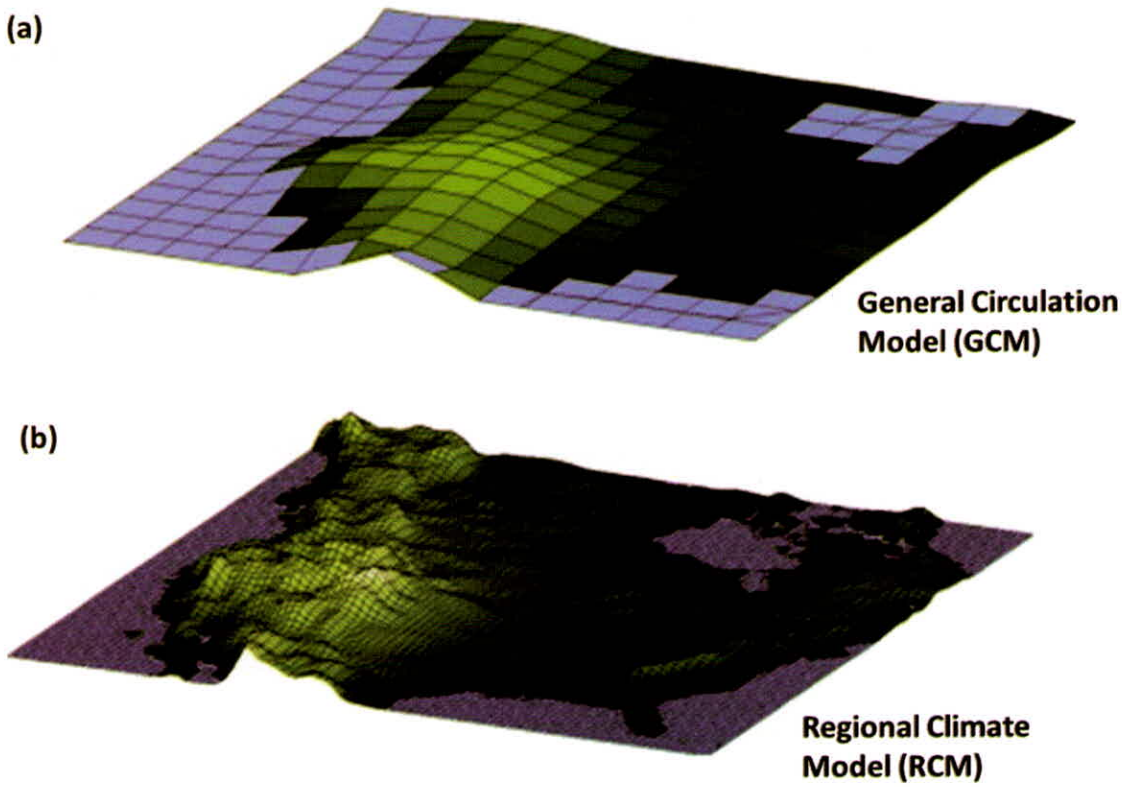


Figure 2.2: *Comparison in spatial resolution between GCM versus RCM (Source: Lee Hannah, in Climate Change Biology (Second Edition), 2015).*

RCMs which are commonly used in different climate change studies around the World include the U.S. Regional Climate Model Version 3 (RegCM3) (Pal et al., 2007); Canadian Regional Climate Model (CRCM) (Mailhot et al., 2007); UK Met Office Hadley Centre's Regional Climate Model Version 3 (HadRM3) (McCarthy et al., 2012); German Regional Climate Model (REMO) (Jacob and Podzun, 1997); Dutch Regional Atmospheric Climate Model (RACMO) (Van Meijgaard, 2008); and German HIRHAM, which combines the dynamics of the High-Resolution Limited Area Model (HIRLAM) (Tuomi et al., 1999) and European Centre-Hamburg (ECHAM) models (Tibaldi et al., 1997) generated under different IPCC CMIP assessments. CORDEX is a World Climate Research Programme (WCRP) framework has been developed to evaluate the RCMs performance through a set of experiments aiming to produce regional climate projections (Singh et al., 2017). CORDEX-East Asia is the branch of the CORDEX initiative produces RCM ensembles based on the dynamical downscaling methods forced by multi-model GCMs. One distinct advantage of RCM application is its higher spatial (or horizontal) resolution, which makes the RCM capable to handle more realistically certain and critically important climate processes (Karmalkar, 2018).

2.3 Downscaling

GCMs are capable in predicting large-scale heterogeneity, climate variability and changes. Therefore, GCMs have been successfully applied in various large-scale studies. However, due to their coarser scale resolutions, GCMs are less capable to explore small-scale changes. Several landscape features such as water bodies, mountains, water-balance in the basin and sub catchment scale, land-cover analysis and climate change impact at a local scale can be better explored utilize RCMs, because they produce at much finer scales than GCMs. However, sometimes RCM fails to incorporate very small scale and location-based heterogeneities and changes (Karmalkar 2018). To address the small-scale heterogeneities, which may be crucial for hydro-climatological studies and other applications, different downscaling methods have been developed (Moalafhi et al., 2017; Ghosh and Mujumdar, 2008). Downscaling depends on the hypothesis that local climate is a composition of large-scale atmospheric features (e.g. Hemisphere, continental, global and regional) and local conditions (e.g. land surface properties and topography).

The derivation of fine-scale climatic information is based on the hypothesis that the local climate is conditioned by relations between local features and large-scale atmospheric characteristics (Moalafhi et al., 2017; Mishra et al., 2014). Climate studies performed on a smaller scale utilizing a similar hypothesis-based approach concluded that it is possible to model local and large-scale interactions and established a relationship between present-day local climate and atmospheric conditions through multiple downscaling processes (Seiler et al., 2018). The downscaling processes enhance the information to the coarser GCM output so more realistic data can produce at a finer scale, capturing sub-grid scale differences (Mishra et al., 2014).

Downscaling of the large scale GCMs variables can be performed in both spatial and temporal aspects with reference to local scale variables. According to Trzaska and Schnarr (2014), "Downscaling is a process that converts a large-scale information (e.g. coarse resolution grid like 500×500 km^2) to finer scale information (e.g. 50 ×50 km^2)". Downscaling can be utilized to convert coarser spatial resolution GCMs to any desired local grid cell (suppose 20 km^2, a higher resolution grid cell) or even at a specific point location (Figure 2.3) (Shukla and Lettenmaier, 2013). Similarly, temporal downscaling can be referred to convert from coarser scale temporal GCM output (e.g. monthly precipitation) to finer scale GCM output (e.g. daily precipitation) (Xue et al., 2014).

In climate modeling, there are two main categories of downscaling distinguished: (i) statistical/ empirical downscaling (Wilby et al., 2014) and (ii) dynamical downscaling (Xue et al., 2014; Mishra et al., 2014; Shukla and Lettenmaier, 2013) (Figure 2.3). The dynamical downscaling method has several numerical advantages over statistical modeling, while dynamical downscaling has found computationally intensive and requires a large amount of datasets and high level of manpower to interpret/produce results (Trzaska and Schnarr, 2014). Each downscaling method contains uncertainties and has their own limitations. No official guidance is available on downscaling or downscaling methods that best meet the user's need. Therefore, the research community is still developing the downscaling methods.

2.3.1 Statistical Downscaling

Statistical downscaling methods have been developed to interpolate large-scale atmospheric predictor variable (e.g. average of precipitation and temperature, circulation characteristics such as mean sea level pressure, radiation, wind circulations etc.) to point scale or at gauge scale (e.g. rainfall, runoff, etc.) (Singh and Goyal, 2017; Singh and Goyal, 2016; Ghosh and Mujumdar, 2008; Wilby et al., 1998). From this point of view, the regional or local climate information is generated by first determining a statistical model which narrates large-scale climate variables called "predictors" to regional and a local variable called "predictand". Once a relationship has been established between predictand and predictor, the model can be setup in historical time duration and simulated scenarios can be generated along with the regression coefficients (e.g. parameters of the regression equation). After calibration and validation, the future climate scenarios can be predicted and forecasted under the presence of 21st century GCM variables and regression parameters.

Statistical downscaling has been successfully applied in various climatic simulations and projection studies where sufficient observed datasets (or predictands) are available to derive the statistical relationships (Singh and Goyal, 2016; Ghosh and Mujumdar, 2008). Statistical downscaling has been widely used in hydro-climatological studies around the world (Singh and Goyal, 2016; Wilby et al., 1998). A graphical user interface (GUI) based Statistical Downscaling Model (SDSM) developed by Wilby et al. (2004) has been successfully applied in various rainfall and temperature projection-based studies (Seiler et al., 2018; Singh et al., 2017). Wilby et al. (2004) used a weather generator based multiple linear regression method to build a relationship between large scale GCM outputs (predictors) and small scale/point scale observed variables (predictands) to forecast long term rainfall scenarios. Recently, an integrated "dynamic-statistical" approach has been presented to enhance the computations at a smaller scale in both temporal and spatial domains (Walton et al., 2015; Sun et al., 2015).

Sun et al. (2015) presented a hybrid downscaling approach which has been found more capable to capture spatial variations in warming even at smaller scales. Several studies utilized a "categorical approach" in statistical downscaling, which includes some classification and clustering based statistical techniques to relate GCM data to different groups as per large scale circulation patterns and data attributes (Bhuvandas et al., 2014; Zorita and Von Storch, 1999). Among multiple downscaling methods, SDSM based statistical downscaling approach has been considered to be the most suitable for downscaling of large scale GCM outputs at a point or gauge scale, especially to forecast climatological variables. (Xue et al., 2014; Bhuvandas et al., 2014). In case of statistical downscaling, the demand of available data is high and this could be a weakness of this method, but on the other hand the computational cost of statistical downscaling is comparatively low. The simplest approach of statistical downscaling cab be described by several sequential procedures as shown in Figure 2.4.

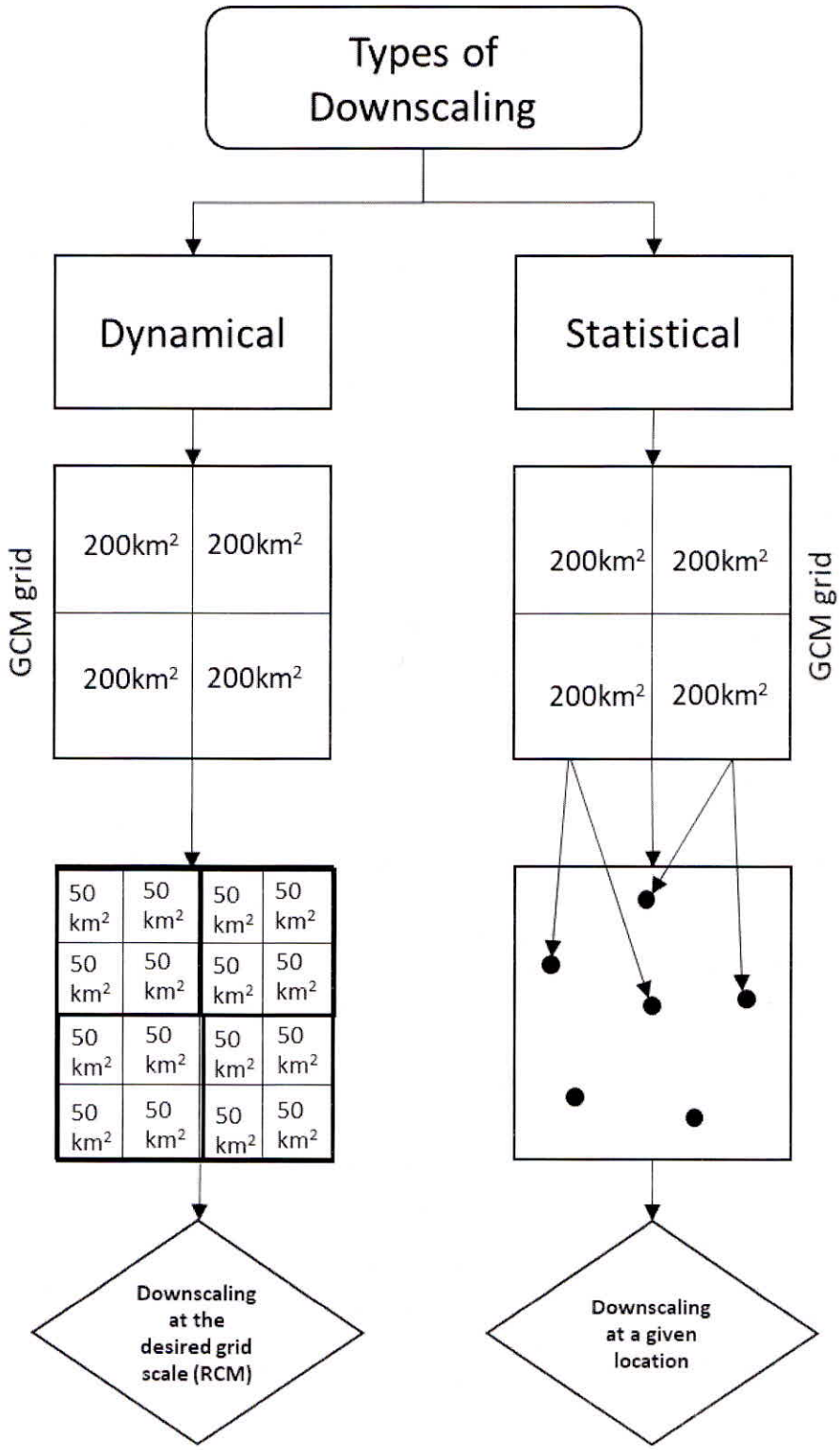


Figure 2.3: *Schematic representation of Dynamic and Statistical Downscaling.*



Figure 2.4: *Schematic flow chart of performing statistical downscaling and climate model scenario generation.*

Selection of GCM

In many climate change impact studies, the authors have faced problems while utilizing the full number of GCM simulations that are available; and thus, often only subsets are used. Each model may produce different outputs because of differences in model structure and model processes. The GCM related uncertainties have been explored utilizing a large number of GCMs and the level of uncertainty in each model has been quantified (Sharma et al., 2018; Joseph et al., 2018; Mishra et al., 2014). Many studies utilized multiple GCMs so that they cover different sources and levels of uncertainties. However, in case of limited computing resources, it is difficult to process all GCMs and quantifying various sources of uncertainties; thus, only part of the known uncertainty is considered (Sharma et al., 2018). Several

climate change studies applied a cluster analysis method to select a subset of full numbers of climate simulations, which are the best representatives for the given area (Joseph et al., 2018; Xue et al., 2014).

By reducing the number of GCMs, the information available related to uncertainty in the projections and ensembles may also be reduced (Wilcke and Bärring, 2016). However, the selection of GCMs is not straightforward; and therefore, various methods have been suggested and tested in different studies which can be utilized such as the range of projected changes in the means (Lutz et al., 2016), based on climate extremes (Ruane and McDermid, 2017; Lutz et al., 2016), based on skill tests and cluster analysis (Lee and Kim, 2017; Lutz et al., 2016). Semenov and Stratonovich (2015) developed 'climate sensitivity indices' to select GCMs based upon mean precipitation and temperature changes. After that, Ruane and McDermid (2017) utilized a representative temperature and precipitation GCM sub-setting procedure and identified five individual GCMs that are able to capture a profile of the full number of GCM ensembles. In sub-setting/selecting GCMs, the aim should be that each GCM represents major type of change and is linked with probabilistic information correlated to the broader ensemble (Lee and Kim, 2017).

Selection of predictors

Statistical downscaling methods produce empirical/statistical links between the large-scale and local-scale variables. Statistical downscaling is not only useful in numerical weather prediction and synoptic climatology, but it also provides a local-scale information, which is very useful in climate change impact assessment studies (Singh and Goyal, 2016; Ghosh and Mujumdar, 2008). The SDSM downscaling tool implies on the empirical relationships between the local-scale predictands and large-scale predictor(s) (Willby et al., 2014). Because of the linear concepts of statistical downscaling, the selection of predictors (e.g. GCM variables) can be made while performing correlation and partial correlation analysis between predictands (e.g. observed variables like precipitation and temperature) and predictors, and the predictor weights can be estimated via ordinary least-square method (Willby et al., 2014). Each GCM model contains numbers of predictor variables and thus some of them can be dropped if they do not represent the property of local variables (Singh and Goyal, 2017). In statistical downscaling, the non-significant predictors may be dropped, if they do not show any significance (Singh and Goyal, 2017). A simple correlation analysis may be performed for the selection of most suitable predictors (Trzaska and Schnarr, 2018; Singh and Goyal, 2016).

To select the first and most suitable large-scale variable is relatively easy, though the judgment of the second, third, fourth and so on is much more subjective (Willby et al., 2014). Thus, several standard statistical evaluation methods can be performed for screening large scale variables corresponding to each local scale variable (Willby et al., 2014). In statistical downscaling, a correlation matrix can be prepared between large-scale predictors and local-scale predictand to find out suitable predictors. Then predictors having high correlation coefficients (a threshold can be used like >=0.7) can be taken and arranged in descending order (Singh and Goyal, 2016; Willby et al., 2014). Then among the selected predictors based on high correlation coefficients, the negative correlated predictors can be dropped from the analysis and only positive correlated predictors can be utilized as shown by Singh and Goyal (2016) and Wilby et al. (2014). The first ranked predictor, having the highest correlation coefficient among others, can be selected and will be defined as the first suitable super predictor (FSSP) (Willby et al., 2014). After this the absolute correlation (R) between predictor and predictand, and the correlation coefficient between individual predictors can also be calculated (Willby et al., 2014). Then the other highly correlated predictors (for precipitation it is 0.5 and above, and for temperature, it is 0.7 and above in this case) will

be taken out in order to remove any multi-co-linearity (Singh and Goyal, 2016). The correlation coefficient up to 0.7 between two predictors is acceptable (Singh and Goyal, 2016; Wilby et al., 2014).

In case of the selection of the second, third and so on, a percentage reduction in a partial correlation (PRP) with respect to absolute correlation can be calculated for each predictor (Singh and Goyal, 2016). The PRP is the percentage reduction in partial correlation with respect to the correlation coefficient. The predictor which has a minimum PRP in partial correlation (Willby et al., 2014) can be selected as the second most suitable predictor (Singh and Goyal., 2016; Willby et al., 2014). This predictor has almost no or a very insignificant multi-co-linearity with the FSSP. The third, fourth and following predictors could be obtained by repeating the same procedure (Willby et al., 2014). A similar methodology for the selection of suitable predictors has been applied by various researchers across the world for the statistical downscaling of precipitation, temperature and other hydro-meteorological variables (Willby et al., 2014).

Calibration and validation

After selection of predictors, the regression model can be set up between predictors and predictands by selecting a homogenous time duration as per the availability of observed and simulated climate data (Willby et al., 2014). The regression model should be prepared by selecting best and suitable predictors only rather than all predictands, because multi-colinearity can affect trends and it must be avoided among predictors (Singh and Goyal, 2016). Many studies performed calibration/validation on a monthly and a daily time scale and both time steps gave satisfactory results (Sharma et al., 2018; Salvi et al., 2016). For the evaluation of calibration and validation results, the statistical evaluation methods such as coefficient of determination (R2), changes in mean, standard deviation and root mean square error (RMSE) have been successfully performed (Singh and Goyal, 2016). The explained variance and standard error methods also utilized to evaluate the performance of statistical regression methods (Salvi et al., 2016), in which the observed data are plotted against the regression model based simulated dataset. In most of the studies, it has been suggested that for regression modeling, a minimum 30 years' time series datasets are required (Willby et al., 2014).

Bias correction

In statistical downscaling, GCMs based simulations produced a significant amount of bias (or uncertainties) when they downscale at a point scale (or, finer scale), because coarser resolutions GCMs fail to explain small scale variations (Singh and Goyal, 2016). At present, GCMs simulations generally produce a significant amount of bias in hydro-climatological projections and forecasting scenarios. To reduce the bias in GCMs, various bias correction (BC) methods have been developed and their applicability in error reduction has been tested in many climate studies (Ghosh and Mujumdar, 2008). BC methods correct the simulated outputs in the presence of observational datasets in a post-processing step (Willby et al., 2014). The detail description of the bias correction methodology and its significance have been presented in the next chapter. After bias correction, a bias factor or mean bias can be derived (Singh and Goyal, 2016). The future scenarios generated by GCMs may further correct by applying the bias factor (Willby et al., 2014).

Scenario generation

In statistical downscaling, once the regression model has been successfully calibrated and validated based on a historical dataset (or training dataset), the optimized regression coefficients (or parameters of the regression equation) can be utilized for the 21st century scenarios generation (Willby

et al., 2014). In statistical downscaling, a conditional sub-model can be utilized for the projection of maximum and minimum temperature without any transformation (Willby et al., 2014) and an unconditional sub-model may be applied in case of stochastic variable (e.g. precipitation) with fourth root transformations (Singh and Goyal, 2016).

2.3.2 Dynamic Downscaling

Dynamic downscaling is generally related to the use of RCM developed from mesoscale (e.g. 10 km^2 to 50 km^2 grids) atmospheric models, similar to GCM based principles. However, RCMs have higher spatial resolution than GCM (Xue et al., 2014; Wang et al., 2014). RCMs represent mesoscale atmospheric information which has been found suitable to produce more realistic and accurate climate information on a regional scale (e.g. 25-50 km^2 grid scale) (Xue et al., 2014). The distinct choice of domain size controls the disagreement between the RCMs and their driving GCMs. Dynamical downscaling enhances the approach of regional climate modeling and delivers better predictors for supplementary statistical downscaling to higher-resolution output (Guyennon et al., 2013).

The use of RCMs in climate modeling has been increased (Karmalkar, 2018; Singh et al., 2017), thus it is important to understand whether and under what conditions the dynamic downscaling is really capable of improving climate simulations/predictions. Few studies have compared the applicability of RCMs against GCMs has been compared mainly to test that whether RCMs are really capable to provide more precise climate information at different scales or not (Singh et al., 2017; Xue et al., 2014)? Although, RCMs may provide feedbacks to their driving GCMs. Most of the dynamic downscaling approaches have presented based on a one-way nesting approach and have no feedback from the RCM to the driving GCM (Xue et al., 2014). The RCM based dynamic downscaling will ultimately be evaluated by its capability to produce realistic simulations/predictions on the smallest scale (Xue et al., 2014). Several studies demonstrated that factors such as lower boundary conditions, domain size, physical processes and horizontal resolution have strong influence on the dynamic downscaling (Xue et al., 2014). Many studies utilized RCMs for projecting long term climate scenarios and concluded that RCMs performed superior than GCMs. The capability of RCM depends not only on the RCM's resolution, but also on the RCM's parameterization (Wang et al., 2014). These days, the RCM based projections of the future climate and many other applications such as producing high resolution data for hydrological assessments have increased as seen in many studies (Shukla and Lettenmaier, 2013).

A comparative assessment has been done between statistical and dynamic downscaling methods to highlight their various features is shown in Table 2.4:

Table 2.4: Comparison between statistical and dynamical downscaling.

	Statistical Downscaling	Dynamical Downscaling
Features	Any scale/down to gauge level/point level information Daily time series information Monthly time series information Scenarios for extreme events (only applicable to some methods)	Provides 20-50 km^2 grid call information Daily time series information Monthly time series information Scenarios for extreme events Historical scenarios Future scenarios

	Historical scenarios (only applicable to some methods) Future scenarios (only applicable to some methods)	
Advantages	Easy computation and efficient for many emissions scenarios and GCMs Methods range from simple to complex for purpose basis Same method can be applicable to all areas/regions/globe and for multiple GCMs Relies on observed climate dataset/variables Tools are freely available Requires medium/low computations resources Requires observational dataset In the absence of sufficient amount of observational data, it may produce large uncertainty in the outputs Assumption is that the existing relationship between large scale GCM and local scale processes will remain constant in the future	Based on physical mechanism and consistent Resolved based on surface processes and complex atmospheric processes occurring at sub-GCM grid scale Accuracy is more and realistic at regional scale 20-50kms grid scales RCMs products are available for uncertainty analysis Requires high computations resources and expertise Requires high amount of datasets Results are dependent as per RCM/GCM, different RCM may give different outputs Affected by bias as per the deriving GCM

2.3.3 Advanced Downscaling Methods

ANN based methods

Artificial neural networks (ANNs) are a pattern recognition tool which have been utilized to reproduce empirical, possible non-linear relationships between a set of 'input' variables and some corresponding 'output' variables (Dorji et al., 2017; Goyal and Ojha, 2012). ANNs works based on the physiology of the brain, through a series of 'nodes' which pass information between one another in a similar way to cells in the brain (Goyal and Ojha, 2012). For a full description of ANN theory, kindly see Bishop (2000) or Picton (2000) published studies. In climate dynamics, a relationship has been established between the GCM and RCM output parameter fields, specifically temperature and rainfall. This was done by representing properties of the GCM and RCM fields to an ANN, and 'training' it to be able to replicate the relationship between the two (Dorji et al., 2017). Similar to statistical downscaling, a linear and non-linear regression method has been employed in the ANN based downscaling approaches. In the ANN based downscaling, a relationship can be built between large-scale and small-scale variables (through input layers) and some weights are generated in their hidden layers to generate the prediction samples (Dorji et al., 2017) (through output layers).

Many studies utilized Multilayer Perceptron (MLP) neural network for the downscaling of various hydro-climatological variables (Dorji et al., 2017; Humphrey et al., 2016). MLP method is widely used to establish the nonlinear relationship between predictor and predictands (Dorji et al., 2017). The neural network improves the performance function between the predicted and observed values. There is a slight difference in statistical downscaling and MLP neural network-based downscaling, because statistical methods are mostly based on the data distribution while MLP makes no assumption (Humphrey et al., 2016). The complexity involved in MLP can be adjusted by increasing or decreasing the number of hidden layer nodes, which determine the number of free parameters in the model (Humphrey et al., 2016). Several studies utilized Bayesian ANN statistical forecasting model for the downscaling of GCMs and RCMs (Humphrey et al., 2016). Overall, ANNs based downscaling models are found more flexible and stable than ordinary statistical downscaling models. ANNs based methods have found better in capturing complex and nonlinear input-output relationships from data without any restrictive assumptions (Vu et al., 2015).

Weather generators (WGs)

Weather Generators (WGs) have significant ability to downscale weather variables and therefore, WGs are widely used in climate change studies, especially the short-term forecasting of meteorological variables. WGs are relatively easy to run and their outcomes are easy to post-process and interpret. Numerous WGs currently being used, including Weather Generator, WGEN (Chen et al., 2015); Climate Generator, CLIMGEN (Mehan et al., 2017); USCLIMATE; Stochastic Weather Generators, WeaGETS; and the Long Ashton Research Station Weather Generator, LARS-WG (Mehan et al., 2017). Dubrovsky et al. (2017) utilized a new gridded multivariate parametric stochastic WG modelled by Markov chain and Gamma distribution for forecasting precipitation in Europe. Dubrovsky et al. (2017) showed significant spatial and temporal variations in forecasted precipitation and the climate change scenarios are derived from the selected RCM simulations (CORDEX database). International Research Institute for Climate and Society (IRI) produced a stochastic weather generator which works based on the generalized linear modeling (GLM) (Kim et al., 2016). The GLM based stochastic WG has been applied mostly to forecast rainfalls and different studies, observation show that weather generator is able to generate the probability distributions of seasonally aggregated rainfalls and minimum and maximum temperature (Kim et al., 2016). Numerous WGs based studies performed in India revealed that WGs are able to forecast short-term and long-term meteorological scenarios (e.g. temperature and precipitation) (Sharma et al., 2018).

Other advanced statistical and machine learning methods

Very few studies utilized an advance downscaling method such as quantile-based regression method for the downscaling of GCM variables (e.g. daily minimum-maximum temperatures and daily precipitation) (Hassanzadeh et al., 2013). Quantile based downscaling successfully improved the projection of temperature and precipitation extremes. Quantile regression methods have been found able to capture the high and low order extreme events in the downscaled projected scenarios; while in other statistical methods, they are underestimated (Hassanzadeh et al., 2013). Rather than using a conventional statistical downscaling method, the data-driven techniques such as genetic programming is also successfully applied in several hydro-climatological studies to get the more robust computational outcomes (Fowler et al. 2007). The GP coupled with the quantile-based regression could be a useful tool to forecast and simulate more robust outcomes of climatic scenario (Hassanzadeh et al., 2013).

Zhai et al. (2018) presented an advanced stepwise clustered downscaling (SCD) approach utilizing multiple RCPs to downscale minimum and maximum temperature in Ottawa and the results of the study made satisfactory observations than previous downscaling methods. In SCD method, the outputs of GCMs and RCPs are used as inputs to the SCD and then downscaled scenarios are generated (Zhai et al., 2018). Azamat et al. (2018) compared two downscaling methods such as statistical downscaling model (SDSM) and smooth support vector machine (SSVM) and the results showed that SSVM performed better in forecasting precipitation scenarios than SDSM; however, SSVM takes a lot of efforts to optimize the best parameters to get better simulations. Advanced downscaling approaches based on machine learning methods such as random forest (RF) (He et al., 2016), support vector machine (SVM) (Ghosh and Mujumdar, 2008), least square support vector machine (LSSVM) (Campozano et al., 2016.), wavelet-least square support vector machine (WLSSVM) (Nourani et al., 2019) and wavelet-artificial neural network (WANN) (Assesm et al., 2017) have significantly utilized in the downscaling of temperature, precipitation and other hydro-meteorological variables and also highlighted their merits-demerits in simulations. Studies performed by Dorji et al. (2017) and Humphrey et al. (2016) compared the advance downscaling techniques to ordinary least-squares regression (OLR) method and their results showed that OLR regression is performed equally to simplest statistical downscaling method (Dorji et al., 2017; Humphrey et al., 2016).

2.3.4 Validation of Downscaling Methods

In climate downscaling, uncertainties related to GCM data, uncertainties associated with downscaling methods and model related uncertainties have been explored across the World (Sharma et al., 2018; Tiwari et al., 2018; Humphrey et al., 2016). The reliability of multi-model GCMs and downscaling methodology has been tested in both historical and 21st century. As per the progressive development of GCMs and RCMs under different IPCC assessments, each model and their ensembles have been widely used to assess short-term and long-term climate changes (Gupta and Jain, 2018; Sharma et al., 2018; Tiwari et al., 2018; Smitha et al., 2018; Singh et al., 2017; Pal et al., 2007). Scientific literatures collected based on the past studies contains a variety of studies regarding the development of downscaling methods to evaluate the potential effects of climate change relevant to Earth-Ocean-Atmospheric processes (Ali and Mishra, 2018). Statistical downscaling works based on the principle of empirical relationships (linear or may be non-liner) between large-scale atmospheric-ocean and local climate characteristics and therefore, statistical downscaling approaches have been easily applied in different heterogenous groups such as linear methods, weather classifications and weather generators (Tiwari et al., 2018; Onyutha et al., 2016; Sunyer et al., 2015). Statistical downscaling methods have found computationally efficient and inexpensive than dynamic downscaling that requires modeling of physical processes (Latombe et al., 2018). The statistical downscaling has been successfully applied for the projection and simulation of precipitation, minimum-maximum temperatures, solar radiation, humidity, soil moisture, streamflow, snowfall, snowmelt and groundwater flows, because the performance of statistical downscaling techniques relies on the selection of regional/local scale parameters (Latombe et al., 2018; Tiwari et al., 2018; Onyutha et al., 2016; Sunyer et al., 2015).

Statistical downscaling methods work on the relationship established between predictors and predictand. However, in case of linear methods, normal distribution of the predictor is required (Singh and Goyal, 2017; Ghosh and Mujumdar, 2008). Latombe et al. (2018) applied statistical downscaling model (SDSM) utilizing GCMs to analyze the climate variability at the time of Last Glacier Maximum (LGM) over western Europe utilizing GCMs and results revealed that the SDSM performed well in

paleoclimate reconstruction at local sites. Salvi et al. (2016) established an empirical relationship between coarse resolution climate variables and high-resolution climate variables performed downscaling successfully under nonstationary climate conditions. Studies also utilized linear genetic programming (LGP) based statistical downscaling to project various hydro-climatological variables such as discharge, precipitation under multi-model GCMs and results showed that LPG is able to highlight the 21st century changes (Sachindra and Perera, 2018, 2016; Tofiq and Guven, 2014). A study conducted by Sunyer et al. (2015) utilized eight different statistical downscaling methods in the assessment of climate change and the relevance of 8 methods to extreme precipitation has been signified in Europe.

To avoid uncertainties in large scale coarser resolution GCMs, Fenta Mekonnen and Disse (2018) applied the statistical downscaling method over GCMs to analyse the future climate change impact on Upper Blue Nile River basin and then applied few bias correction methods to minimize uncertainty in outcomes. SDSM based analysis using CanESM2 CMIP5 GCMs are able to produce more accurate average rainfall predictions than raw GCMs (Fenta Mekonnen and Disse, 2018). Azmat et al. (2018) utilized multiple GCMs and compared the statistical downscaling with Smooth Support Vector Machine (SSVM) (one of the data mining methods) for the improvement of climate projections and concluded that SSVM performed superior than other methods. However, both approaches were able to simulate precipitation and temperature with a certain amount of uncertainties. Humphrey et al. (2016) presented a hybrid statistical ANN based forecasting model to project the monthly streamflow. The results of this study showed that the statistical ANN based approach was more suitable than dynamicaa dynamical forecasting modelt al. (2015) applied two different statistical downscaling methods: (i) delta change method for the computation of mean precipitation and different return period precipitation events and (ii) quantile-quantile (Q-Q) transformation for downscale monthly distribution of precipitations utilizing RCMs. Results showed a significant amount of uncertainty existed in both methods, because their results lead to a very different prediction of the direction and magnitude of change (Sarr et al. 2015). Goswami et al. (2018) presented a coupled framework employing statistical downscaling and copulas for projecting precipitation extremes over eastern Himalayas and calculated that copulas based 21st Century projections are more relevant to real scenario than projections were downscaled using simple statistical methods.

Xue et al. (2014) explored the controlling factors that have strong influence on dynamic downscaling ability in intra-seasonal simulations and future projection. Meresa et al. (2016) utilized multiple GCMs and RCMs for the projection of droughts in Polish catchments and observed a significant diversity in the climate projections of GCMs and RCMs over the region. A study conducted by Vu et al. (2015) utilized RCMs and dynamic downscaling to project future hydro-meteorological drought scenarios and their results have been found sensitive in the analysis. Seiler et al. (2018) applied dynamic downscaling products to minimize bias in the simulation of explosive extratropical cyclones. The CanESM2 GCMs integrated with the CanRCM4 and this reduces the frequency bias up to -22%. Moalafhi et al. (2017) used dynamic downscaling for reconstructing hydro-climatological data in southern Africa. Sun et al. (2016) linked ecohydrological model with (Weather Research and Forecasting Model) WRF utilizing dynamically downscaled RCMs dataset to project water yield and ecosystem productivity across the whole United States. A large spatial variability in the hydrological and ecosystem productivity responses has been highlighted, because different uncertainty assumed in the simulated outcomes. Karmalkar (2018) utilized NA-CORDEX and NARCCAP ensembles to explore uncertainties

in regional climate change projections. It is found that NA-CORDEX GCMs poorly responded during winter over half of the United states and the Great Plains in the summer.

2.4 Applicability of Downscaling Methods and GCMs in Indian Context

2.4.1 Downscaling Methods Suitability in India

India has a very diverse hydro-climatology at a regional scale (Tiwari et al., 2017; Singh and Goyal, 2016). In this section, capabilities of statistical and dynamical downscaling have been evaluated in Indian hydro-meteorological conditions at both larger and smaller scales. Different downscaling approaches have found capable for the downscaling of various hydro-climatological variables and the downscaled products have been successfully utilized in various climate change studies across India (Goswami et al., 2017; Tiwari et al., 2017; Tiwari et al., 2014; Singh and Goyal, 2016; Ghosh and Mujumdar, 2008). Tiwari et al. (2018) utilized dynamic and statistical downscaling methods to predict winter precipitation in Northern India and the results indicated that the downscaled observations generated from statistical methods performed better than dynamical downscaling. However, both downscaling methods such as statistical and dynamic gave reliable predictions than directly involved GCM based predictions (Tiwari et al. 2018).

Goyal and Ojha (2012) developed a downscaling model utilizing the Multiple Linear Regression (MLR) and ANN for the projection of minimum and maximum temperature to a lake-basin scale. The ANN based downscaling results have given more accurate observations than MLR method, illustrating that ANN based observations contain less bias than MLR based observations. Sharma et al. (2018) applied statistical and dynamic downscaling methods to assess the uncertainty in the projections of hydro-climatic variables over India are utilizing GCMs and their results clearly highlighted that statistical downscaling-based observations are able to capture spatio-temporal variability in hydro-climatological variables, whereas the dynamic downscaling projections were poorly performed. Joseph et al. (2018) used dynamically downscaled RCMs and statistically downscaled GCMs outputs for comparing climate model uncertainty and hydrological parameter uncertainty in the Ganga River basin and the results showed significant amount of uncertainties in the future projections, especially in case of dynamically downscaled RCMs. However, uncertainties also exhibited a seasonal dependency in a climate model.

Despite various applications of downscaling in simulation and projections of climate variables, several studies assessed the direct applicability of GCMs and RCMs at regional and smaller scales utilizing advanced bias correction methods (Gupta and Jain, 2018; Smitha et al., 2018; Apurv et al., 2015). However, their direct applicability is still uncertain under regional and small-scale climate change assessment. Gupta and Jain (2018) utilized dynamically downscaled RCMs across India to investigate the musical impact of climate change on droughts and their results showed an increase in evapotranspiration due to the projected rise in temperature in most parts of India and causing droughts, but this study did not quantify uncertainties in their projections.

In this chapter, the applicability of dynamic and statistical downscaling methods has been discussed. Both downscaling methods have performed well in different climate change forecasting and assessment studies around the World. However, each method has shown its limitations and advantages as per the desired area of interest. Several advance downscaling methods such as ANN based approaches, Artificial Intelligence methods, including SVM and Random Forest (RF) etc. and Weather Generators (WGs) have been presented to explore their applicability in various climate studies across the World and India too. Given the diversity of developed downscaling methods, it is best to first evaluate the needs,

relevant techniques, and limitations of the results of each method as per the desired goal and area of interest.

In the assessment of climate change and its impacts at regional, sub-regional scales and location based, a comprehensive appraisal of the information needs and the relevance of existing information should be carried out first. If the need for an original downscaling of the projections is confirmed, the method should be selected based on the information needs and also, importantly, on available resources (data, computing resources, expertise, and time-frames). Therefore, a decision tree (Figure 2.5) has been formulated to help the researchers and the scientists in determining an appropriate downscaling method.

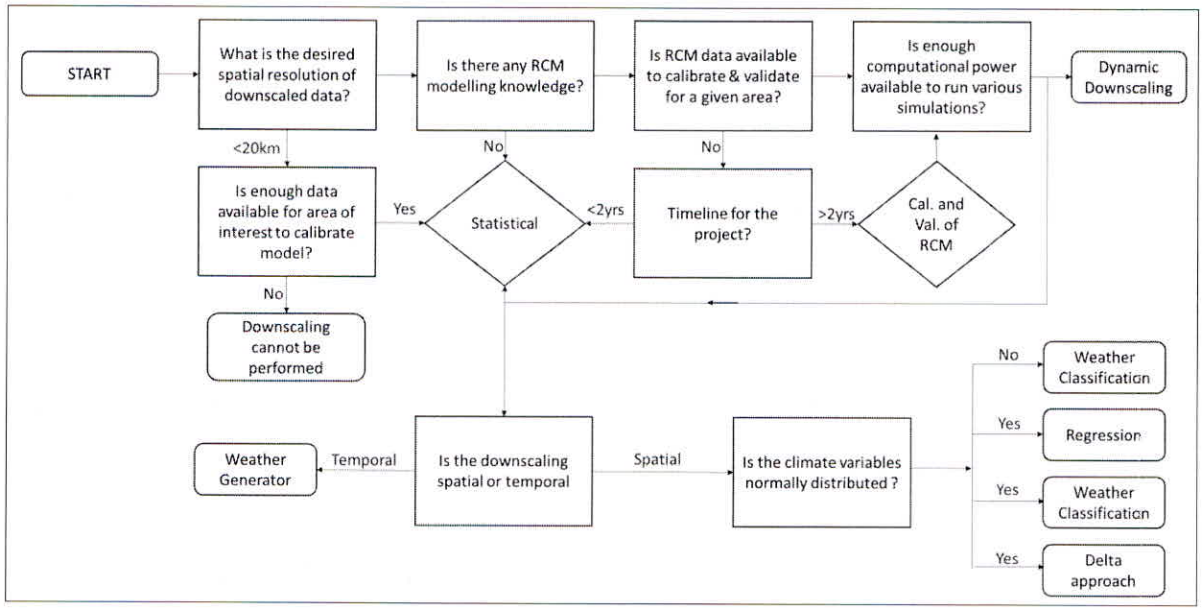


Figure 2.5: *Decision tree showing for different downscaling methods.*

2.4.2 GCMs Suitability in India

In India, very few studies have been completed to evaluate the GCMs applicability and to find out best GCMs for India (Ali and Mishra, 2018; Singh et al., 2017; Raju and Kumar, 2014). Several studies highlighted that no suitable GCMs are available in India region that may produce accurate predictions; for example, precipitation and temperature scenarios (Tiwari et al., 2014). Ali and Mishra (2018) compared the applicability of GCMs in terms of bias content and results show that five GCMs (e.g. MIROC5, MIROC-ESM IPSL-199, CM5A-MR, ACCESS1-0, and CNRM-CM5BEST-GCMs) show relatively lesser bias in P95 (median bias 1-15%) as compared to others. In another study done by Balvanshi and Tiwari (2018), the applicability of multi-model CMP5 GCMs has been tested over Madhya Pradesh Central India and GCMs such as CanESM2, CGCM3, GFDL2.0, HadCM3 and MIROC3.2 were found suitable for the analysis.

Mishra et al. (2014) tested the reliability of RCMs and GCMs over precipitation extremes in India and resulted that the mean ensemble of CORDEX-RCMs exhibited somewhat superior observations; however, the whole RCMs failed to expressively outperform GCMs. Singh et al. (2017) compared the applicability of CORDEX-RCMs (e.g. RegCM4) and CMIP5 GCMs (GFDL-CM3, GFDL-ESM2M, GFDL-CM2P1 etc.) for analyzing the hydro-meteorological changes at smaller scales over Sikkim Himalayas and the results showed that RCMs performed well only in case of temperature

projections under stationary conditions; while in case of precipitation, GCMs and RCMs did not account much variability and represented similar amount of uncertainty in their outputs.

Table 2.5: Best GCMs recommended for climate change studies in India.

GCM	Resolution (Lat ×Lon)	Simulation Period	Origin	No. of Simulation Runs
BCC-CSM and BCC-CSM 1.1 (m)	64 × 128	1850-2099	China	3
	160 × 320			
CanESM2	64 × 128	1850-2100	Canada	1
CCSM4	192 × 288	1850-2099	USA	6
CNRM-CM5	128 × 256	1850-2100	France	10
GFDL CM3	90 × 144	1850-2100	USA	1
HadGEM2-ES	145 × 192	1850-2100	UK	4
IPSL-CM5A-LR	95 × 96	1850-2100	France	2

Smitha et al. (2018) used raw RCMs and GCMs (e.g. CNRM-CM5.0, GFDL-CM3.0) and applied bias correction methods such as local intensity scaling, power transformation and distributed mapping to correct precipitation over six different watersheds based on different climatic conditions; also concluded that bias corrected RCM has the largest influence on the accuracy of daily rainfalls. Apurv et al. (2015) utilized raw CMIP5 GCMs (e.g. GOALS-g2, BCC-CSM1-1, IPSL-CM5A, CanCM4 and MRI-CGCM3) and then applied bias corrections to analyze decadal floods over the Brahmaputra basin and resulted significant flood frequency observations under regional scale varying climate conditions. Raju and Kumar (2014) ranked the applicability of GCMs as per Indian climatic conditions and their assessment showed that GFDL2.0, INGV-ECHAM4, UKMO-HADCM3, MIROC3, BCCRBCCM2.0 and GFDL2.1 are most suitable GCMs identified. Based on the detail literature, the best GCMs that may be applicable to India have been presented in Table 2.5.

2.5 Concluding Remarks

This chapter describes the significance of different downscaling methods in hydro-climatological studies. The application of GCMs and RCMs under different downscaling methods are evaluated. Based on the literature used in this chapter, it is concluded that raw GCMs are less applicable to capturing small- and large-scale climate information. Whereas, statistical and dynamic downscaled GCMs and RCMs outputs are capable to capture larger scale and regional-scale climatic variations across the world. This chapter comprehensively addresses few important topics of climate modeling such are GCMs projection capacity, selection of downscaling method, their limitations, applicability of GCMs and RCMs under different climate conditions etc. Dynamically downscaled RCMs have shown strong influence on the small scale and regional scale hydro-climatological changes. It has been seen that RCMs have much

capability to explore regional scale climatic variations because of its finer resolution, but are computationally expensive as it involves complex physics of atmospheric processes.

Due to less resources and high parameter demands in their processing, dynamic downscaling is not widely performed. Statistical downscaling approaches together with bias correction methods are helpful in the transformation of large-scale variables to local-scale variables. The statistical downscaling is well performed to overcome the special issue to get large-scale information at the finer scale. The scope of statistical downscaling of GCMs is capable to improve the skill of the prediction at local-scale. It is also clear that only GCMs or RCMs cannot give a proper estimation of hydro-climatological variables at different scales, because GCMs are mainly developed to predict the average general circulation pattern of the atmosphere-ocean-earth. Therefore, the coupling of downscaled GCMs and with hydrological models along with other physical, topographical and local meteorological parameters is necessary to produce reliable simulations and predictions of hydro-climatological variables. In this context, GCM derived climate perturbations can be utilized as model input in hydrological models. Although, RCMs have better spatial resolutions and able to capture the regional scale assessment, but their applicability is also limited and sometimes they also found less predictable in the case of point scale observation. The selection of downscaling method and GCMs/RCMs should be based on the scale and area specific, so appropriate RCMs and GCMs can be preferred that may enhance the prediction capability of the model. A comprehensive model validation procedure must be accounted to the selected and formulated models before they are utilized to simulate future climate change impacts.

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CHAPTER 3

CLIMATE CHANGE AND TEMPERATURE

P. K. Singh

3.0 Introduction

The 'Climate Change is Real' and 'the temperatures are rising' worldwide. There is a sense of mutual agreement among the world's leading climate agencies about this 'Change' as shown in Figure 3.1. About 97% of the research papers published in the field of climate science agree that the humans are the real drivers of the global warming and the climate change in recent times (Cook et al., 2016). The Paris Agreement (United Nations Framework Convention on Climate Change, UNFCCC, 2015) is specifically materialised and executed for developing effective plans for mitigating the greenhouse gases (GHGs)emissions and limit the global average temperature increase up to 1.5^0C above pre-industrial levels to avert the adverse and catastrophic impacts of climate change worldwide. India is also committed to achieve the emission reduction targets through reducing emission rates by 2030 and utilizing more of the non-fossil fuels and through carbon sequestration, increasing forest cover and changing land use land cover (LULC), particularly in agricultural sector.

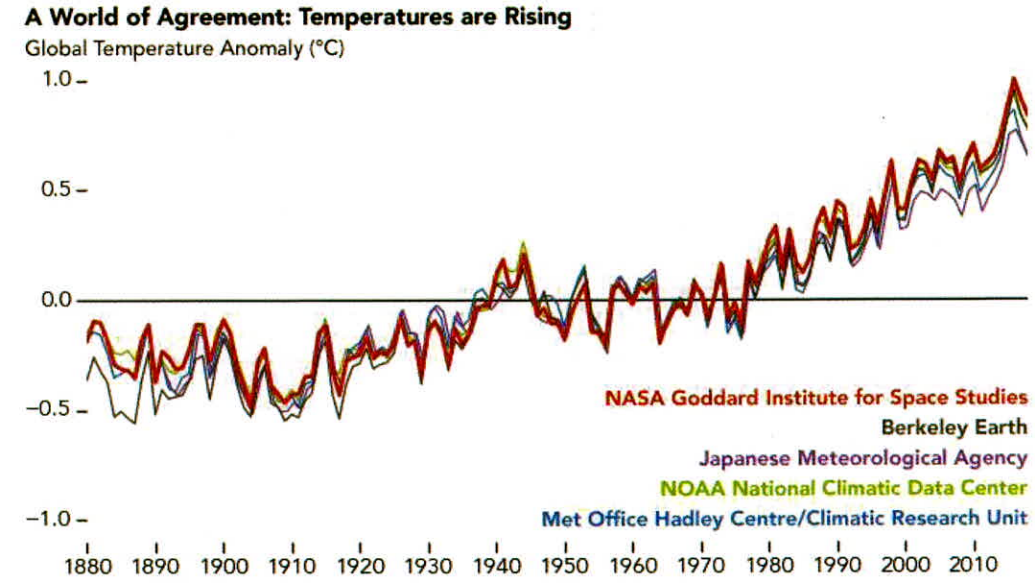


***Figure 3.1**: The rising temperatures (Source: https://climate.nasa.gov/scientific-consensus/)*

India has 17.5% of the world's population but occupies only 2.4% of the land resources and 4% of the water resources of the planet as a whole. India has agrarian economy and about 60% of the Indian agriculture is rainfed and hence the impacts of climate change on this sector will be far reaching on food and nutritional sustainability and has been placed at the 13th position among the most vulnerable countries to the climate change in the world. Notably, the temperature is one of the most important parameter of the climate system as a whole. The Assessment Report 5 (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014) states that the surface temperature (ST) will increase during the 21st

century under all emission scenarios and will have daunting impacts on agriculture, land and water resources, environment, ecosystems, biodiversity and society as a whole as shown in Figure 3.2.

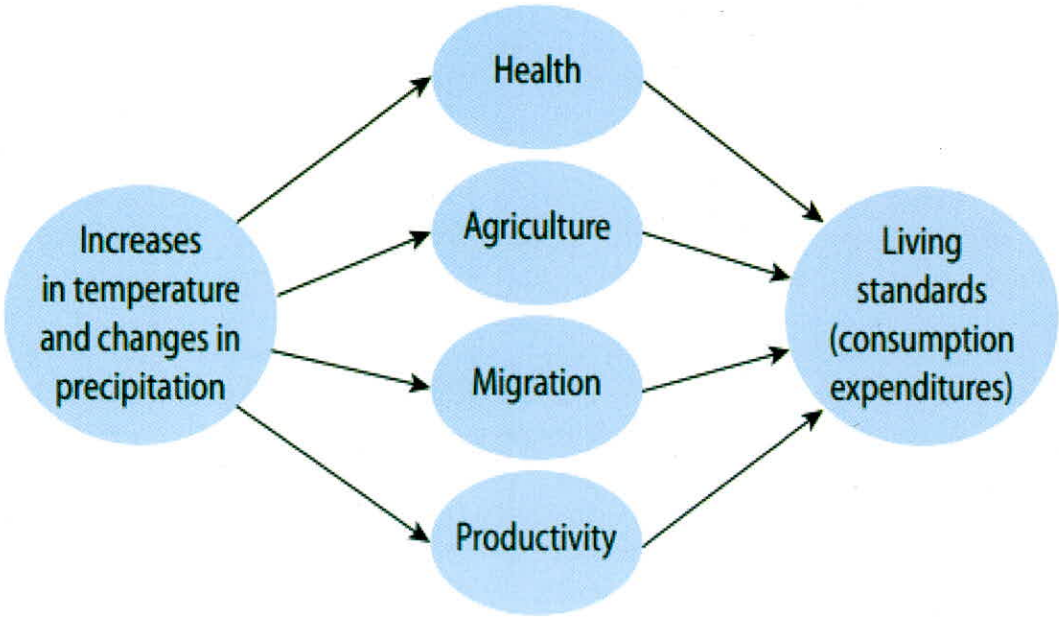


***Figure 3.2**: Interlinkages of climate change and different systems (Source: Mani et al., 2018)*

The anthropogenic influences on Earth's climate system are very pronounced and the emission of the GHGs (mainly Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), and fluorinated gases (F-gases) have increased since the pre-industrial era, which is largely attributed to the ever growing industrial, economic and other developmental activities coupled with the population growth (IPCC, 2014). Other than the land use land cover (LULC) change and anthropogenic aerosols, the GHGs are one of the most significant drivers of climate change phenomenon (IPCC, 2013), in which the CO_2 is the major component (73%) of GHGs followed by CH_4 (18%), N_2O (6%), and F-gases (3%).The CO_2 emissions from fossil fuels/energy are higher as compared to the other GHGs during the period of 1990-2017 (Figure 3.3). This rise in CO_2 concentrations is mainly attributed to the large scale industrialization (Olivier and Peters, 2018).

If we look at the climate history of the Earth relative to pre-industrial baseline (1850-1900) between evolution of life, global carbon cycle and temperature anomaly as shown in Figure 3.4 (Salawitch et al., 2017), the *Era 1* shows that there has been continuous increase of atmospheric CO2 due to anthropogenic activity leading to a temperature anomaly of 0.8^0C to 1.0^0C at a global scale. Notably, the climate change will be one of the greatest socio-environmental-economic threats to the entire world in the 21st century (Mahmood and Babel, 2014). The climate change phenomenon is unequivocal and has been accelerating since 1950s and the GHGs emissions are one of the major forcings/determinants impacting the change phenomenon at large. Most of the studies find that, if the current pace of unbounded economic growth continues, then by the end of the 21st century, the GHGs concentration may even cross the barrier of RCP 8.5. At a large, there are enough evidences of the anthropogenic footprints on the global warming (Basha et al., 2017). The climate change will further pose several constraints to the growth and developmental activities in South Asia, particularly in India (Ross et al., 2018). It may further adversely impact the agricultural production, water quality and quality,

hydro-power production, and on overall economy (Bapuji Rao et al., 2014; Ali et al., 2018; Duran-Encalada et al., 2017; and Gupta et al., 2014) an on many other aspects necessary for sustaining coupled human-environment systems.

The climate change phenomenon and their impounding impacts on nature and society have been greatly dwelt upon by various researchers, e.g., Sanchez et al. (2004), Mishra et al. (2015), Rohini et al. (2016), Mishra et al. (2017), and Panda et al. (2017). The climate change will have further severe impacts on the intensity and duration of winter and summer storms, heat waves, and hot and cold days and nights (Mastrandrea et al., 2011; Mahmood and Babel, 2014).

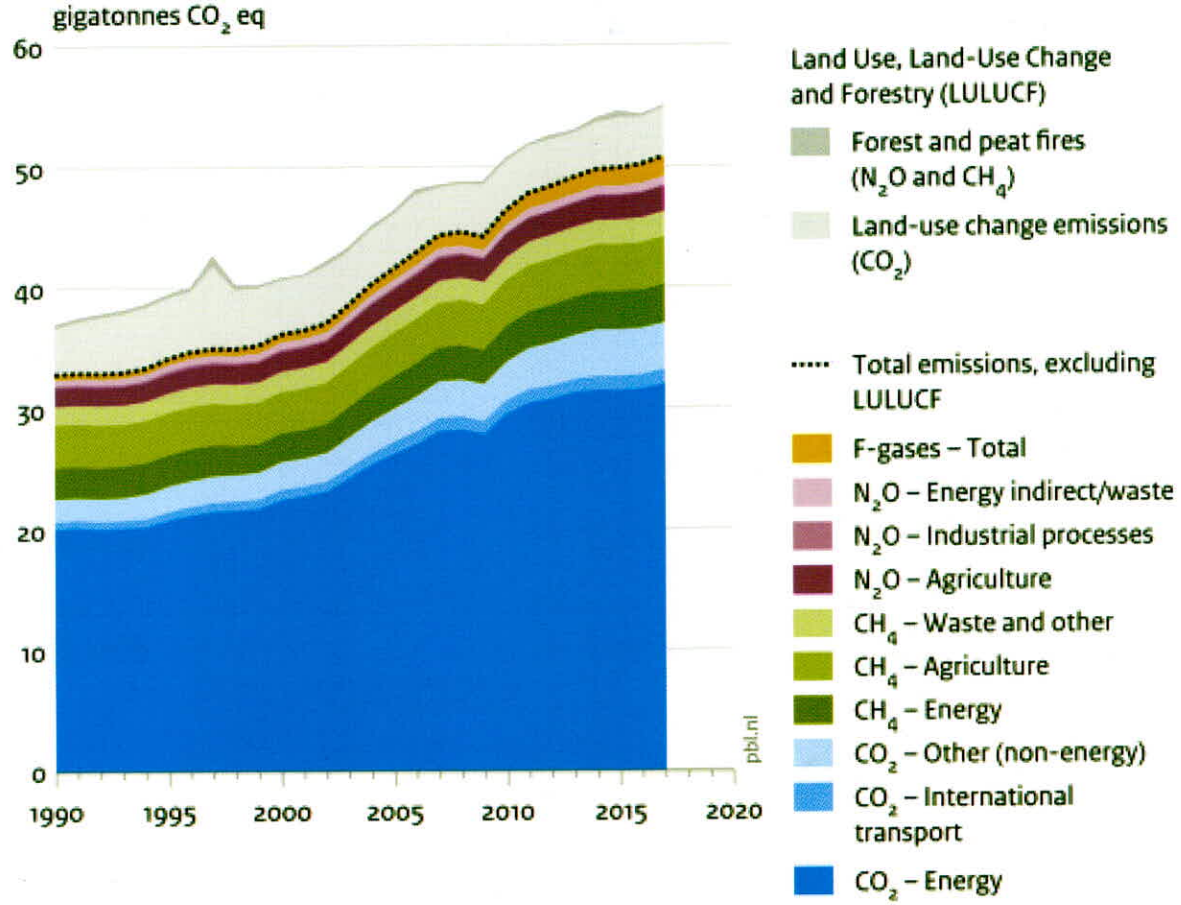


***Figure 3.3**: Trends in global GHGs emissions: types and sources (Source: PBL Netherlands Environmental Assessment Agency, Olivier and Peters, 2018)*

Worldwide, there is an increase in the number of warm days and nights and decrease in the number of cold days and nights between the period 1951 and 2010 (IPCC, 2013). In addition, there has been a continuous increase in the intensity, duration and frequency of warm spells and heat waves since the year 1950 (IPCC, 2013), which could lead to significant adverse impacts on the environment and society as a whole. The temperatures rise will further result into an increase in the frequency of heat waves and the extreme precipitation events will become more severe and frequent in nature in most parts of the world. Mondal et al. (2015) analysed the seasonal and annual temperature trends and percentage of change all over India for the period of 1901–2007 and they found that the mean temperature is significantly increasing in the majority of the regions and all seasons.

The Western Himalayas are found to have the highest increase in mean temperature, whereas, the entire northern and central India have significant rise in maximum temperature. Further, for India as a whole, they reported an increase in the mean temperature of 0.003^{0}C/year. Similarly, Annual Climate Summary (ACS) by India Meteorological Department (IMD) (2017) reported a rapid rise in all India mean STs over India, particularly since about 1980 during all the seasons and on annual average as shown in Figure 3.5. Here, it would be appropriate to mention that during the period of 1980's, India has improved its growth rate to 5.7% with a greater stability in most of the sectors, especially in industrial, domestic and agriculture (Nagaraj, 2000).

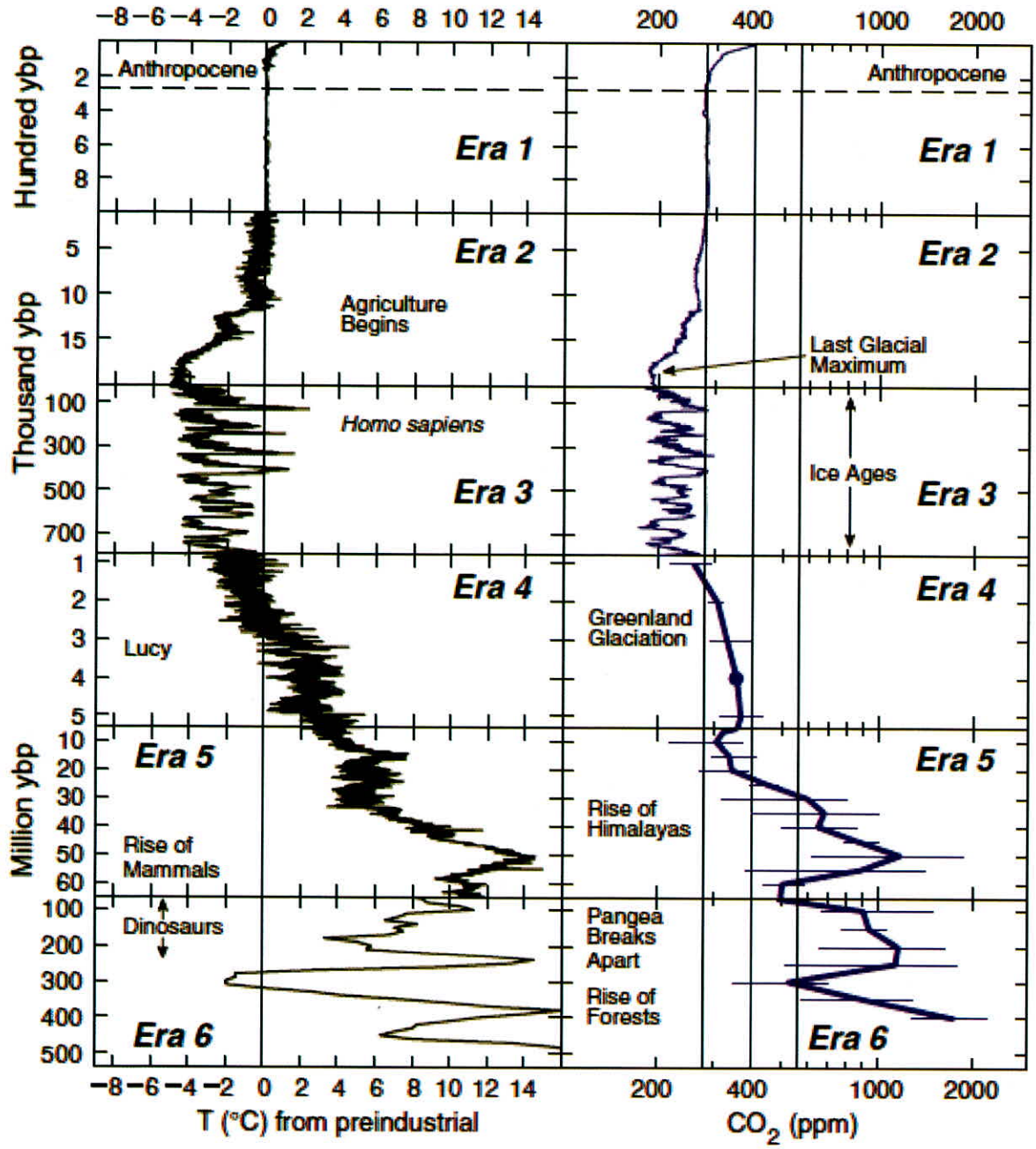


***Figure. 3.4.**: Climate history of Earth, past 500 million years (Salawitch et al., 2017).*

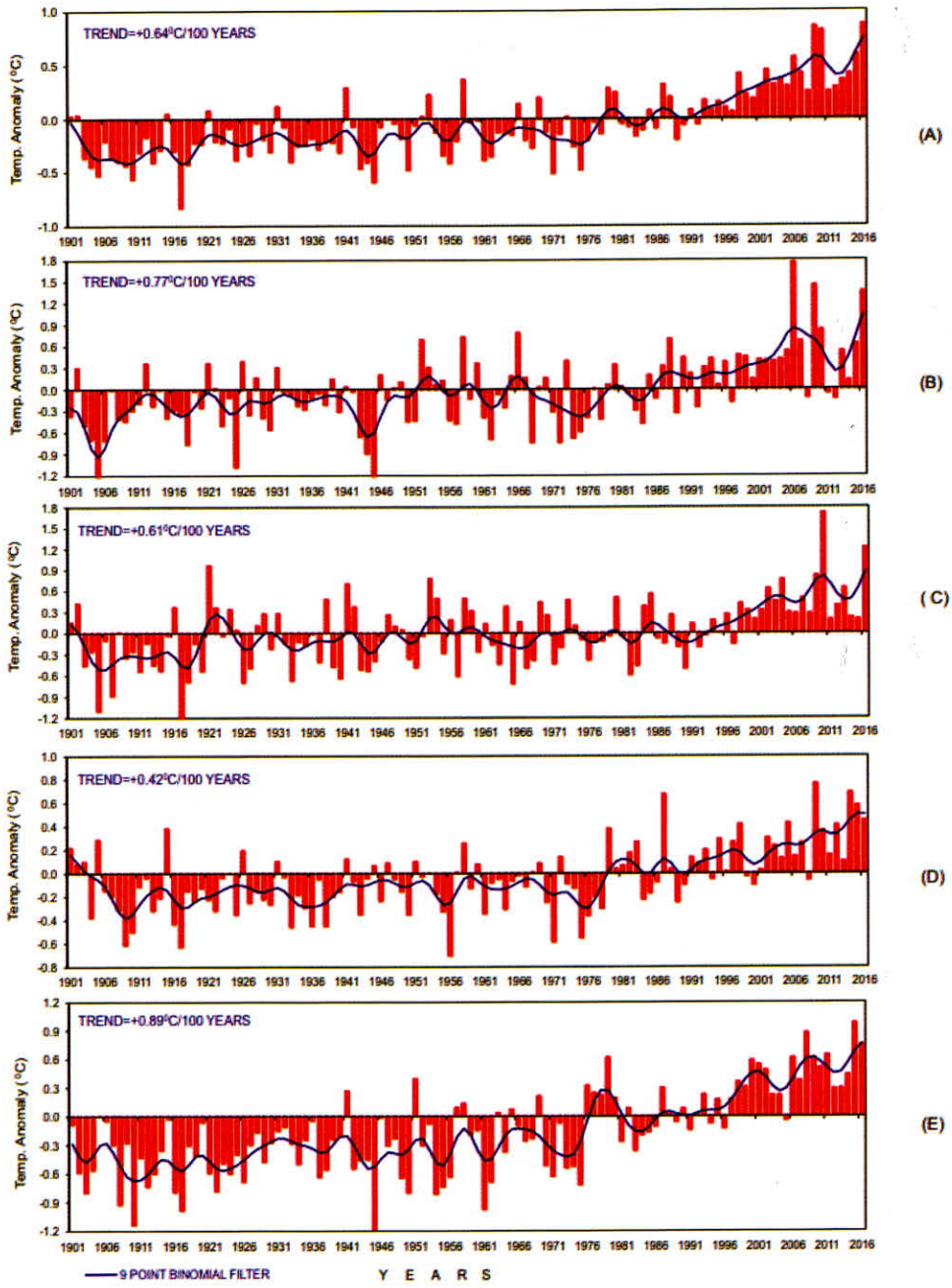


Figure 3.5: *All India mean temperature anomalies for the period of 1901-2016. (A)-represents annual, (B)-winter, (C)-pre-monsoon, (D)-monsoon, and (E)-post-monsoon. (Source: Annual Climate Summary, IMD, 2017).*

Keeping-in-view of the above, it would be interesting to diagnose the nature and patterns of long-term temperature changes over India and the world as a whole and explore the major factors/forcings responsible for making this phenomenon to happen. This diagnosis will help understand how these changes may effect various policy decisions for the sustenance of agricultural, infrastructural and industrial, water and land resources systems in India.

3.1 Past Surface Temperature Trends

3.1.1 Global Scenario

An understanding of the climate of the past will help improve our understanding on the behaviour of the modern climate change (Folland et al., 2001; Jansen et al., 2007; Mann et al., 2008). The study of past surface temperature trends is also essential for an accurate assessment of relative contributions of natural and anthropogenic influences on Earth's climate (Huang et al., 2000) as has also been very categorically shown (with respect to *Era*) in Figure 3.4. For this purpose, before 19th century, the 'proxy' data sources such as tree rings, corals, ice-cores and historical records were widely in use worldwide (Mann et al., 2008). The global mean surface temperature (GMST) is widely used as an indicator of global climate change (Rahmstorf et al., 2017) and has increased by 0.85^{0}C [0.65-1,06] ^{0}C over the period of 1880-2012 (IPCC, 2013) since the late 19th century and 0.89^{0}C [0.69-1.08] ^{0}C over the period of 1901-2012 based on independently produced dataset as shown in Figure 3.6 (IPCC. 2013).

Recently, Rahmstorf et al. (2017) conducted a change point analysis (CPA) of the past GMST change using five datasets, namely, NASA GISTEMP (Hansen et al 2010, GISTEMP Team 2016), NOAA (Smith and Reynolds, 2005; Smith et al., 2008), HadCRUT4 (Morice et al., 2012), the revision of HadCRUT by Cowtan and Way (2014), and the Berkeley Earth Surface Temperature (Rohde et al 2013) as shown in Figure 3.7. It can be seen from Figure 3.7 that the year 1980 can be taken as a change point or point of inflection. As for as pre-1980 is concerned, there have been both increasing and decreasing trends in global temperature and 1912 and 1945 can be taken as the points of inflection. From 1945 to 1980, there is a decreasing trend in the GMST change, whereas from 1912 to 1945 there is an increasing trend is GMST change.

3.1.2 Indian Scenario

According to the Annual Climate Summary (ACS) (IMD, 2017), the annual surface temperatures in India have increased during the period of 1901-2017 and this rise in temperature is mainly due to increase in GHGs concentrations in the atmosphere (Kothawale and Rupa Kumar, 2005; Jaswal et al., 2015; and Bal et al., 2016; Basha et al., 2017; and Ross et al., 2018). The long-term (1981-2015) annual average temperature and its linear trends for different parts of the country were developed by Centre for Climate Change Research- Indian Institute of Tropical Meteorology (CCCR-IITM) (2017) and are shown in Figure 3.8. The warming trends are more pronounced in the western Himalayan region, north west and extreme eastern parts of the country. The study also shows that the southern part show comparatively lower warming trends as compared to the rest parts of the country. For reference, the temperature homogeneous regions of the India are also shown in Figure 3.9.

The ACS states that there is an increasing trend in annual average temperature of 0.66^{0}C/ 100 year with the maximum variation during the post-monsoon season, i.e., 0.79^{0}C/100 year and the least, i.e., 0.43^{0}C/100 year during the monsoon season over the for the period of 1901-2017 (ACS-IMD, 2017). Purnadurga et al. (2017) investigated the daily maximum temperature variability over India for the period of 2001-2014 and 1971-2001 as base-line and found that the temperature difference (increase) is more pronounced in the northern parts as compared to the southern parts to the order of 1.4^{0}C-0.8^{0}C as shown in Figure 3.10. The values of mean maximum temperature for different homogeneous regions and India as a whole are also given in Table 3.1.

Long-term trends (for 107 years, i.e., 1901-2007) for minimum, maximum and mean temperatures for all the seven temperature homogeneous regions and India as a whole were analysed by

Mondal et al. (2015) and shown in Figure 3.11. This shows that the minimum temperature of EC, WC and IP regions of India is having an increasing trend over a time span of 107 years and a decreasing trend for NW region of India. The WH region is found to have highest increase in minimum temperature (0.008^0C/year) in the post monsoon season with significant decrease (-0.006^0C/year) in the winter season. Figure 3.11 also show that there is significant increase in maximum temperature in all the seven regions of India with highest increase in WH region (0.006^0C/year). This increase in maximum temperature is found to be the highest during the winter season (0.013^0C/year). The other regions such as WC, IP, NW, NC, NE regions of India show increasing trend in maximum temperature. A similar trend was also reported by Subash and Sikka (2014). The annual mean temperature is found to increase for all the regions and seasons of India with highest increase in WH region, i.e., 0.004^0C/year over the span of 107 years. The increase in the mean temperature is found to be highest during the winter season (0.009^0C/year) followed by pre-monsoon (0.008^0C/year) and post-monsoon season (0.006^0c/year) (Mondal et al., 2015). Remarkably, the increase in max. min., and mean temperatures is dominant during the post-monsoon and winter seasons.

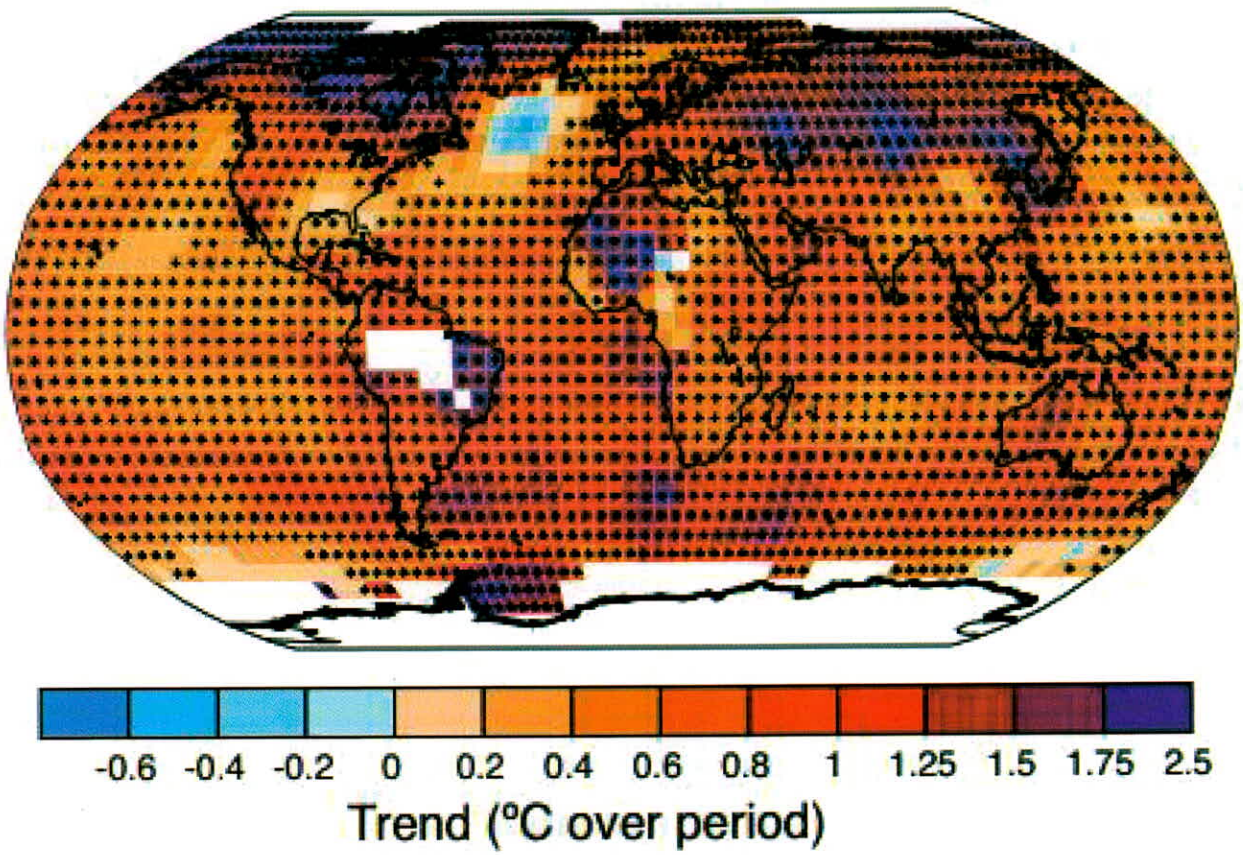


***Figure 3.6**: Surface temperature trends across the world since 1901 to 2012 (IPCC, 2013).*

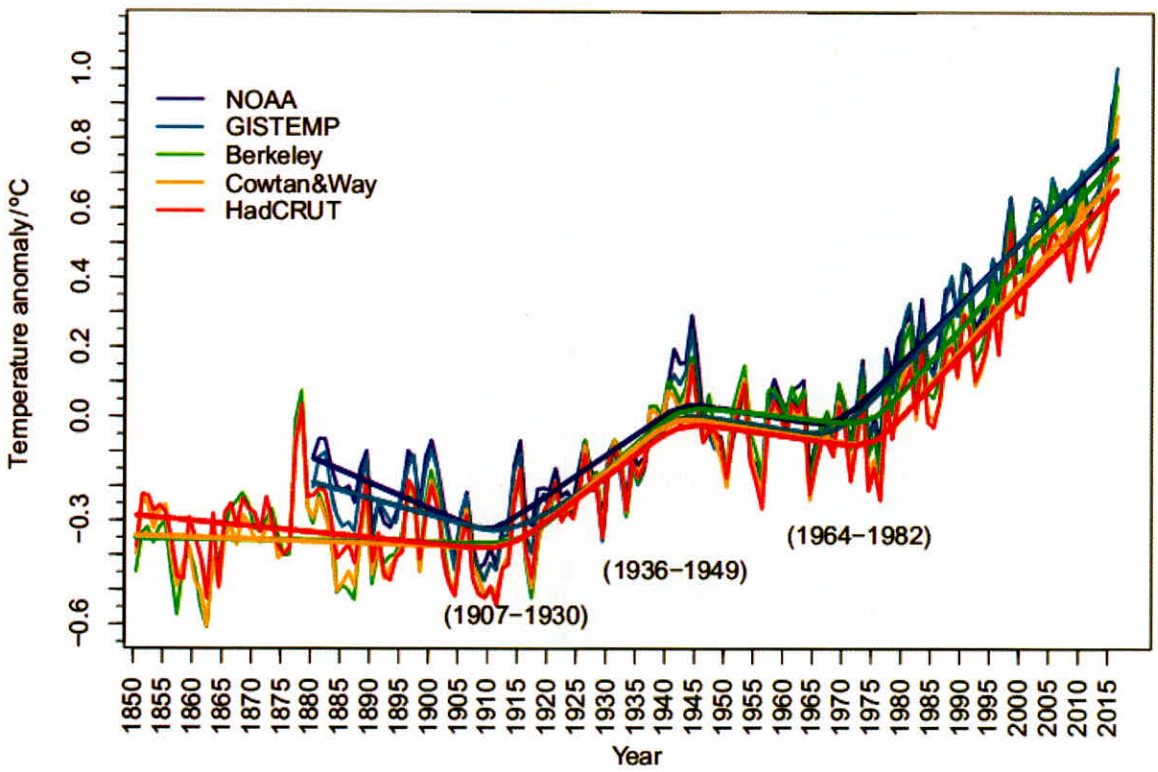


***Figure 3.7**: Global mean surface temperature (GMST) trends from 1850-2015. (Source: Rahmstorf et al., 2017)*

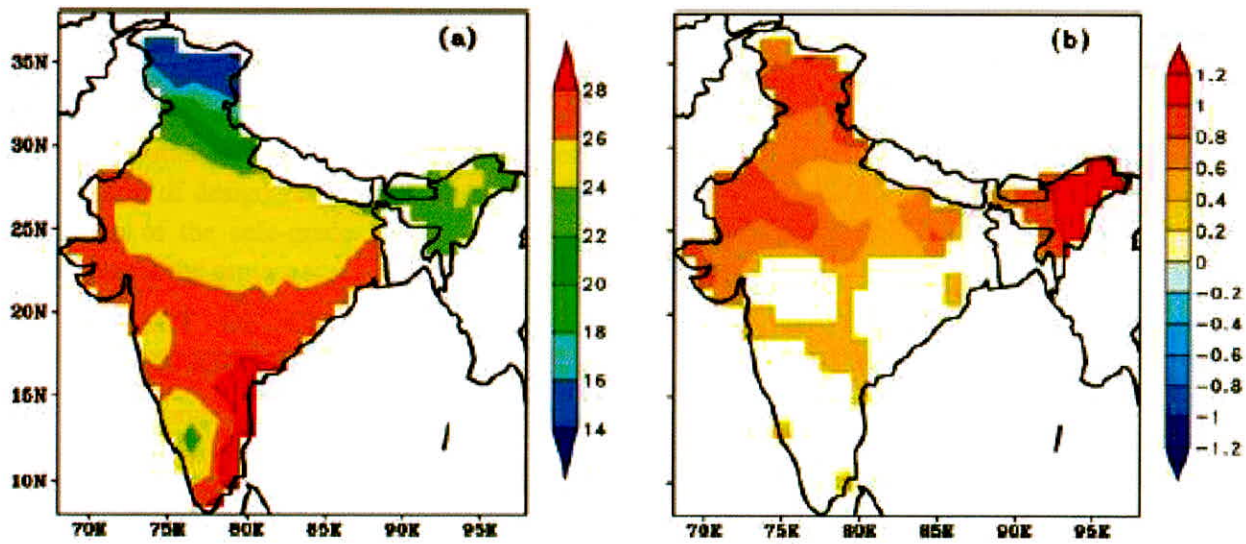


***Figure 3.8**: Long-term (1981-2015) annual average temperature (a) and variability trends (b) for India (Source: CCCR-IITM, 2017).*

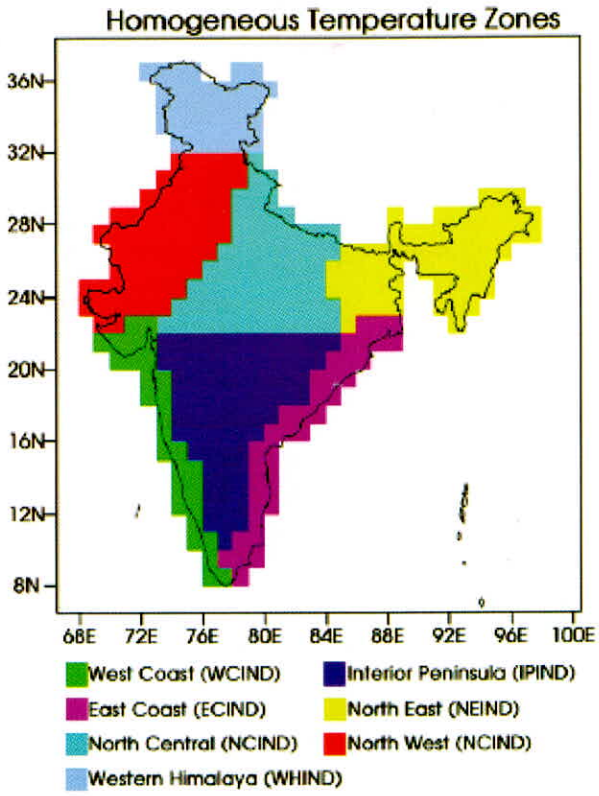


***Figure 3.9**: Homogeneous temperature zones in India (Dillepkumar et al., 2018).*

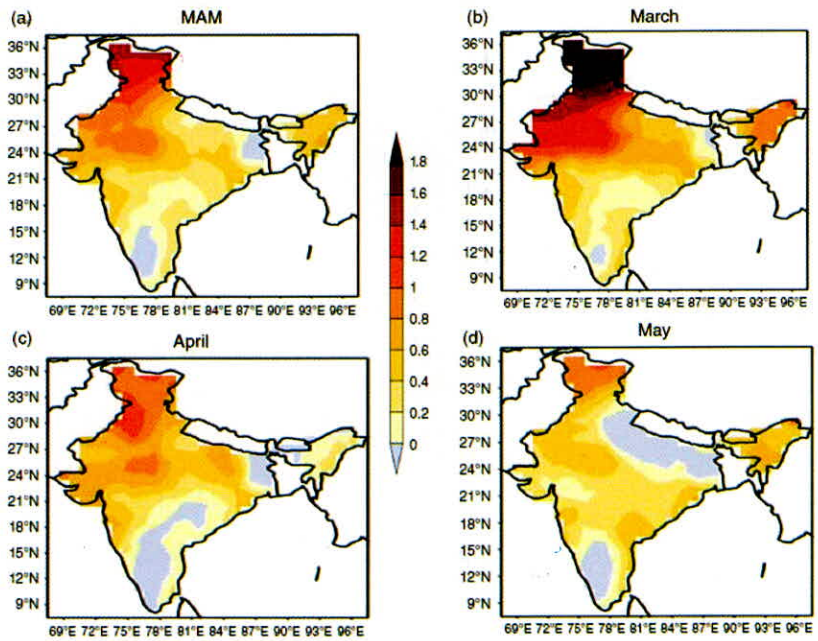


***Figure 3.10**.: Maps showing difference in the max. temperature variability between the periods of 2001–2014 and 1971–2000 for (a) summer season (March, April and May average), (b) March, (c) April and (d) May as an individual (Source: Purnadurga et al., 2017).*

Table 3.1. Long-term mean maximum temperature (^{0}C) over India and seven homogeneous regions over the periods of 1971–2000 and 2001–2014 (Source: Purnadurga et al., 2017).

Region	March		April		May		MAM	
	1971-2000	2001-2014	1971-2000	2001-2014	1971-2000	2001-2014	1971-2000	2001-2014
All India	31.2	32.0	34.9	35.3	36.3	36.7	34.1	34.7
WH	16.2	18.4	22.6	23.5	26.7	27.6	21.8	23.2
NW	29.9	31.3	36.7	37.5	40.2	40.5	35.6	36.4
NC	32.4	33.2	38.4	38.9	41.1	37.3	37.3	37.7
NE	28.1	29.0	29.3	29.4	31.0	29.3	29.3	29.8
WC	34.9	35.3	36.9	37.4	37.1	36.2	36.2	36.6
IP	36.4	36.6	39.3	39.4	40.7	38.7	38.7	38.9
EC	35.0	35.4	37.2	37.4	38.9	36.9	36.9	37.2

where: WH= Western Himalayas; NW= North West; NC= North Central; NE= North East; WC=West Coast; EC= East Coast; and IP=Interior Peninsula.

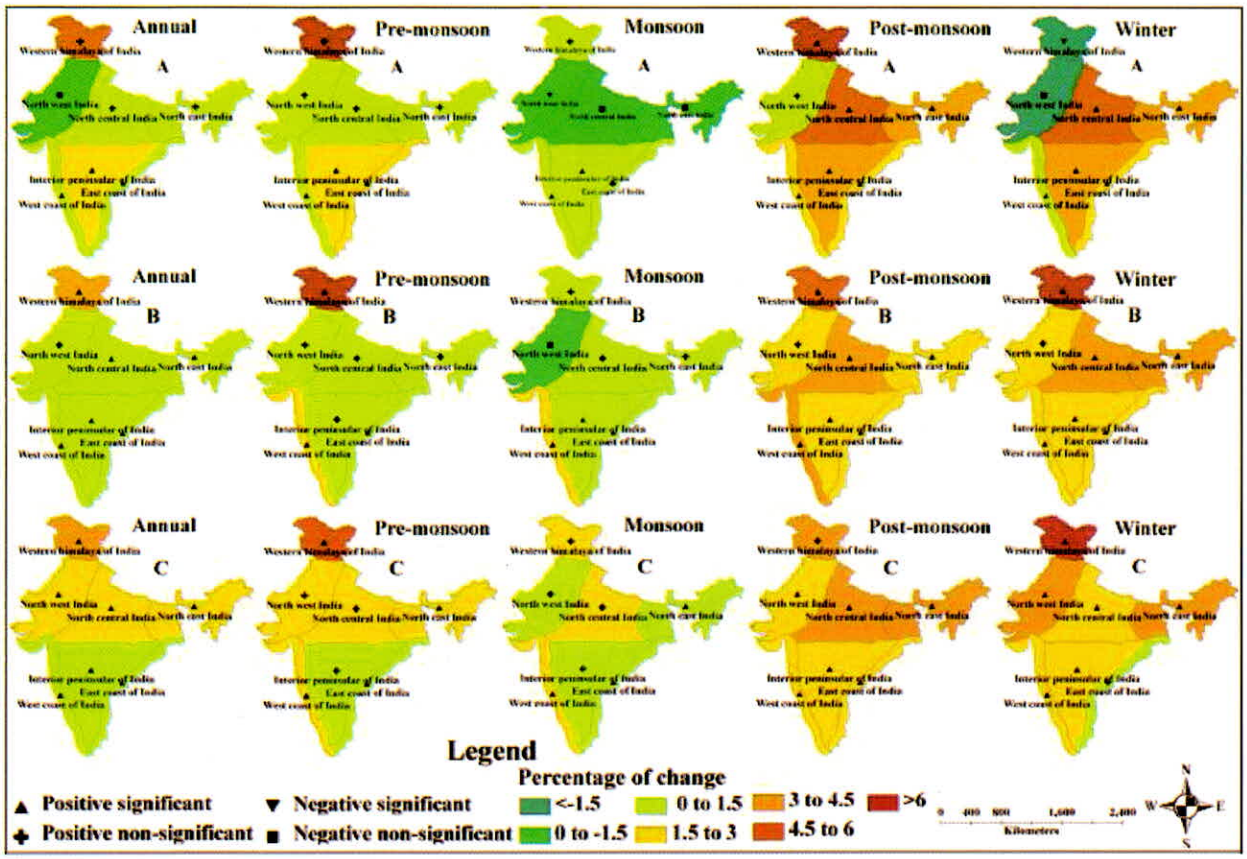


***Figure 3.11**: Spatial patters of the trends for minimum (A), mean (B) and maximum (C) temperature for seven regions and all India for a span of 107 years (1901-2007) (Source: Mondal et al., 2015).*

3.2 Projections of Surface Temperature due to Climate Change

The climate models have been developed to study the Earth's present climate and explore the Earth's past and future climate systems along with an assessment of the impacts of variability of drivers/forcings of the climate system in space and time. The simulations developed by these models along with different RCPs are used for future projections of climatic variables, such as temperature, precipitation, etc.

3.2.1 Global Scenario

The global average temperature is found to increase in the range of 0.65–1.06 ^{0}C with an average of 0.85 ^{0}C for the period of 1800–2012 (IPCC, 2013), and an overall increase of 0.74±0.18 ^{0}C during the period of 1906–2005 (IPCC, 2007). This increasing trend in temperature is further projected to accelerate during the 21st century under all the RCPs (Mahmood and Babel, 2014) and it is projected to increase by 5.5^{0}C by the end of 21st century (Stocker et al., 2013). The projected values of increase in global mean surface temperature at the end of 21st century will be in the range of 0.3–1.7 ^{0}C (RCP 2.6), 1.1–2.6 ^{0}C (RCP4.5), 1.4–3.1 ^{0}C (RCP 6.0), 2.6–4.8 ^{0}C (RCP 8.5) relative to 1986–2005 and shown in Figure 3.12a (IPCC, 2014). The spatial variation of the global mean surface temperature is also shown in Figure 3.12b. Table 3.2 shows the global mean surface temperature relative to 1865-2005 for the mid and late 21st century for RCP 2.6 and RCP 8.5. Table 3.2 also depicts the range of the variation of the global mean surface temperature (min. and max.) with their mean value.

Steffen et al. (2018) coined the term "Hothouse Earth" which indicates an increase of global average temperature of 4-5°C higher than the pre-industrial level with an increase of sea level from 10-60 m higher than today's sea levels. The authors find that the planet 'Earth' will become un-inhabitable, if the "Hothouse Earth" condition becomes a reality. It was found that the GHGs are the major forcings responsible for these conditions and advocated for an emission-less world trade and economy.

Table 3.2: Projection of global mean surface temperature for the periods of 2046-2065 to 2081-2100 relative to the 1986–2005 (IPCC, 2014).

		2046-2065		2081-2100	
	Scenario	Mean	Likely range	Mean	Likely range
Global mean surface temperature change (^{0}C)	RCP2.6	1.0	0.4-1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9-2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8-1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4-2.6	3.7	2.6 to 4.8

Bathiany et al. (2018) analysed 37 climate models for detecting the changes in the standard deviation (SD) of monthly temperature anomalies using the data comprising of the historical simulations from 1850 to the 21st century with the highest greenhouse gas emission, i.e., RCP8.5. The study reported several hotspots of increase in SD of monthly temperature anomalies over Amazonia, Southern Africa, Australia, the Sahel, the Arabian Peninsula, India, and Southeast Asia as shown in Figure 3.13.

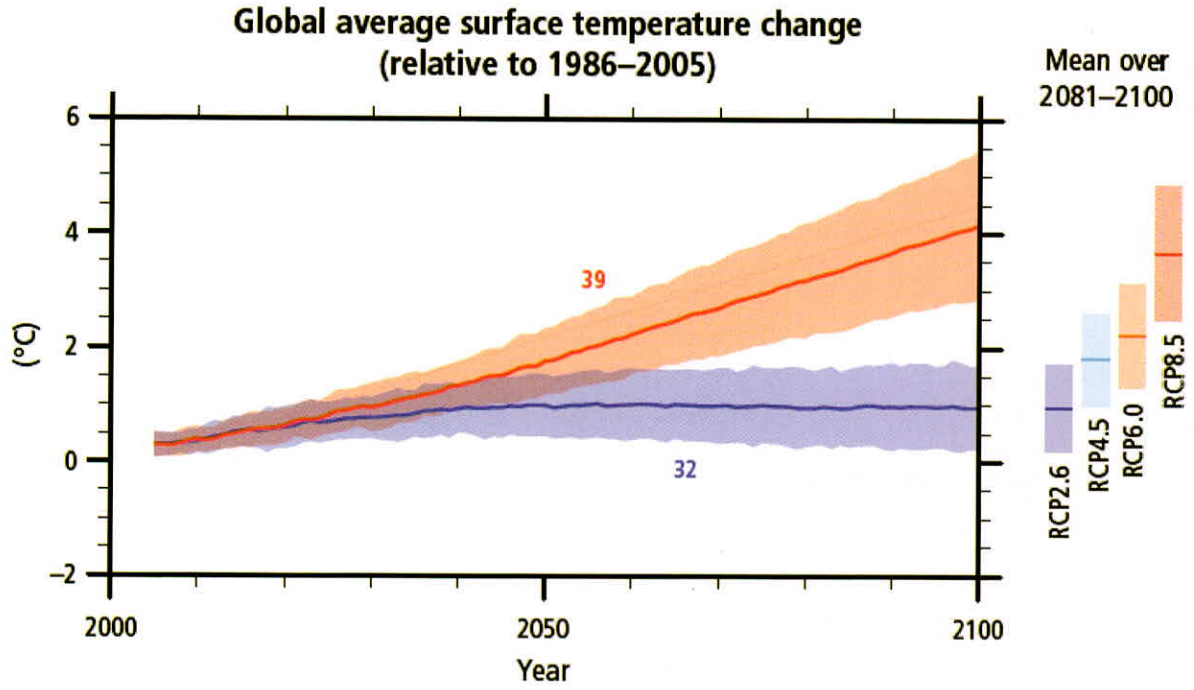


***Figure 3.12a**: Global average surface temperature change. The shading represents 5-95% confidence interval (Source: IPCC, 2014).*

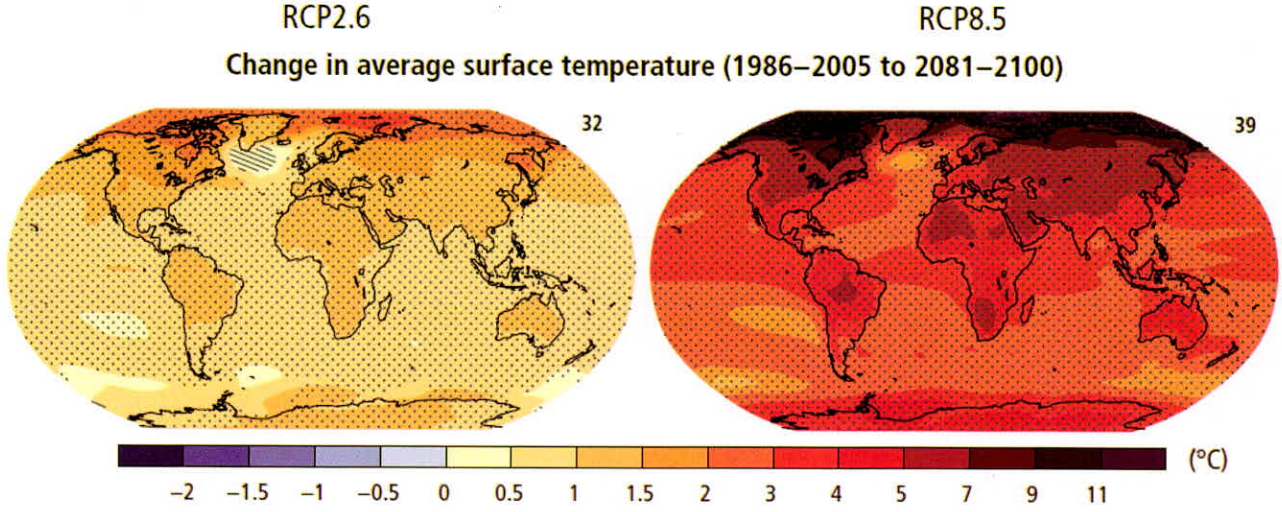


***Figure 3.12b**: Spatial variation of global average surface temperature change (Source: IPCC, 2014).*

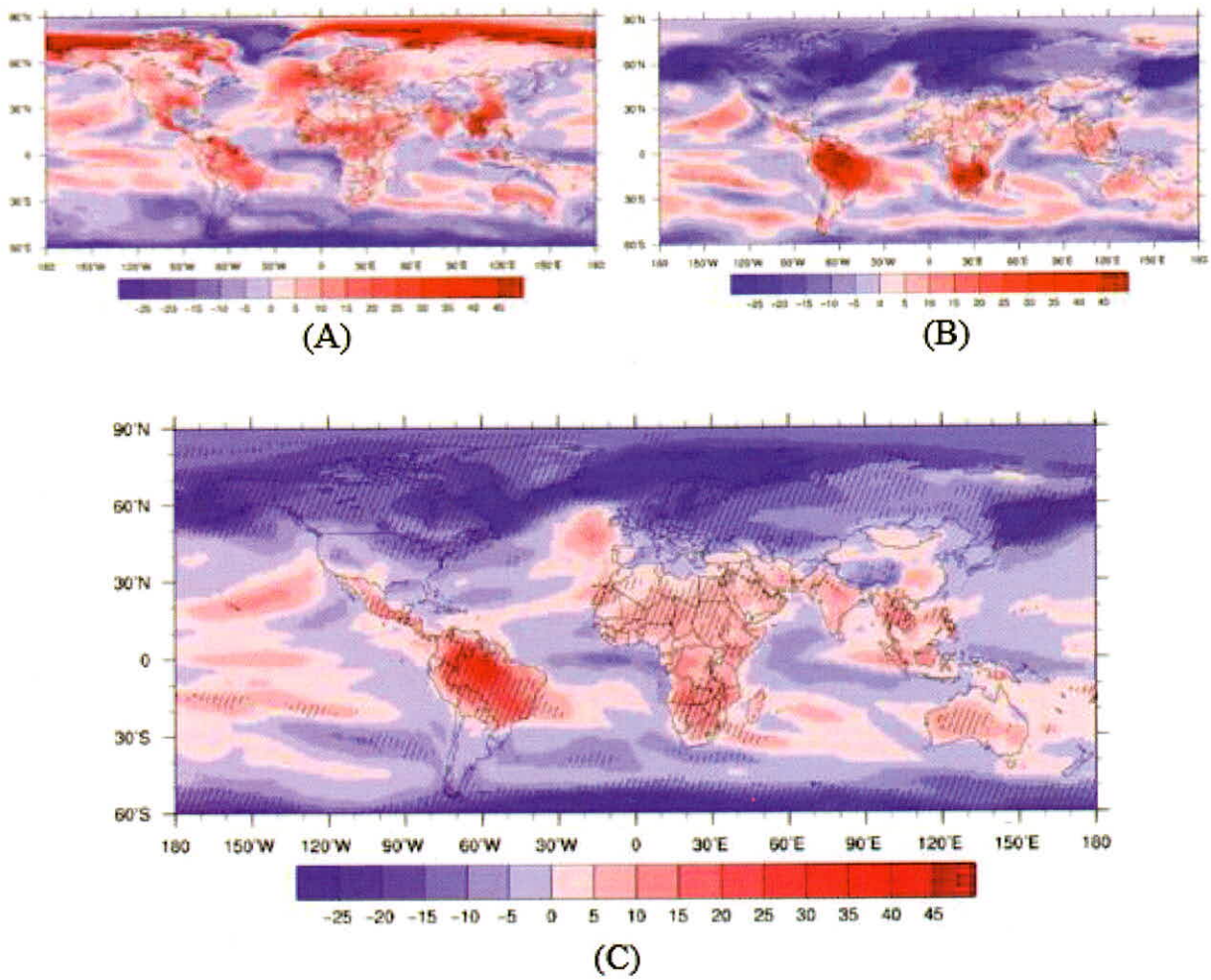


***Figure 3.13**: Relative changes of SD of monthly temperature anomalies for the period of 1850- 2100. (A): Boreal summer-June-July-August (JJA), (B): Austral summer-December- January-February (DJF), and (C): the whole year. (Source: Bathiany et al., 2018)*

3.2.2 Indian Scenario

India is highly vulnerable to climate change and a consistent increasing trend in mean, minimum, and maximum temperatures over India has been observed during the last century (Kothawale and Kumar, 2005; Kothawale et al., 2010; and Murari et al., 2015) with unevenness in trends during the different seasons of the year (Das and Hunt, 2007). Kumar et al. (2013) found that the temperature rise may range from 2.5 °C to 5.5 °C with maximum susceptibility over Himalayas, north, central and western parts of India with a lower influence on the southern part of India and will have more warm days and nights as compared to the cold days and night. As mentioned previously, the climate change phenomenon in India is largely attributed to the complex interactions between natural and anthropogenic forcings (Bal et al., 2016; Basha et al., 2017).

Bathiany et al. (2018) also found that the climate change in India is mainly due to larger influence of atmospheric variability than the soil drying, i.e., a reduction in soil moisture. Bal et al. (2016) used PRECIS simulations and found that India may experience an increase of 3.4 ^{0}C in the maximum air

temperature by the end of 21st century with reference to the baseline (1975-2005) under A1B scenario. Future changes in maximum and minimum temperatures across all the states of India were also projected by Bal et al. (2016). It was found that the change in the maximum temperature will vary from 0.9°C-1.1°C, 1.9°C-2.5°C, and 2.4°C-4.2°C for 2020s (2005-2035), 2050s (2035-2065) and 2080s (2065-2095), respectively under SRES A1B scenario.

Future projections of STs for India were also developed by Basha et al. (2017) by using RCP2.6 and RCP8.5 and it was found that the mean temperature will increase by 3.2°C by the end of the 21st century as shown in Figure 3.14. A similar projection was also made by Bal et al. (2016) as discussed above. These findings show that there will be on an average increase of average annual ST by 3.2°C all over India and therefore suitable measures have to be adopted to mitigate the adverse impacts arising out of this increase in the surface temperature. The study also finds that the increase in the temperature relative to 1901–1960 base line under different RCPs, i.e., RCP2.6, RCP4.5, RCP6.0 and RCP8.5 will be 1.8 °C, 2.0 °C, 3.5 °C, and 5.0 °C, respectively. The study indicates a warming trend of 0.2 K/decade over India, if the long-term (2006-2099) period is considered for analysis. Further, the far-future projections, i.e., the period from 2080-2099 indicates a cooling trend for all over India, except for southern India.

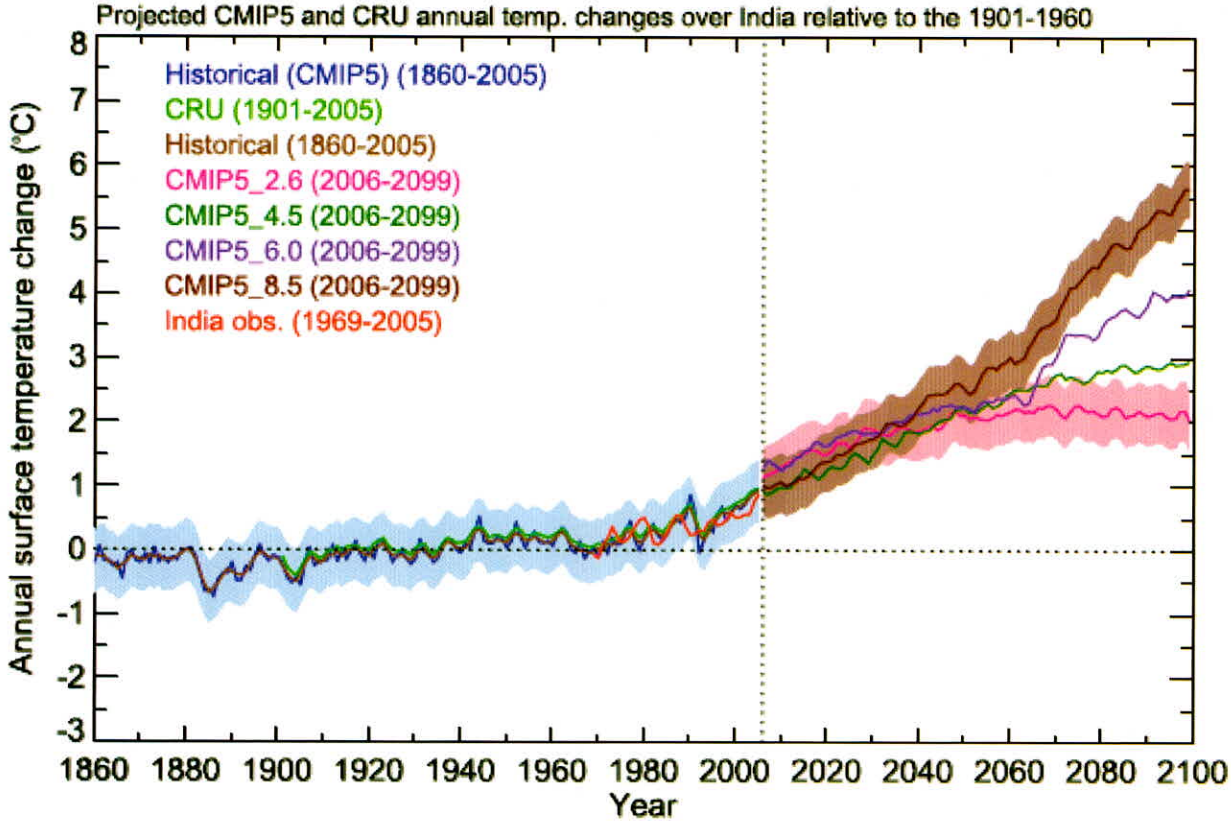


Figure 3.14: *Future projection of annual mean surface temperature over India for the period: 1860–2100 relative to the base-line period: 1901–1960. (Source: Basha et al., 2017).*

Patwardhan et al. (2016) assessed the impacts of climate change on seasonal maximum and minimum temperature and precipitation using PRECIS RCM model for five temperature homogeneous regions (Figure 3.15) excluding the hilly regions of country (i.e., Jammu and Kashmir, Himachal

Pradesh, Uttarakhand, North East regions). The study finds that the mean maximum surface air temperature for the pre-monsoon season (MAM-March-April-May) and mean minimum temperature for the winter season (JF-January and February) may increase by 4.0^{0}C by the end of 21st century using A1B scenario. Regions-wise the temperature anomalies (max. and min.) for different periods, i.e., 2020s, 2050s, and 2080s are also given in Table 3.2 and Table 3.3.It can be observed from the Table 3.2 and Table 3.3 that the rise in min. temperature is more than the rise in the max. temperature for all the regions, except Peninsular region at end of 21st century.

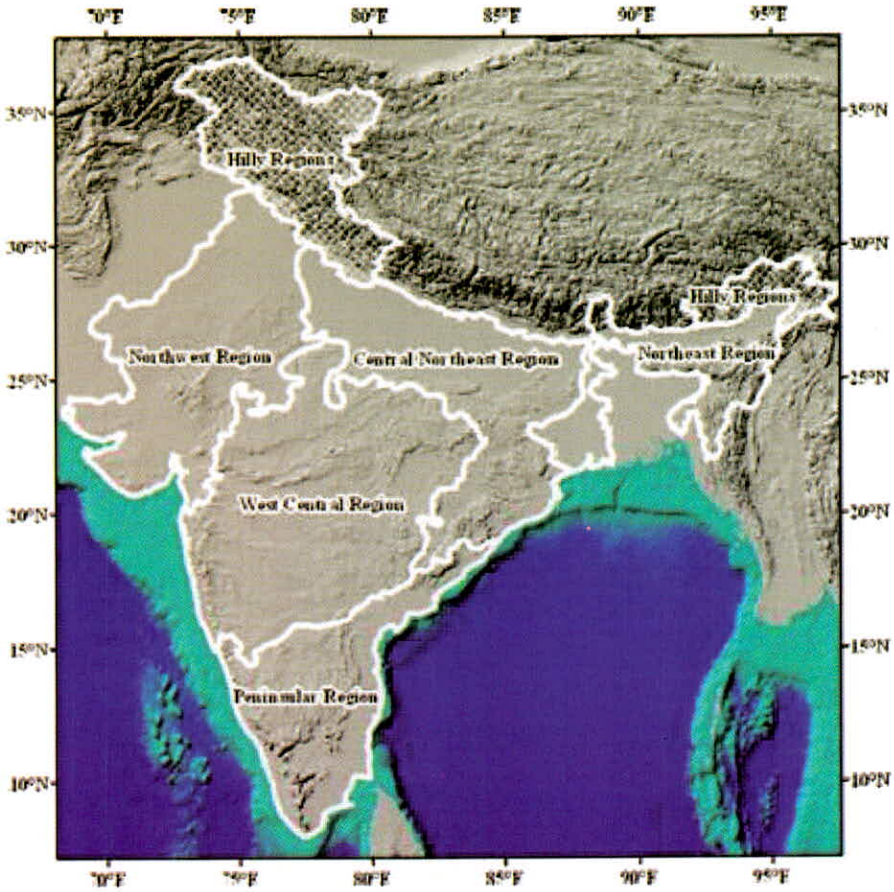


***Figure 3.15**: Five temperature homogeneous regions excluding the hilly regions of country (Source: Patwardhan et al., 2016)*

Table 3.2: Anomaly in maximum temperature for future projections relative to 1970 based on A1B scenario for four different regions and MAM season of India (Source: Patwardhan et al., 2016)

Region	Anomaly in maximum temperature (^{0}C)		
	2020s	2050s	2080s
North-west	1.6 (1.3-1.9)	3.0 (2.6-3.6)	4.1 (3.7-4.5)
Central-NE	1.7 (1.4-1.9)	3.1 (2.7-3.5)	4.4 (4.1-4.7)
Northeast	1.2 (1.1-1.4)	2.5 (2.2-2.6)	3.7 (3.5-3.9)
West central	1.6 (1.5-1.7)	3.0 (2.6-3.5)	4.1 (3.7-4.3)
Peninsular	1.4 (1.2-1.5)	2.7 (2.4-2.9)	3.8 (3.6-3.9)

Table 3.3: Anomaly in minimum temperature for future projections relative to 1970 based on A1B scenario for four different regions and JF season of India (Source: Patwardhan et al., 2016).

Region	Anomaly in minimum temperature (^{0}C)		
	2020s	2050s	2080s
North-west	1.7 (1.5-1.8)	3.6 (2.8-3.6)	4.3 (3.6-4.7)
Central-NE	1.8 (1.7-1.9)	3.6 (3.4-3.7)	4.6 (4.4-4.9)
Northeast	1.7 (1.6-1.9)	3.4 (3.1-3.7)	3.6 (4.2-4.9)
West central	1.9 (1.5-2.0)	3.2 (2.9-3.5)	4.2 (4.0-4.4)
Peninsular	1.4 (1.0-1.7)	2.7 (2.5-2.9)	3.8 (3.7-3.8)

3.3 Impacts of Different Forcings on Surface Temperature

As discussed above, the anthropogenic activities led to the change in Earth's climate. A linear and deterministic response relationship may be assumed between the 'Earth System' and the anthropogenic influences by the humans or the society as a whole worldwide (Steffen et al. 2018), i.e. higher the anthropogenic forcing will lead to higher GHGs emissions and higher increase in global STs. The factors responsible for creating an imbalance between the natural Energy Balance system of Earth-Atmosphere either by anthropogenic or natural are known as climate forcings. These imbalances lead to change in the energy balance (warming or cooling) of the atmosphere, land and ocean systems. The anthropogenic influences such as increased rate of GHGs emissions, increased aerosols, LULC changes, volcanic activity are the main climate forcings responsible for global warming and increase in STs. These forcings are also known as radiative forcings(RF) responsible for perturbation of energy in Earth system and expressed in the unit of W/m^2. A value greater than zero indicates for near-surface warming and less than zero stands for cooling as shown in Figure 3.16. As per the AR5 (IPCC, 2014), total anthropogenic RF for 2011 relative to 1750 is 2.3 W/m^2 and this corresponds to a CO2-equivalent concentration of 430 ppm with an (uncertainty range 340 to 520 ppm).

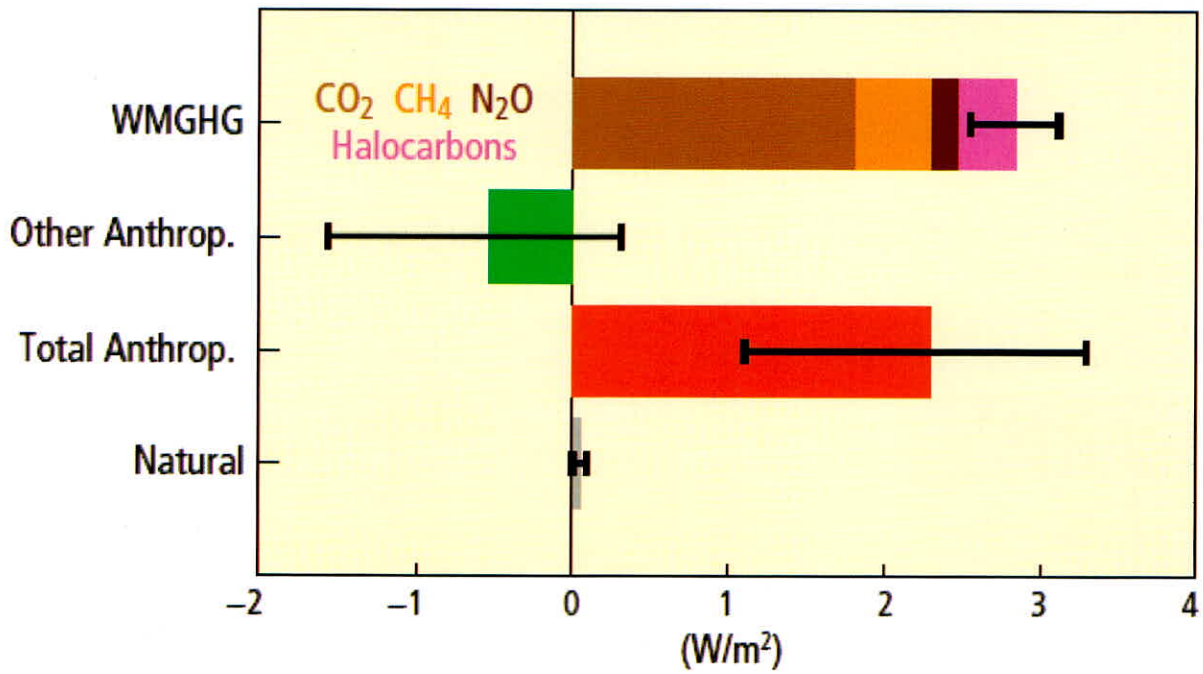


***Figure 3.16**: Variability of different forcings during the period of 1750-2011 (IPCC, 2014).*

3.3.1 Impacts of GHGs Emissions on Surface Temperature

As discussed in the beginning of this chapter and shown in Figure 3.3, the CO2 is the most important component of GHGs and has the largest contribution to the global warming. Figures 3.17 show a resemblance between the CO2 and long-term temperature change in late past at varying time scales. The warming is increasing consistently with CO2 level and the year 1975-80 can be taken as a point of inflexion.

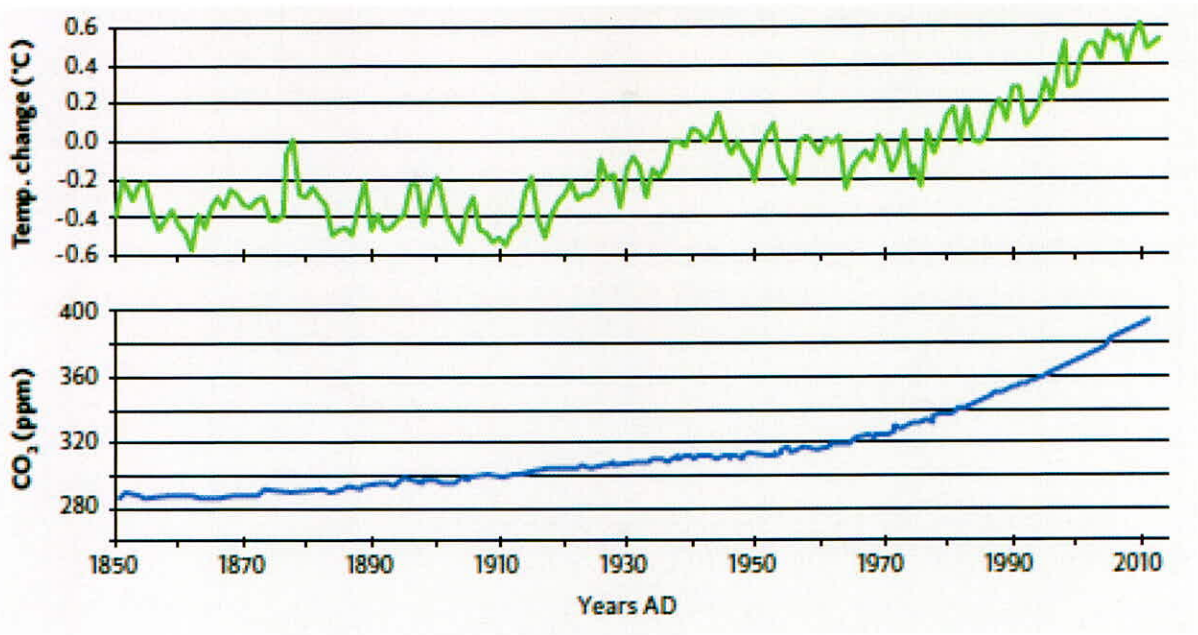


***Figure 3.17**: CO2 and corresponding temperature anomaly over the period of 1850-2010 (Source: The science of climate change: Questions and answers; Australian Academy of Science, Canberra, 2015).*

The increased concentration of GHGs is one of the major drivers of the climate change (Holmes et al., 2016; Dileepkumar et al., 2018) as depicted in Figure 3.18. The concentrations of the three major components of GHGs, i.e., CO2, CH4 and N2O has increased from 280 to 380 ppm, 800-1800 ppb, and 270-310 ppb, respectively over a span of 250 years (1975-2000) (IPCC, 2014). Figure 3.19 also shows the contribution of the internal and external forcings to global warming over the period of 1951-2010. The aerosols (Meehl et al., 2011, Morice, 2011, Kaufmann et al., 2011; and Wilcox et al., 2013), solar irradiance (Tett et al., 2002) and LULC (Bonan, 2008; Fall et al, 2010; Pielke et al., 2011; Deng et al., 2013; Zhang et al., 2016; Chang et al., 2018) also have propounding impacts on global warming. The aerosols may have negative warming impacts, i.e., cooling and the LULC change (LULCC) is the second largest contributor of global warming after GHGs (Mahmood et al., 2010). A brief discussion on the impacts of LULC change on global warming is being presented in the following sub-section.

3.3.2. Impacts of LULC Change (LULCC) on Surface Temperature

The change in LULC affects the global climate change through biogeochemical, biogeographical, and biophysical effects (Zhang and Liang, 2018) on the terrestrial surface and atmosphere (Pielke et al., 2011). It alters the surface solar and long-wave radiation and change the heat, water vapour and CO2, aerosols, etc. (Pielke et al., 2011). The biogeochemical effects mainly account for the carbon cycle and

associated changes in atmospheric CO_2, whereas, the biophysical factors accounts for land surface albedo, evapotranspiration (ET) and surface roughness (Brovkin et al., 2013a&b).

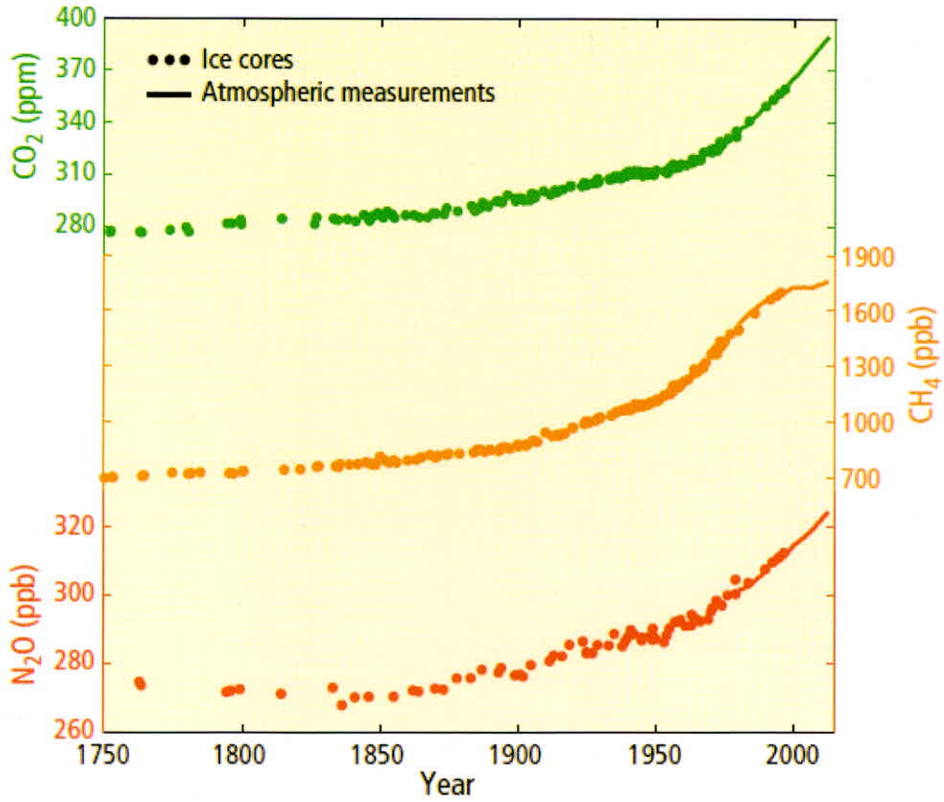


***Figure 3.18**: Variability of GHGs concentrations with time (Source: IPCC, 2014).*

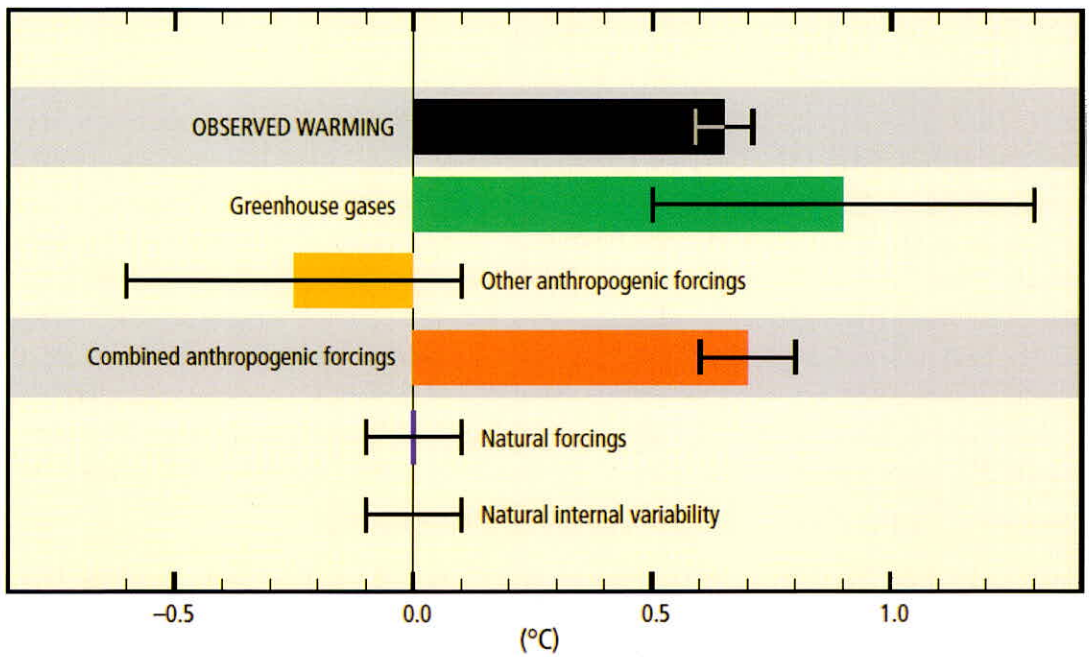


***Figure 3.19**: Contributions of internal and external forcings to global warming (Source: IPCC, 2014)*

According to de Noblet-Ducoudr´e et al. (2012), the biophysical factors are associated with the larger variability and uncertainty and depend on the location and time. Several studies have shown that the RF from LULCC also significantly impacts temperature trends (Bonan, 1997; Feddema et al., 2005; Christy et al., 2006, Roy et al., 2007; Wichansky et al., 2008) and there is a high consensus that the LULCC should also be included in characterizing climate change and modelling processes (Pielke et al., 2002, 2004, 2007; Joshi et al., 2003; NRC, 2005; Williams, 2005). It may also significantly influence many climatological variables such as maxi, mini. and diurnal temperature range (Gallo et al., 1996; Hale et al., 2006, 2008). As per AR5 (IPCC, 2014), there is an increase in the land surface albedo and decrease in the RF by -0.15 ±0.10 W/m^{2}due to global LULCC, which is resulting in a decrease in the land surface temperature (LST) and this could be one of the reasons that LULCC was not given due considerations in IPCC assessments (Pielke et al., 2011). At the same time, there may be the chances of an increase in the LST due to non-RF influences such as changes in plant phenology and ET, which could lead to an increase in the LST because of the decrease in ET (Pitman et al. 2009; Lawrence and Chase 2010), which depends upon the location and time. Some researchers also argue that land use changes to agriculture may further decrease LST (Mahmood et al., 2006; Roy et al., 2007; Lobell and Bonfils, 2008), however as discussed above it will depend on the location and time and hence more rigorous works are still needed to explore the impacts of LULCC on climate change possible coupling with the earth system models (ESMs), probably on regional scale.

Pielke et al., (2011) states that the distribution of LULCC is highly regionalised (Fig. 3.20) and depicts larger variability in LULCCs in Asia as compared to the rest of the regions of the world as analysed for a period of 10000BC to 2000 AD. Lawrence and Chase (2010) also states that that LULCC has a widespread regional warming but limited global influence on near-surface temperatures and precipitation. Zhang et al. (2016) explored region-wise temperature anomalies due to LULCC and found that there will be an increase in LST by 1.0^{0}C to 2.0^{0}C through reduced ET (+ve RF) in South Asia and East Asia regions (Niyogi et al.,2002; Davin and de Noblet-Ducoudré, 2010). The Europe and North America (high-altitude regions) will have a decrease in LST by 1.0^{0}C to 2.0^{0}C due to increased land surface albedo (Brovkin et al., 1999; Betts et al., 2007) and reduced RF. Zhang and Liang (2018) found that LSTs show a cooling effect when the crop land is transformed to forests (-ve RF) and a warming effect when the crop land is transformed in to urban land use (+ve RF). These results are shown in Figure 3.21 a-d. It is interesting to further note that the impacts of LULCC on climate change are largely governed by ET dynamics, rather than RFs (Lawrence and Chase, 2010). The changes in LULC may have their impacts at different scales, i.e., local, regional or global climatic processes (Brown et al. 2013). The LULC change is mostly anthropogenic in nature and it has direct impacts on STs. Halder et al. (2016) found that the LULC can cause for change in the daily maximum and mean temperature up to 1-1.5^{0}C. Nayak and Mandal (2012) found that LULC change from forest to agriculture and urban may contribute to the temperature increase by 0.06^{0}C per decade for the western part of India, and the combined impacts of LULC and GHGs may contribute up to 0.13^{0}C per decade for the western India.

Santer et al. (2013) specifically categorised the influence of anthropogenic factors on climate and found that the increased composition of GHGs, enhanced levels of aerosols, depletion of stratosphere ozone layer are the major external forcings inducing the climate change phenomenon. Christidis et al. (2012) also reported similar results and state that artificial forcings (all forcings-natural forcings) may quadrupled the probability of occurrence of occurrence of the warmer years than the warmest year since year 1900 in at least 23 identified regions of the world.

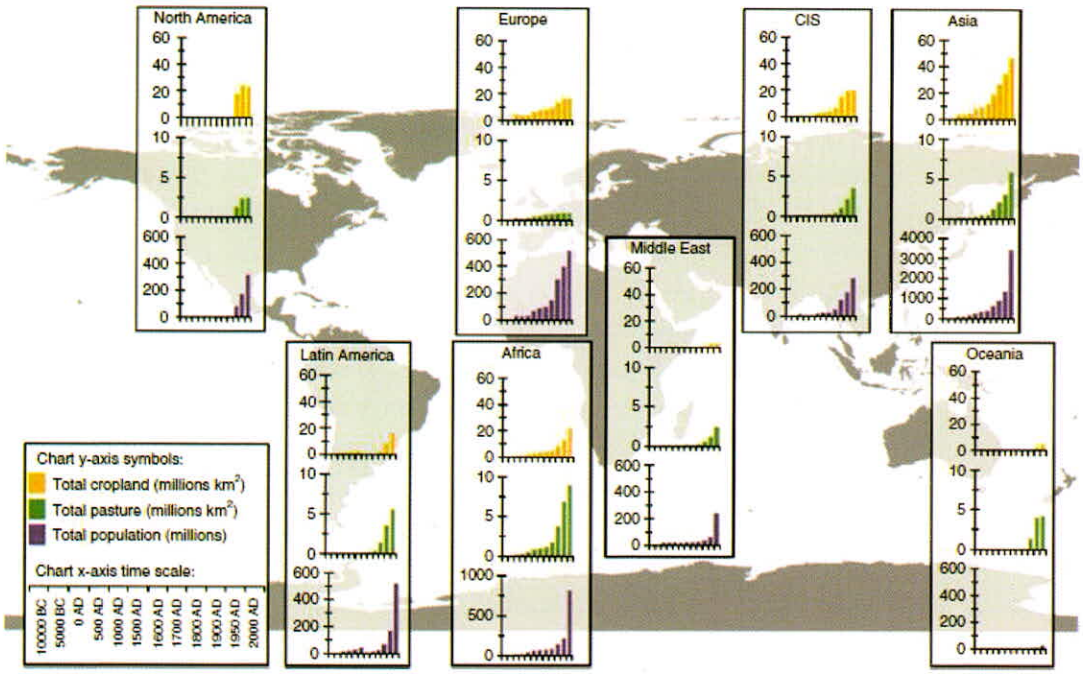


***Figure 3.20**: Long-term variability of regional population, cropland, and pasture (Source: Pielke et al., 2011)*

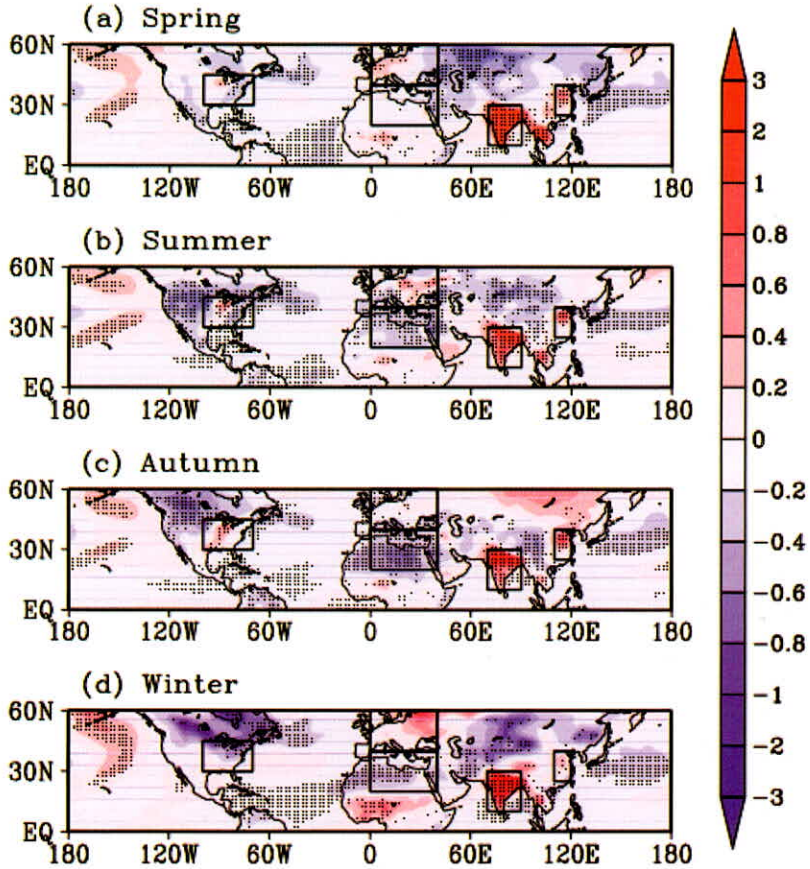


***Figure 3.21**: a-d: Regional temperature anomalies due to LULCC (IPCC, 2014).*

Therefore, an assessment of relative impacts of different natural/anthropogenic/all climatic forcings on STs will be of immense utility for building adaptive capacity and management practices to subvert the adverse effects of climate change on human and natural environment. Basha et al. (2017) categorically analysed the relative impacts of different forcings such as anthropogenic and natural on STs along with CRU STs over India for the 19th and 20th centuries are shown in Fig. 3.22a-f. The figures are self-explanatory and various inferences can be drawn as for as the least and most critical forcings are concerned.

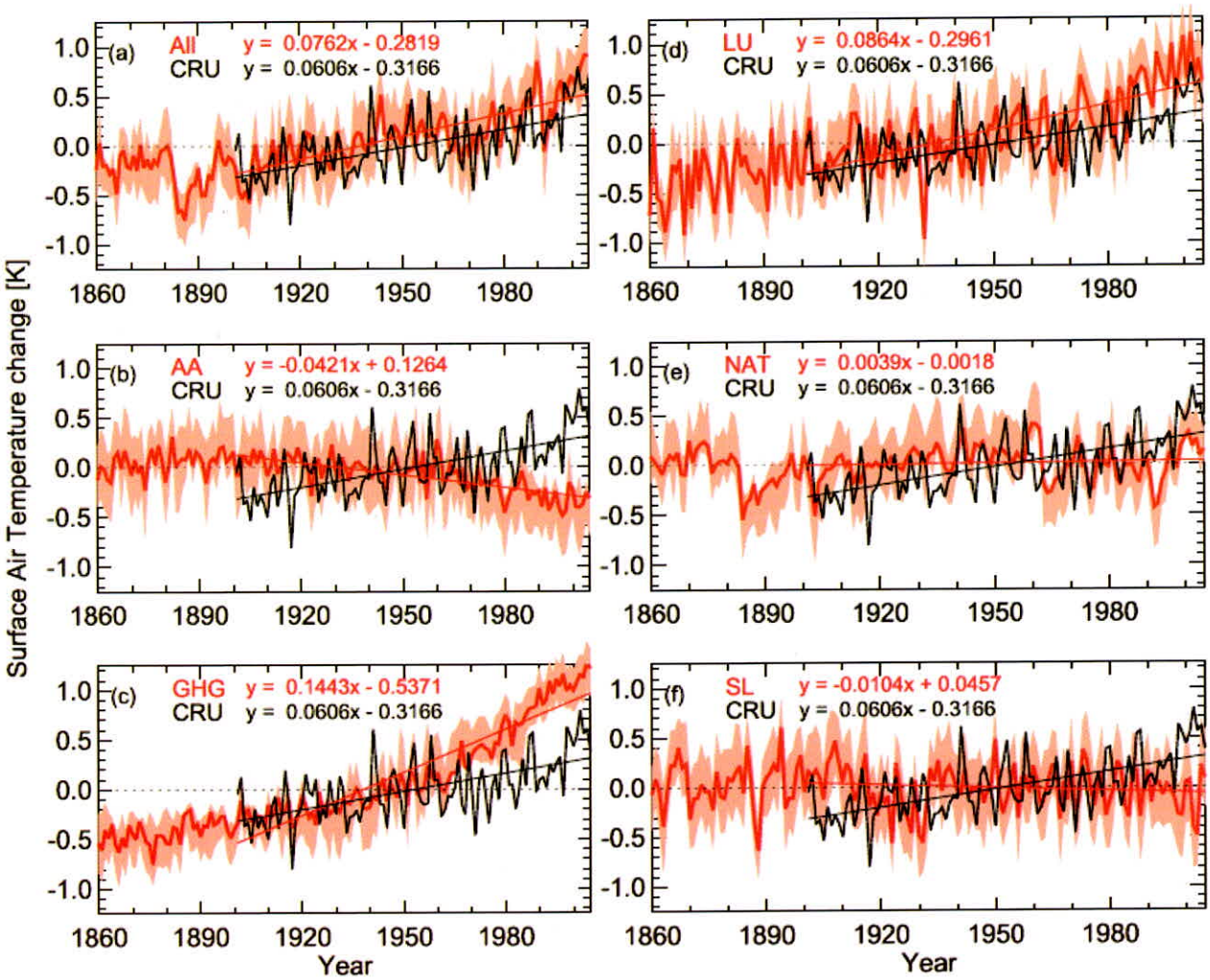


Figure 3.22: *(a-f): Annual ST anomalies variation with climate forcings (natural and anthropogenic) for the period of 1860–2005 (Source: Basha et al., 2017).*

It can be observed from Figures 3.22 a&d that there is a sudden rise in slope of the regression line as compared to the rest of the illustrations. This period of sudden rise is lying between 1960-70, the period of green revolution and industrial advancements in the country. Figure 3.22d shows that after the year 1970, there is a continuous increase in temperature anomaly due to LULC change. Figure 3.22c even has steeper slope than the Figure 3.22d. This shows that the industrial GHGs emissions are more responsible for temperature anomalies than the rest of the forcings.

Overall, the results show that the increasing trend in surface temperatures is more due to GHGs emissions as compared to LU and lowest for anthropogenic aerosols, natural (volcanic activity and solar

irradiance) and solar radiation. The variability of different forcings, particularly for GHGs and LU is found to be more during winter and summer than the rest of the seasons. Therefore, the decreasing order of the relative impacts of various climatic forcings can be arranged as: GHGs>LULC>aerosols>solar radiation and natural forcings.

3.4 Climate Extremes

According to National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA), year 2018 was the warmest year since 1880 by an anomaly of 0.83^0C. Due to climate extremes, there will be an upsurge of the climatic extremes such as droughts, floods, frequency and duration of heat and cold waves and the number of population affected by these extreme events. Hence, there is a need to further explore the potential impacts of climatic hazards in the different regions /zones of the India and the population likely to be affected, particularly in the backdrop of 'Global Warming of 1.5^0C' and Paris Agreement (UNFCCC, 2015). As for as the modelling of the climate extremes is concerned, there are very few works available in climate literature exploring the phenomenon of heat waves, cold waves, their frequency and the length of days exceeding various temperature thresholds (Sterling et al., 2000). However, more recently, some noteworthy works have been done by Knowlton et al. (2014), Jaswal et al. (2015), Rohini et al. (2016), Mazdiyasni et al. (2017), Mishra et al. (2017), Ali and Mishra (2018), and Oldenborgh et al. (2018) on temperature extremes/heat wave and population exposure in current, 1.5 ^{0}C, and 2.0 ^{0}C worlds for India. In general, there is an increase in number of high-temperature (HT) days in the northern, southern and western parts of India with a decrease in the eastern parts of India (Jaswal et al., 2015).

India has witnessed severe heat related mortalities in the recent past, e.g., the events of year 2010, 2013 and 2015, which reported the human mortality of the order of 1300, 1500, and 2500 across India (Mazdiyasni et al., 2017 and Knowlton et al., 2014) and by the middle and end of the 21st century, there will be a manifold increase in population's susceptibility, i.e., of the order of 15 to 92 times respectively in 2.0^0C world (Mishra et al., 2017). Ghatak et al. (2017) found that in India, generally, the heat waves attain their peak during late May and early June of each year. It was also found that the heat wave phenomenon may get further re-enforced in agricultural intensive regions of North and Central India. Notably, most of these studies consider the daily-maximum or daily minimum or daily average air temperature for characterization of heat/cold waves in India and ignores the concurrency of these events. However, more recently, Mukherjee and Mishra (2018) have also considered the concurrency of the heat waves and found that the anthropogenic emissions are the major drivers for 1-day and 3-day concurrent hot day and hot night (CHDHN) events.

Mishra et al. (2017) have very categorically shown that there may be a sudden increase in the frequency of severe heat waves over India for 2.0^0C world by the end of 21st century. Figures 3.23a-c show the occurrence of the heat waves in India during 1951-2015 and Figure 3.24A-E show inter-relationship between temperature and heat waves in India for the period of 1960–2009. There has been an increase in the duration and the length of duration of heat waves in India (Rohini et al., 2016) and may be largely attributed to the atmospheric anomalies/variability mainly resulting due to an increase in the GHGs concentration. These heat waves will have a considerable impact on the health of humans and environment as well (Mishra et al., 2017) and may also increase the mortality rate (Mazdiyasni et al., 2017). Figure 3.24 shows that major part in (B, C, D, and E) is having red pixels indicating that heat waves are prominent in these regions. Southern and western regions of India experienced more heat waves as compared to the other regions during 1960-2009 period.

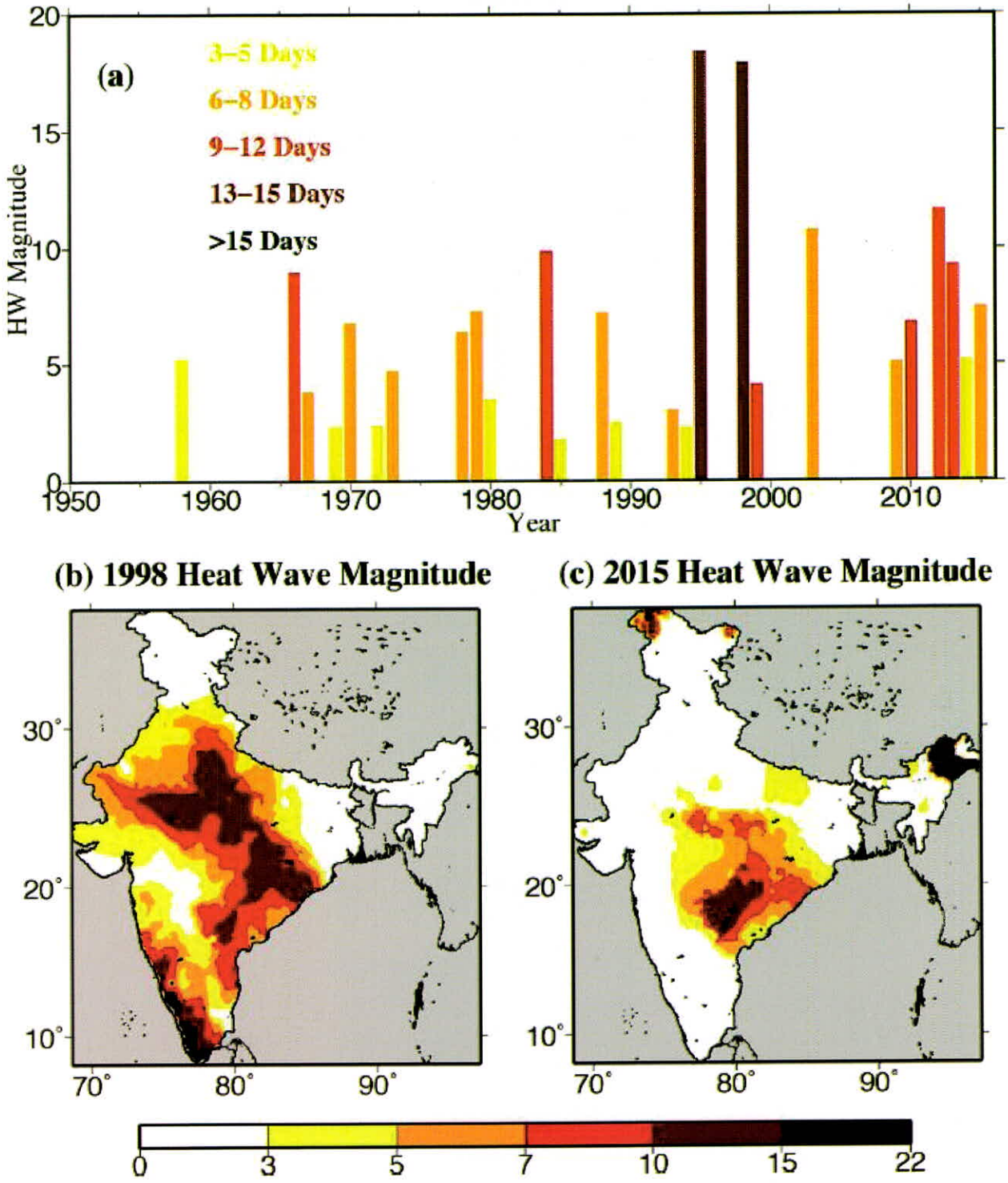


***Figure 3.23a-c**: Occurrence of heat waves in India for the period of 1951–2015 (Source: Mishra et al., 2017).*

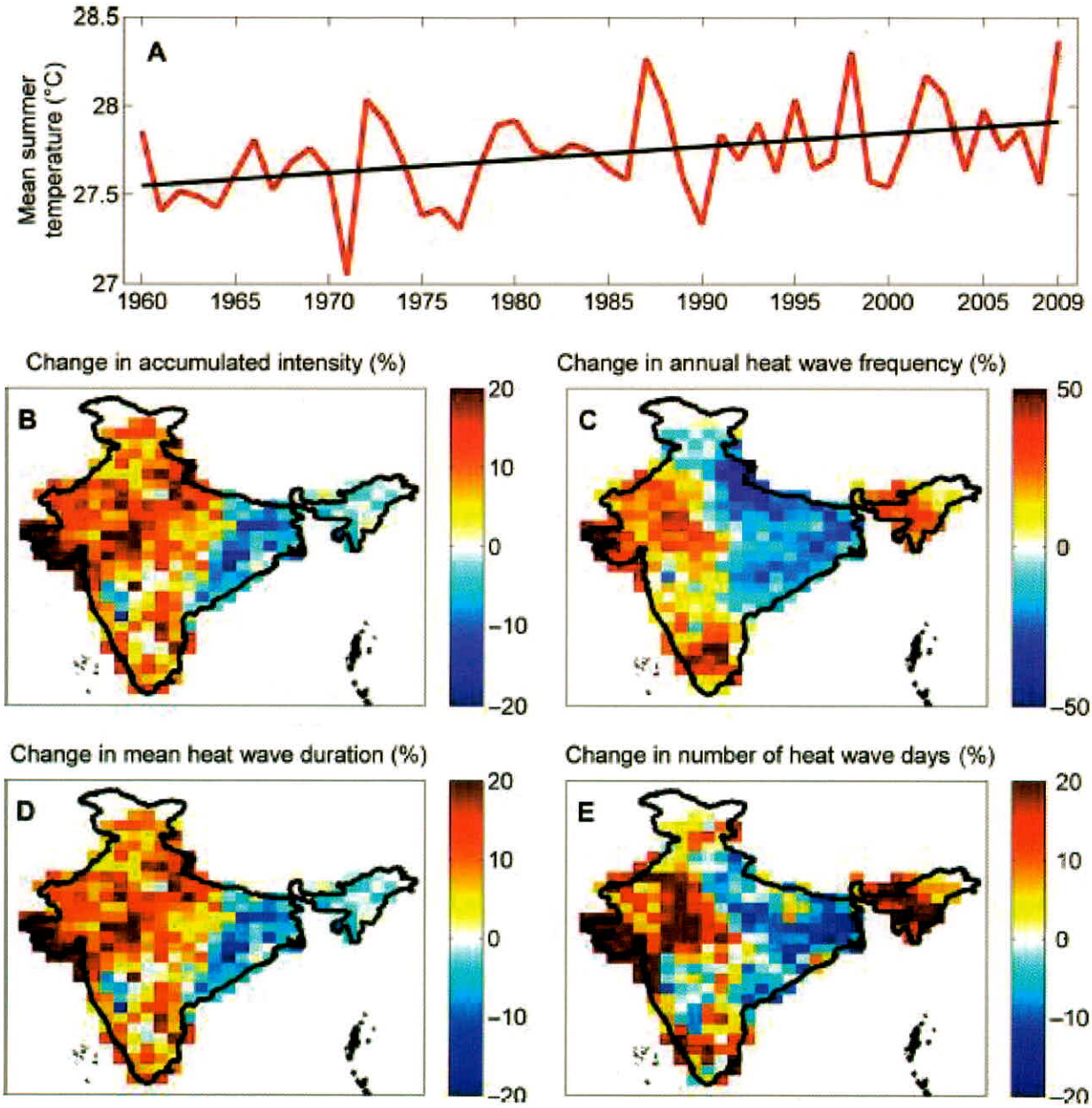


***Figure 3.24A-E**: Inter-relationship between temperature and heat waves in India for the period of 1960−2009 (Source: Mazdiyasni et al., 2017)*

Mazdiyasni et al. (2017) found that the heat wave threshold across India is 36.0^{0}C, except for the WH and NE regions, which possess a lower value. The study finds that an increase of 0.5^{0}C in annual mean temperature will increase the mortality rate by 32% (Figure 3.25A) and the number of consecutive two or more heat wave days will increase the mass mortality rate from 46% to 82% (78% increase) (Figure 3.25B). Figure 3.25C shows the relationship between number of heat waves days, mean summer temperature and the probability of deaths > 100 persons.

The results indicate the degree of susceptibility of Indian population to heat waves and would be more severe looking in to the projected increase in the annual mean and maximum temperatures across

the major regions of India. Therefore, the issue of heat waves in India is typical climate change phenomenon and needs due attention for minimizing its adverse impacts over the society as a whole.

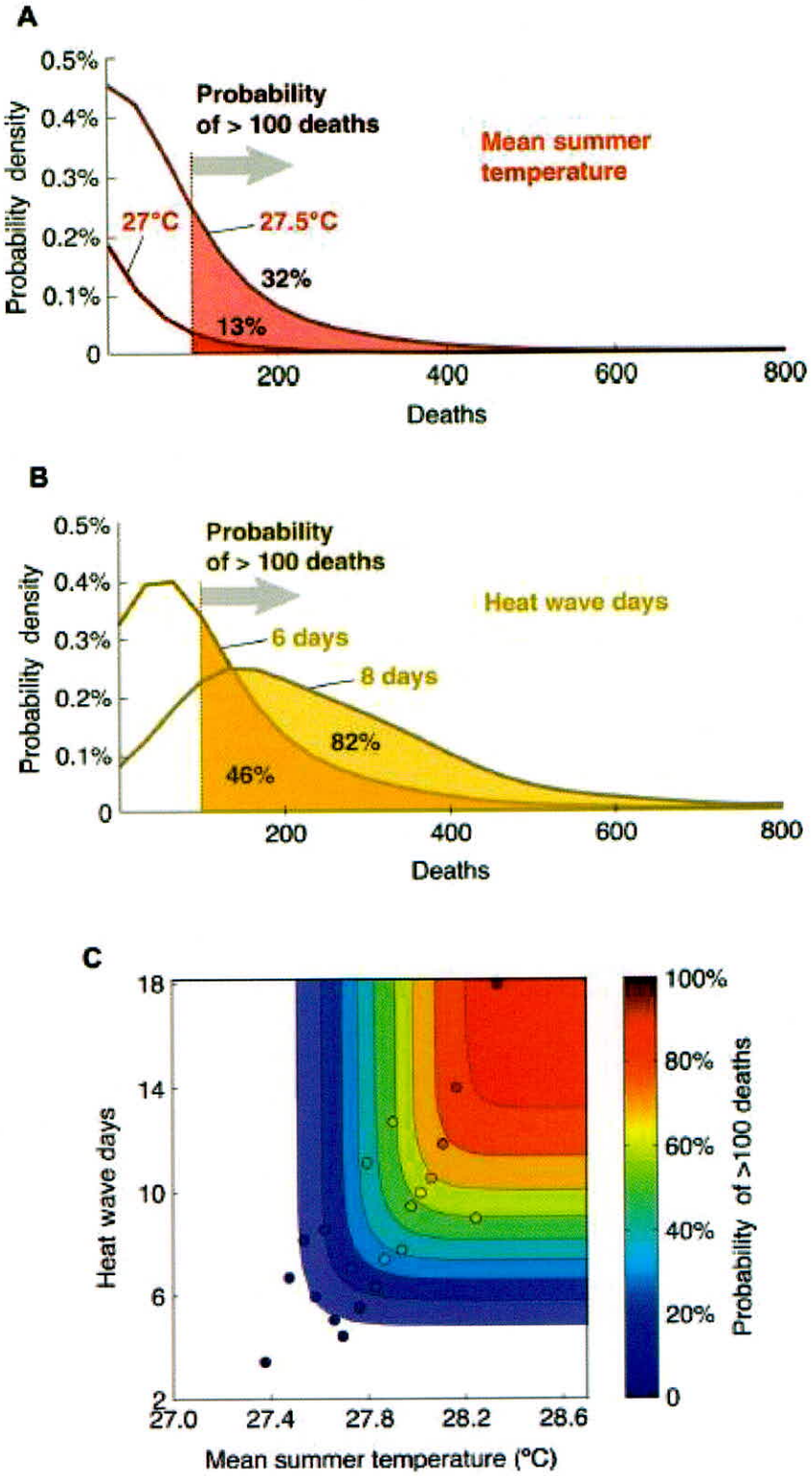


***Figure 3.25 A-C**: Relationship between probability of deaths greater than 100, mean summer temperature, no. of heat wave days, and number of deaths (Source: Source: Mazdiyasni et al., 2017).*

3.5 Climate Change Performance Index (CCPI)

The climate change performance index (CCPI) is a standard index developed to enhance the transparency in climate politics worldwide through standard index developed to achieve the goal of the Paris Agreement by the partner countries and European Union. It has the ultimate aim to reduce the GHGs emission nearly 'zero' by 2050. The basic components of CCPI are given in Figure 3.26. The CCPI has four main components as: (1) GHGs emissions, (2) Renewable energy, (3) Energy use, and (4) Climate policy. Each country is evaluated based on the performance achieved in fourteen indicators (Figure 3.27) falling under these four groups. Based on the CCPI, Sweden is at the top position followed by Morocco and Lithuania. India is ranked at 11th place rated as 'High' with a score of 62.93 as shown in Figure 3.27. India has increased in CCPI ranking from 14th to 11th (Figure 3.27) by making use of more and more renewable energy resources and there is ample scope for further improvements by reducing the GHGs emission. (CCPI, 2019).

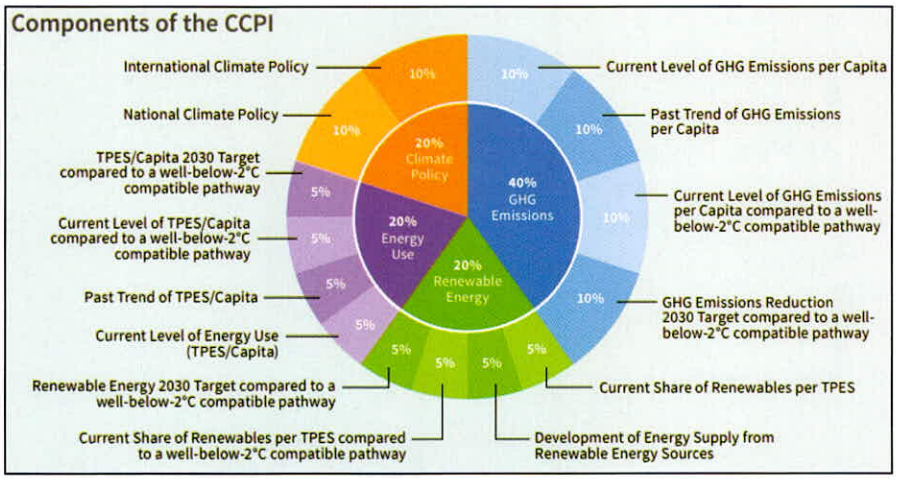


***Figure 3.26**: Components of CCPI (Source: Germanwatch, New Climate Institute & Climate Action Network).*

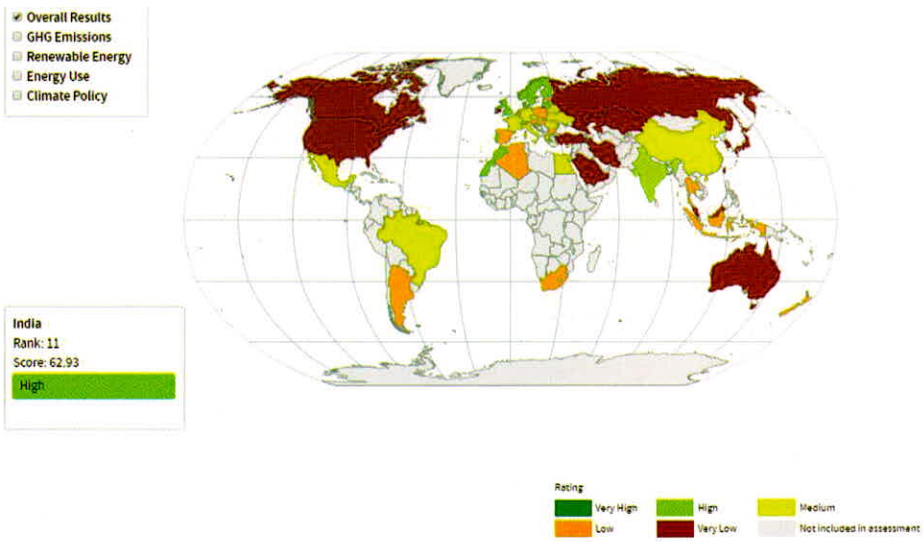


***Figure 3.27**: CCPI index of the world for 2019 (Source: https://www.climate-change-performance-index.org/).*

3.6. Concluding Remarks

1. Worldwide, the temperature is projected to accelerate during the 21st century under all the RCPs and it is projected to increase by 5.5^{0}C by the end of 21st century. The projected values of increase in mean temperature may vary in the range of 0.3–1.7 ^{0}C (RCP 2.6), 1.1–2.6 ^{0}C (RCP4.5), 1.4–3.1 ^{0}C (RCP 6.0), 2.6–4.8 ^{0}C (RCP 8.5) for 2081–2100, relative to 1986–2005.
2. There is a rapid rise in surface temperatures over India, particularly since about 1980 and may vary from 2.5 ^{0}C to 5.5 ^{0}C at the end of 21st century under GHG scenarios with maximum susceptibility over Himalayas, north, central and western parts of India with a lower influence on the southern part of India and will have more warm days and nights as compared to the cold days and night.
3. There is an increasing trend in annual average temperature of 0.006^{0}C per year with the maximum variation during the post-monsoon season, i.e., 0.0079^{0}C per year and the least (0.0043^{0}C/year) during the monsoon season for the period of 1901-2010.The temperature difference (increase) is more pronounced in the northern parts to the order of 1.4^{0}C-0.8^{0}C as compared to the southern parts.
4. There is a continuous and sudden variation in temperature anomalies over India due to GHGs and LULC change, particularly after the year 1970 (the period of green revolution and industrial advancements). The increasing trend in surface temperatures is more due to GHGs emissions as compared to LU and lowest for the anthropogenic aerosols, natural (volcanic activity and solar irradiance) and solar radiation. The climate change in India is mainly due to larger influence of atmospheric variability than the soil drying, i.e., a reduction in soil moisture.
5. There is an increase in number of high-temperature (HT) days in the northern, southern and western parts of India with a decrease in the eastern parts of India. Heat waves in India attain their peak during late May and early June of each year. The heat wave phenomenon may get further re-enforced in agricultural intensive regions of North and Central India.
6. There will be a sudden increase (30 times) in the frequency of severe heat waves over India for 2.0^{0}C world by the end of 21st century along with an increase in the duration and the length of duration and may also increase the mortality rate.
7. The "Hothouse Earth" condition (if developed?) would lead towards un-inhabitable planet and the GHGs would be the major forcings responsible for this condition. Hence, there is a need for emission-less world trade and economy.
8. There is a need of development of land-based CO2 removal through carbon sequestration/carbon sinks in forest, rural and agricultural landscapes to absorb the atmospheric carbon to achieve the Paris Agreement, i.e., to limit the global average temperature increase up to 1.5^{0}C (below 2.^{0}C) above pre-industrial levels.
9. There is also a need of action for 'natural climate solutions', which are very natural and cost effective, i.e., protection, management and restoration of various critical ecosystems — forests, grasslands, wetlands and croplands.

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CHAPTER 4

CLIMATE CHANGE AND PRECIPITATION

Manohar Arora and Sunil Gurrapu

4.0. Introduction

The changing climate is projected to impose significant changes on various components of the hydrological cycle, influencing the spatial distribution of water resources. For example, the increasing green-house gases in atmosphere and changes in radiative forcing cause significant changes in precipitation patterns globally (Trenberth et al., 2003). Although the projections of global average annual precipitation indicate increase, the changes are not uniform spatially and vary from region to region, with varying magnitude and intensity (IPCC, 2013). The projections from various global climate models (GCMs) indicate significant changes in the magnitude, intensity, and pattern of precipitation in many parts of the world (e.g. Kumar et al., 2006; Trenberth, 2011; Pradhan et al., 2018). Several recent studies on changes precipitation from across the globe indicate that the increase in magnitude and intensity of extreme events is much larger when compared to the changes in mean conditions (e.g. Kharinet al., 2007; Wasko and Sharma, 2015; Shashikanth et al., 2018). The detrimental effects of increase in precipitation intensity and magnitude include higher rates of surface runoff resulting in increased risk of flash floods, and decreased rates of groundwater recharge, among many others (Lal, 2003; Guhathakurta et al., 2011). Increase in precipitation intensity can be attributed to the high amounts of atmospheric moisture accumulated as a result of warming climate, governed by the Clausius–Clapeyron (C–C) relation which states that the saturated vapour pressure increases with temperature by approximately 7% for every 1°C. Therefore, any rise in temperature due to changing climate may cause increase in high intensity rainstorms (Liu et al., 2009; Shiu et al., 2012). These heavy rainstorms deplete the available atmospheric moisture and as a result the occurrence of light and moderate precipitation events are decreased (Goswami et al., 2006). Notably, the light and moderate precipitation events are critical sources of available water, and therefore it is of utmost importance to evaluate and understand the changing patterns of precipitation for effective planning and management of water resources.

The hydroclimate of India is characterised by the southwest (SW) and northeast (NE) monsoon which brings water to the country. The majority of the annual precipitation (approx. 75%) is received during SW monsoon season (Oza and Kishtawal, 2014) extending to a period of four months (June – September) and starts in early June from Kerala and northeast India. The rainfall from moisture rich monsoon winds advances from south to north across Indian peninsula and from east to west across north India. The rainfall during SW monsoon season is referred to as Indian summer monsoon rainfall (ISMR) (Attri and Tyagi, 2010) and is quantified as the weighted average of the SW monsoon rainfall measured at several rain gauge stations well-distributed across India. The land-atmosphere interactions significantly influence the monsoon precipitation characteristics, and the pattern of ISMR is highly variable spatially and temporally (Medina et al., 2010; Asharaf et al., 2012). Although, the knowledge of factors contributing to the variability in monsoon precipitation is incomplete, it is generally attributed to the differential heating of the land and ocean systems during summer season. Around September, the sun retreats to the south leading to cooling of the northern Indian subcontinent and thus the air pressure builds up over northern India, whereas the surface waters of Indian Ocean remain

warmer and the corresponding atmospheric pressure is low. This leads to pressure differences between the ocean and the Indian landmass, causing the high pressure winds to sweep down the Himalayas towards the low pressure regions of Indian Ocean, moving over the vast plains of Indo-Gangetic region. These are referred to as NE Monsoon winds or retreating SW monsoon winds. The cold and dry winds acquire moisture from the Bay of Bengal and rains over southern India, prominently in the state of Tamil Nadu. Tamil Nadu receives significant amount (50% to 60%) of rainfall during the NE monsoon season, which extends from October to December. In addition to the monsoon driven rainfall, the extreme northern parts of India experience periodic spells of rainfall or snowfall during winter months and are termed as western disturbances. These spells of precipitation, also called as Indian winter monsoon (Dimri et al., 2016) are caused by the influence of extra-tropical weather systems. Approximately, four to five instances of western disturbances occur over the Indian region causing precipitation. Although the magnitude and intensity of precipitation differ with each instance, this accounts up to one-third of the total annual precipitation received in this region.

4.1. Factors affecting Precipitation and its Variability

Annual precipitation of India is substantially influenced by several factors including differential heating of Indian subcontinent and the surrounding seas, shifts in the position of inter-tropical convergence zone (ITCZ), jet streams in the troposphere, aerosol loading in the atmosphere, and changes in the sea surface temperature and pressure over the equatorial Pacific Ocean, in addition to the local physiographical and topographical features of the Indian subcontinent. For example, the potential evaporation in the atmosphere above oceans surrounding Indian subcontinent is influenced by the varying sea surface temperatures, which in turn leads to ISMR variability (Meehl and Arblaster, 2003). In general, spatial distribution of rainfall across India is highly variable because of the heterogeneous climate, local topography and the effect of regional and large-scale phenomena. For example, monsoon trough and Himalayas have dominant influence on the interannual variability of precipitation over central India. Likewise, western Himalayas and arid Thar Dessert substantially influence the rainfall over northwest region of India. The eastern Himalayas along with the large forested region influence the rainfall patterns in the northeast region (Prabhuet al., 2017).

It is well established that the inter annual variability of ISMR is strongly related to that of El Niño-Southern Oscillation (ENSO) (Roy et al., 2003; Rajeevan and Pai, 2007; Dwivediet al., 2015; Kucharski and Abid, 2017). ENSO comprises of oceanic (El Niño) and atmospheric components (Southern Oscillation) and is a phenomenon happening over tropical Pacific Ocean with a periodicity of approximately 5 years (Rasmussen and Wallace, 1983). El Niño is a pattern that describes the unusual warming of surface waters in the eastern tropical Pacific Ocean (Trenberth, 1997) and Southern Oscillation is associated with the changing surface pressures over the tropical Pacific Ocean (Walker and Bliss, 1932). During El Niño years, the surface waters in the central and eastern Pacific Ocean undergoes abnormal warming compared to their western counterpart and in this process, the high pressure zone above the eastern Pacific Ocean is weakened reversing the direction of east moving winds (easterly winds) (Trenberth, 1997). In contrary, a year is referred to as a La Niña year when these conditions are reversed. In India, El Niño and La Niña episodes are typically associated with abnormally dry (drought) and wet (flood) conditions. There is less rainfall across India during El Niño and several droughts (i.e. ISMR is 20% below normal) have occurred in association with El Niño (Soman and Slingo, 1997).

Ashok et al. (2004) reported that the influence of ENSO on ISMR is modified by another ocean-atmosphere phenomenon occurring over the Indian Ocean, i.e., the Indian Ocean Dipole (IOD). IOD is associated with the oscillating sea surface temperatures (SSTs) over Indian Ocean, between positive, neutral and negative phases (Webster et al., 1999). A strong IOD event neutralises the impact of ENSO on ISMR, i.e. the influence of ENSO is reduced when it is in-phase with IOD (Ashok et al., 2004). Similarly, the Pacific Decadal Oscillation (PDO)also influences the effect of ENSO on ISMR, i.e. the impact of El Niño (La Niña) is enhanced (reduced) when the PDO is in warm phase (Krishnamurthy and Krishnamurthy 2014). PDO is a ENSO like phenomenon of Pacific climate variability and is a robust and recurring phenomenon with a periodicity of approximately 30-years (Mantua and Hare, 2002). In a more recent study, Malik et al. (2017) demonstrated that PDO, in addition to other low frequency oscillations such as Atlantic Multi-Decadal Oscillation (AMO) and Total Solar Irradiance (TSI) plays a considerable role in controlling the dry and wet periods of the ISMR.

4.2. Current Scenarios

4.2.1. Global Perspective: Several researchers analysed historically observed precipitation across the globe to determine changes in its pattern (e.g. Akinremiet al., 1999; Zhang et al., 2000; Singh and Sontakke, 2002; Mwale et al., 2004; Alexander et al., 2006). The general consensus from these studies is that there is about 2% increases in the global precipitation over the land, although the change is not uniform spatially and temporally (Doherty et al., 1999). Summarising the global research on changing patterns of precipitation during 20th century, Dore (2005) indicated that the wet areas have become wetter and dry and arid areas have become drier.

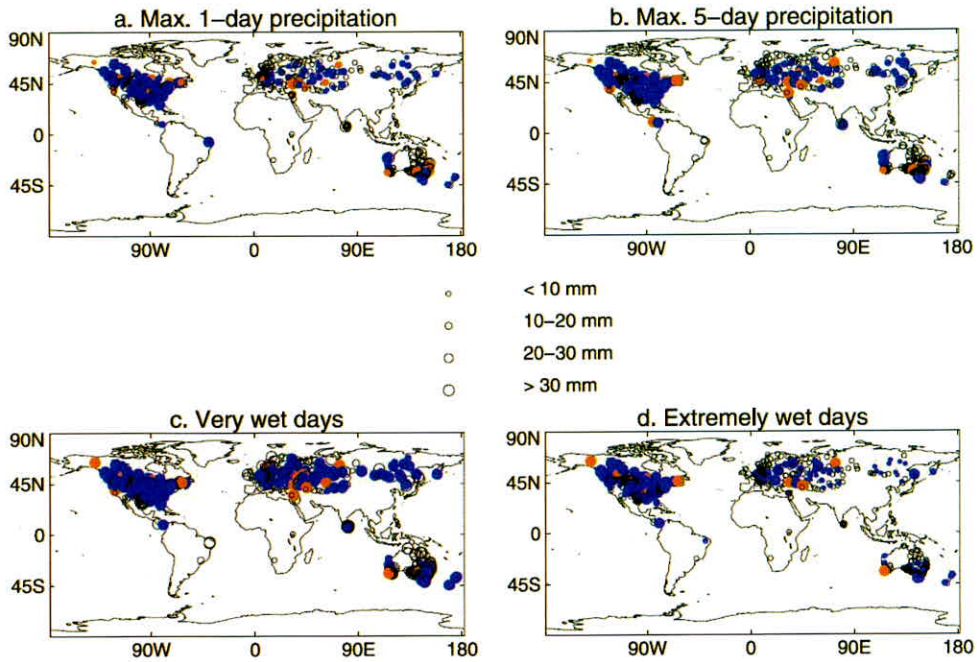


Figure 4.1*. The 100-year trends for a selection of precipitation indices for the period 1901–2003 for a subset of stations with at least 80% complete data between 1901 and 2003. Black circles indicate anon-significant change. Blue (red) solid circles indicate a significant increase (decrease) at the 5% level (Source: Alexander et al., 2006).*

Overall, there is an increase in precipitation over higher mid-latitudes (e.g. Akinremi et al., 1999), reduced precipitation over China, Australia and island states in Pacific Ocean (e.g. Chen et al., 1992; Smith et al., 2000), and increased variance in equatorial region (e.g. Guhathakarta et al.,2015).Nearly 100 years of observed precipitation from about 600 stations spread across northern hemisphere mid-latitudes demonstrate wetter conditions throughout the 20th century (Alexander et al., 2006) (Figure 4.1). Changes in precipitation vary not only across space and time, but also in the magnitude and intensity. For example, Donat et al. (2016) identified a significant increase in extreme daily precipitation for the past six decades and averaged over both the dry and wet regimes, although the changes in total precipitation were inconsistent. Globally, the number of extreme rainfall events have significantly increased over the last three decades (Lehmann et al., 2015).

4.2.2. Indian Perspective

Knowledge of spatial and temporal variability of ISMR over Indian subcontinent is vital in better understanding its pattern (e.g. Guhathakarta and Rajeevan, 2006; Guhathakarta et al., 2015; Mohapatra et al., 2018; Viswambharan, 2018). In this context, temporal trend analyses of historical SW monsoon rainfall or ISMR data indicates a decreasing trend in general. For example, Mohapatra et al. (2018) observed a weak decreasing trend in ISMR, based on the linear trend analysis of 113 years of ISMR data. Exploring the spatial variability, they observed decreasing trends in ISMR over northeast India and increasing trends in northwest India over the last two decades. Ghosh et al. (2016) observed significantly decreasing trends across south, northeast and northwest India during 1951 – 2004.

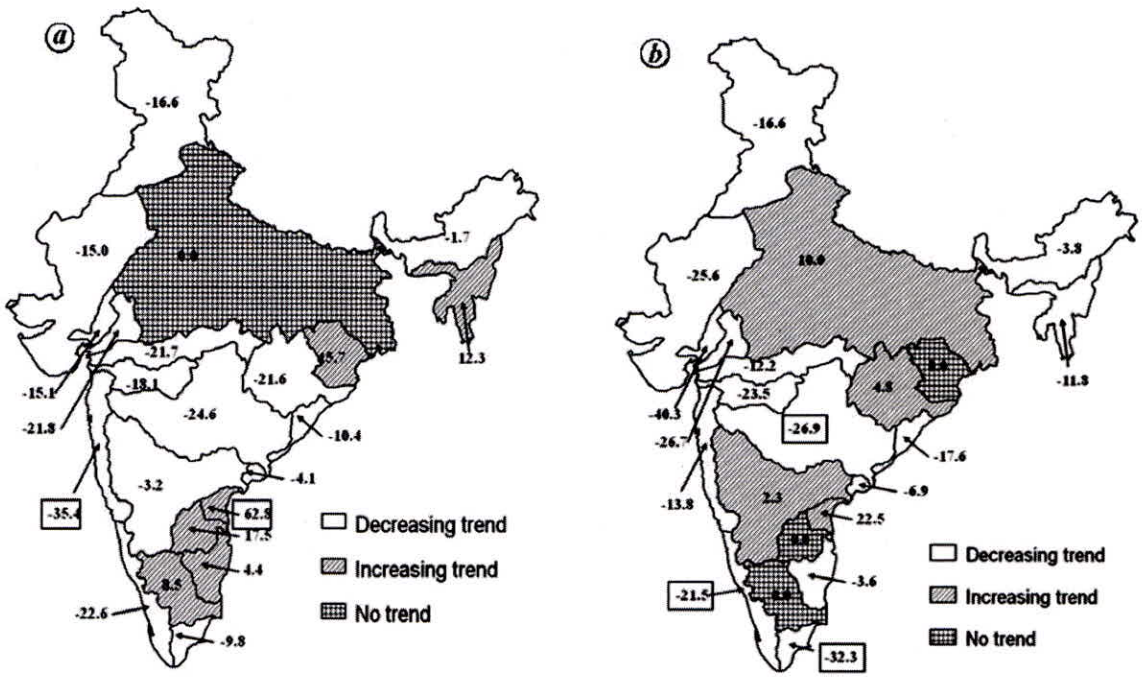


Figure 4.2*. Trends and magnitude pertaining to rainfall changes for different river basins in India. Significant trends are displayed in boxes. (a)annual rainfall (% of mean/100 years); (b) annual rainy days (% of mean/100 years) (Source: Jain and Kumar, 2012).*

Kothawale and Rajeevan (2017) observed similar trends at a sub-divisional scale. For example, sub-divisions of northwest region (i.e., east Rajasthan, Saurashtra, Kutch & Diu) show significant increasing trend and the sub-divisions of northeast region (i.e., east Uttar Pradesh, Assam, Meghalaya,

& sub-Himalayan West Bengal) exhibit significant decreasing trend. Although seasonal trend analyses explain the temporal variability to some extent, it does not demonstrate the actual patterns at monthly timescale. Thus analysing the ISMR for both spatial and temporal variability, Viswambharan (2018) observed contrasting trends in rainfall over different regions of India in each month of the summer season for the period 1980 – 2015. It was found that June monthly rainfall declined significantly over the southwest coast of India, whereas the July and September monthly rainfall is above normal over central India and below normal near foothills of the Himalayas and southeast India. Exploring the spatial variability in rainfall trends at a watershed scale, Jain and Kumar (2012) observed mixed trends in annual precipitation and annual rainy days (Figure 4.2). They observed an increasing (decreasing) trend in annual rainfall in 6 (15) watersheds, although majority of them are statistically not significant, Figure 4.2.

Period of record (number of years) or the type of record (observed or reanalysed) used in the analysis of temporal or spatial trends in the magnitude or frequency of ISMR play a vital role in defining the trend. For example, Varikoden et al. (2013) observed a significant decreasing trend in July monthly rainfall over central India during 1901 – 2003, whereas Viswambharan (2018) observed an increasing trend (above normal) in July rainfall during 1980 – 2015. Similarly, Guhathakarta et al. (2015) observed contrasting trends in 110 years (1901 – 2011) of ISMR data, when analysed over two different periods 1901 – 1950 (increasing trend) and 1951 – 2011 (decreasing trend) as shown in Figure 4.3.

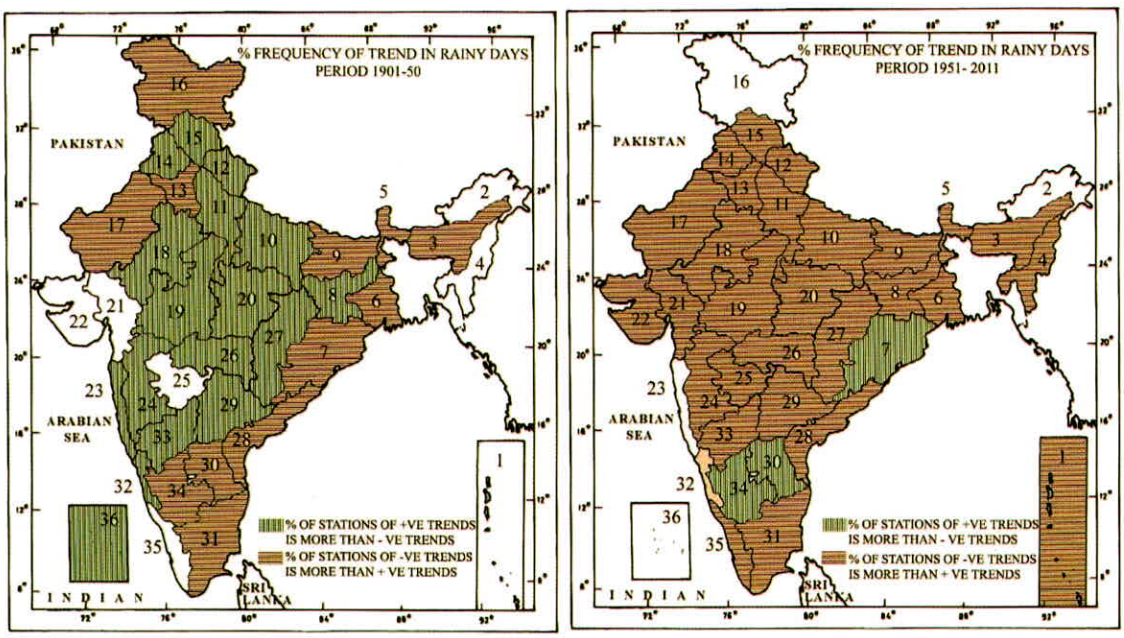


Figure 4.3. *Meteorological subdivisions showing frequency of stations having positive (increasing) trends more or less than negative (decreasing) trends in rainy days during the period (a) 1901 – 1950 and (b) 1951 – 2011 (Source: Guhathakurta et al., 2015).*

The decreasing trend in ISMR over the past few decades (e.g. Guhathakarta et al., 2015; Ghosh et al., 2016) could be a part of the natural 50- to 80-year mode of multi-decadal variability. Concurrently, Guhathakarta et al. (2015) demonstrated that the decreasing trend in ISMR over

monsoon core region of India post-1950 is a result of multi-decadal epochal variability. The tele-connections between ISMR and the ocean-atmosphere oscillations and their impacts on the increasing or decreasing trends of ISMR has been studied exhaustively (e.g. Mishra et al., 2012). The precipitation patterns are also influenced by land use changes across the country. For example, Paul et al. (2016) observed that the deforestation resulted in weakening of ISMR, because of the reduced evapotranspiration and the subsequent decrease in the recycled component of precipitation. Summary of historically observed trends in various aspects of precipitation, such as magnitude, intensity and extremes, from selected studies are listed in Table 4.1, in the order of publication date.

Globally, the general consensus is that the impact of climate change is felt more strongly through the changes or shifts in climate extremes. Some recent extreme events across Indian subcontinent, e.g. Mumbai (2005), Kedarnath (2013), Chennai (2015), and Kerala (2018) raised a concern over the changing extreme climate(e.g. De et al.,2005; Cho et al.,2016; Mishra et al., 2018). Several studies from the past have investigated the trends in heavy precipitation events across India (e.g. Kumar et al.,1992;Ray and Shiwale,2001;Goswamiet al.,2006; Rajeevanet al.,2008;Dash et al.,2009) and found that there is a substantial increase in the magnitude and frequency of extreme precipitation events (annual maximum precipitation) in majority of India during second half of the 20th century. For example, Joshi and Rajeevan (2006) observed significant increasing trends in the extreme rainfall (contribution of heaviest rainfall to the total seasonal rainfall) events over the west coast and northwest parts of Indian peninsula. In a more recent study, Mukherjee et al. (2018) observed a substantial increase in the frequency of extreme precipitation over southern and central India post-1982 and Guhathakarta et al. (2015) observed a similar trend over the monsoon core region of India (majority of the central India) during 1951 – 2000.However, when the period of analysis was extended up to 2010, this increasing trend was no more significant (Guhathakarta et al., 2015). Irrespective of these inferences, the number of extreme rainfall events increased by three times during 1950 – 2015 over central India (Roxy et al., 2017). In a more recent study, Mishra et al. (2018) noticed contrasting trends in heavy precipitation (increasing), light and moderate precipitation (decreasing) events.

Table 4.1. Summary of historically observed trends in various aspects of rainfall from across India, from selected studies as indicated.

Sl. No.	Author(s)	Parameter	Period / Dataset	Region	Trend
1.	Goswamiet al., 2008	Frequency of heavy ($P \geq 100$ mm) and very heavy rainfall ($P \geq 150$ mm) events	1951 – 2000	Central India	Significant increasing trend
		Frequency of moderate rainfall ($5 \text{ mm} \leq P < 100$ mm) events			Significant decreasing trend
2.	Joshi and Rajeevan, 2008	Globally accepted 10 extreme rainfall indices	1901 – 2000	West Coast and Northwest India	Increasing

3.	Rajeevanet al., 2008	Frequency of extreme rainfall	1901 – 2004 (Gridded Dataset)	Central India	Increased at the rate of 6% per decade
4.	Singh et al., 2008	Annual rainfall	Length of data varied from 90 – 100 years	River basins of northwest and central India	Increasing
		1. Pre-monsoon 2. Post-monsoon 3. Monsoon 4. Winter			1. Increasing 2. Increasing 3. No trend 4. Decreasing
5.	Dash et al., 2011	Heavy intensity short-spell rainfall	1951 – 2008 (Gridded Dataset)	In India as a whole and in majority of agro-met divisions.	Increased
		Moderate intensity long-spell rainfall			Decreased
6.	Jain and Kumar, 2012	Annual and seasonal rainfall		22 river basins spread across India subcontinent	Large variability in trends
7.	Jain et al., 2013	Monthly, seasonal and annual rainfall	1871 – 2008	Hydrometeorological subdivision and regional scale for northeast India.	Large variability was observed at subdivision scale, but there was no clear pattern both spatially & temporally
8.	Verikoden et al., 2013	ISMR	1901 – 2003 (Gridded dataset)	Southeast, Northwest and North east regions	Increasing
				Central and west coast regions	Decreasing
		July monthly rainfall		Northeast region	Significant increasing trend
				West coast and central India	Significant decreasing trend
9.	Guhathakarta et al., 2015	Frequency of very heavy rainfall ($P \geq 150$ mm)	1951 – 2000	Monsoon core region of India	Increasing
		Number of Rainy Days	1901 – 2011	Major parts of India	Increasing

			1951 – 2011		Decreasing
10.	Ghosh et al., 2016	Mean ISMR	1951 – 2004 (Gridded dataset)	South, Northeast and Northwest India	Significant decreasing trend
		Intensity and frequency of extreme rainfall events		Central India	Significant increasing trend
				Northeast India	Significant decreasing trend
11.	Roxy et al., 2017	Extreme rainfall evens	1950 – 2015	Central India	Threefold increase in number of events
12.	Mohapatra et al., 2018	Annual mean rainfall	1901 – 2013 (Gridded Dataset)	Spatial mean	Weak decreasing trend
				Northeast India	Decreasing trend (last 2 decades)
				Northwest India	Increasing trend (last 2 decades)
13.	Mukherjee et al., 2018	Annual maximum precipitation	1972 – 2015	More prominent in South India	Increasing
		Frequency of extreme precipitation	Beyond 1982	South and Central India	Increasing
14.	Viswambharan, 2018	June monthly rainfall	1980 – 2015	South west coast of India	Significant decline
		July and September rainfall		Central India	Above normal
				Foothills of Himalayas and southeast India	Below normal

The variability in heavy precipitation events are speculated to be associated with the changes in sea surface temperatures (SST) over Indian Ocean (e.g. Goswamiet al., 2006; Rajeevanet al., 2008). Exploring the frequency of light precipitation days, Dash et al. (2011) observed a decline in the moderate and low-intensity rain events. These sample studies indicate the necessity of better understanding the extreme climate and its impact on precipitation regime which can help us in better planning adaptation strategies for projected changes in the future climate.

4.3. Future Scenarios

4.3.1. Precipitation Projections

Evaluating several models under historical experiment of Coupled Model Inter comparison Project (CMIP5), Sarthi et al. (2015) found that few models are capable of capturing ISMR as observed by the Indian Meteorological Department (IMD) and Global Precipitation Climatology Project (GPCP). The GCMs from CMIP5 suite projected an increase in all-India precipitation, under the business-as-usual emission scenario (Chaturvedi et al., 2012). Compared to the baseline (1961 – 1990) scenario, these models project an increase in precipitation ranging between 5% (by 2030) and 14% (by 2080) as shown in Figure 4.4.

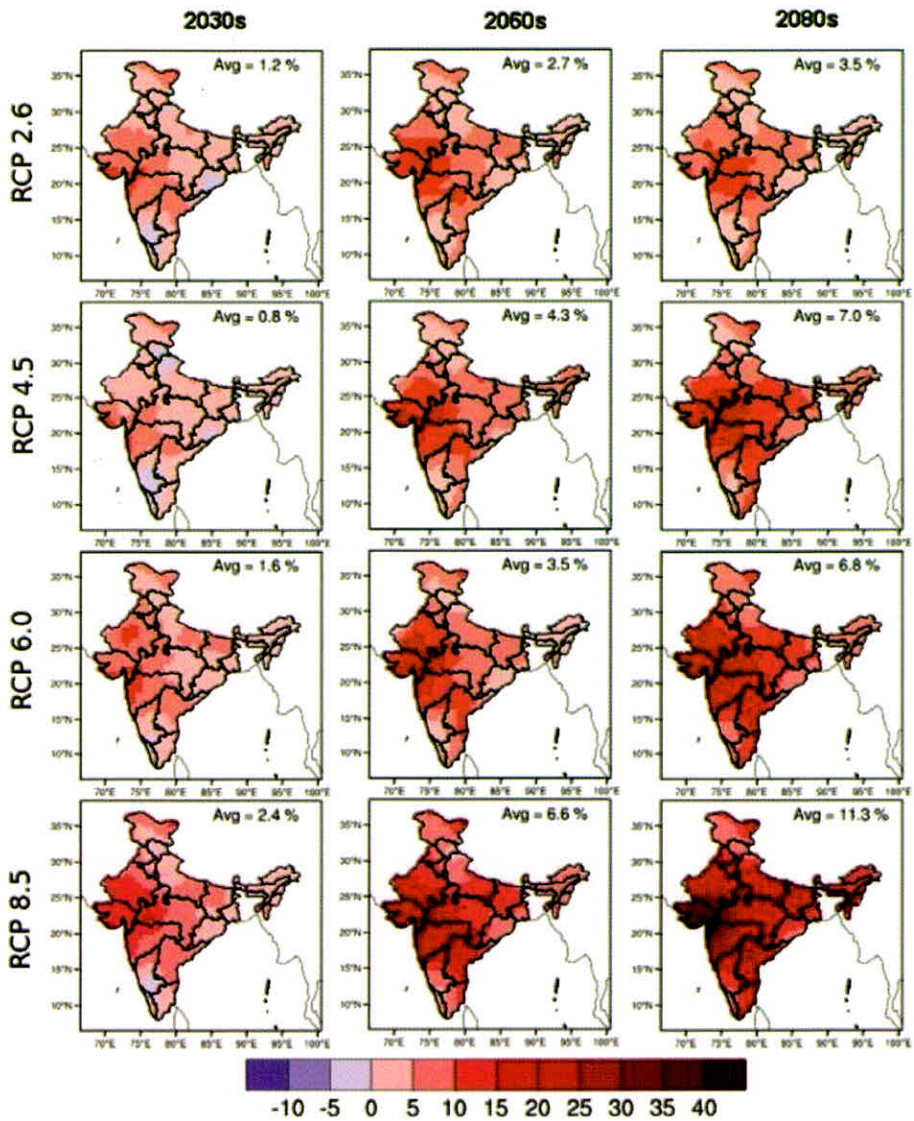


Figure 4.4. *CMIP5 model ensemble mean precipitation change (%) projected for 2030s (2021–2050), 2060s (2046–2075) and 2080s (2070–2099) relative to the pre-industrial period (1880s, i.e. over 1861–1900). (Source: Chaturvedi et al., 2012)*

In another study, evaluating future climate projections of the 21st century based on the RCP4.5 and RCP8.5 scenarios, Woo et al. (2018) projected an increase in ISMR over northwest and decrease over northeast India. They also depicted an increase over west, and south peninsular and a reduction over north-central India. Niu et al. (2005) assessed future climate simulations from seven RCMs driven by three GCMs based on the IPCC A1B emission scenario and projected the changes in summer monsoon climate during 2041 – 2060 over Indian Peninsula. The study found a significant increase in ISMR over southern India, southeast Indian peninsula in specific. They also demonstrated that the majority of RCMs driven by the same GCM project early onset of monsoon. In contrast, Dobler and Ahrens (2011) and Asharaf and Ahrens, (2015) found a decreasing trend in ISMR based on the simulations from RCM Consortium for Small-Scale Modelling in Climate Mode (COSMO-CLM) (Figure 4.5).

Overall, majority of the GCMs projected an increase in precipitation magnitude and intensity across India (e.g. Chaturvedi et al., 2012; Akhter et al., 2017; Li et al., 2017). Summary of the projected changes in annual and seasonal precipitation (i.e. magnitude and intensity), from selected studies are listed in Table 4.2, in the order of publication date.

Table 4.2. Summary of selected studies with precipitation projections for India.

Sl. No.	Author(s)	Parameter	Baseline period	Emission Concentration	Projected Change
1.	Niu et al., 2005	ISMR	1981 - 2000	IPCC A1B emission scenario	Significant increase over southern India, and southeast Indian peninsula
2.	Dobler and Ahrens, 2011	All India monsoon rainfall	1971 – 2000	SRES A2, A1B, and B1	Decreasing trend over northwestern India
3.	Chaturvedi et al., 2012	Multimodel model mean precipitation over India	1961 – 1990	RCP6.0 and RCP8.5	Increase from 4 – 5 % by 2030s Increase from 6 – 14% by 2080s
4.	Li et al., 2017	South Asian Summer Monsoon		RCP2.6, RCP4.0, and RCP8.5	Intensified monsoon precipitation over Asia-Pacific region

5.	Akhter et al., 2017	Rainfall projections over homogenous zones of India		RCP4.5, and RCP8.5	Increase over Northwest India, West Peninsular India, Northeast India, and south peninsular India. Slight decrease over the North Central India, and Eastern Pacific
6.	Woo et al., 2018	ISMR	1979 – 2009	RCP4.5 and RCP 8.5	1. Increase over northwest and west-south peninsular India 2. Decrease over northeast India

4.3.2. Uncertainty in Precipitation Projections

The GCMs are comparatively reliable in projecting temperature and precipitation (IPCC, 2013), although these projections need considerable improvements (Dai, 2006; McMahon, 2015; Sabeerali et al., 2015). Chaturvedi et al. (2012) indicated that the uncertainty associated with the future climate may be reduced when looking at long-term projections, however, the uncertainty in precipitation projections is still a major problem and needs to be addressed. Uncertainty in the projected precipitation is primarily due to the failure of GCMs in capturing the local processes or phenomenon controlling the regional climate. Although higher resolution models are required to capture the regional climate, because of the complexity associated with representing the physics of the regional climatic processes and the computational capabilities of the models, GCMs are restricted to larger spatial scales.

Therefore, to accomplish the goal of simulating regional climate, various downscaling techniques were developed and adopted, to account for the lower scale phenomenon affecting the regional climate. For example, the south Asian monsoon and its variability is better captured by a dynamically downscaled regional climate model, second version of the earth systems model from Indian Institute of Tropical Meteorology, IITM-ESMv2 (Swapna et al., 2018). Evaluating the performance of IITM-ESMv2 and several CMIP5 models in simulating ISMR, Swapna et al. (2018) observed that the IITM-ESMv2 performed relatively better in simulating ISMR (Figure 4.6). The effect of topographical features is critical in mountainous regions, however the impact of regional phenomenon in these areas, i.e. orographic effect is seldom captured by the GCMs. Impact of such regional phenomenon on precipitation is better captured by a statistical downscaling model developed by Salvi et al. (2013).

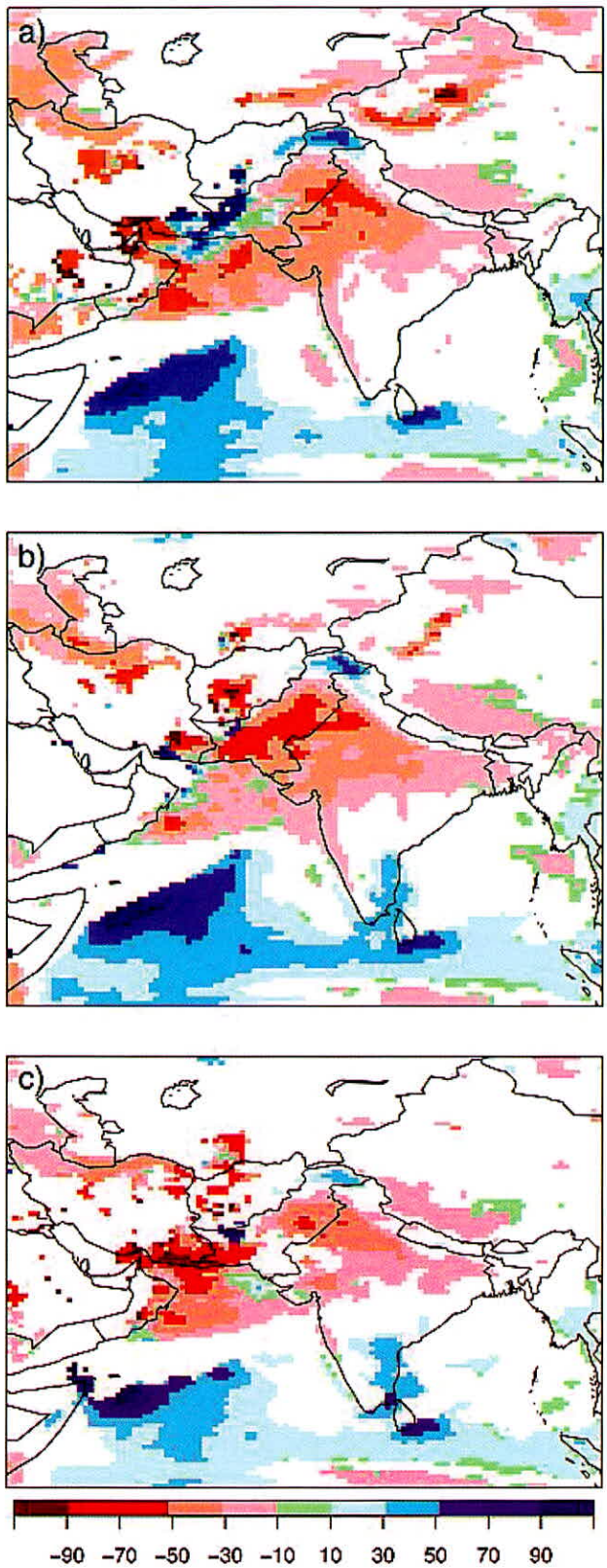


Figure 4.5. *Linear trends in monsoon rainfall (% / century) during the time period 1960 – 2100 in (a) the A2, (b) the A1B, and (c) the B1 COSMO-CLM runs. Colored areas show significant trends (at the 5% significance level). (Source: Dobler and Ahrens, 2011).*

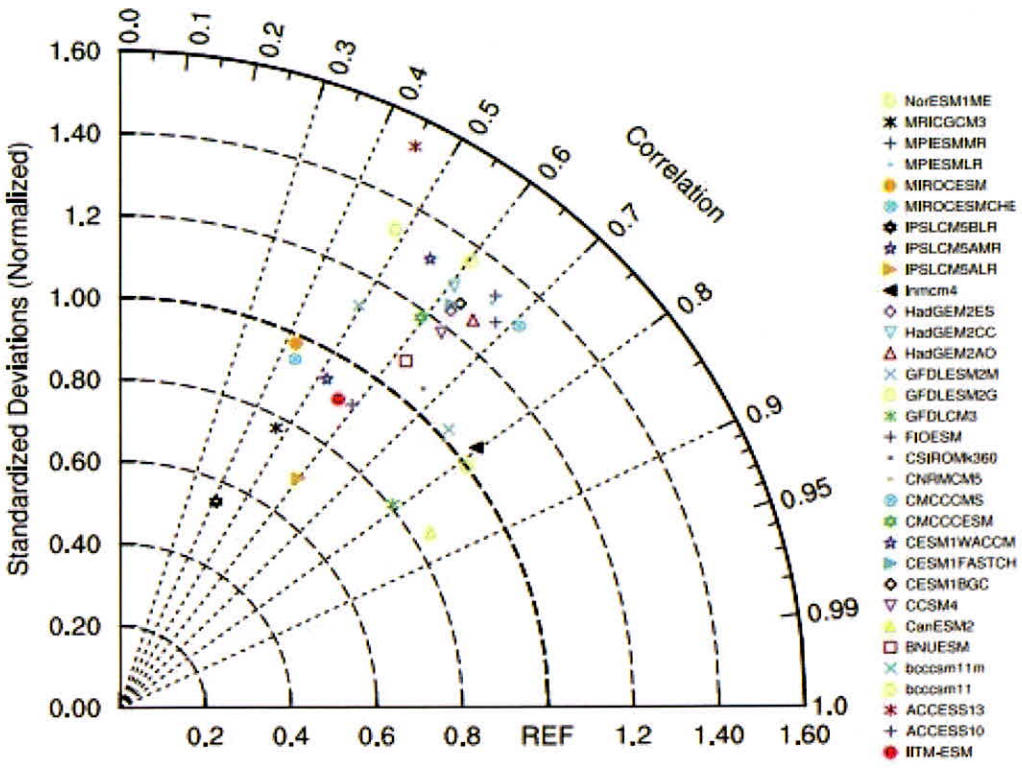


***Figure 4.6**. Taylor diagram showing the spatial correlation and standard deviation of ISMR from IITM-ESMv2 and CMIP5 models. (Source: Swapna et al., 2018)*

Projections from this model indicate an increase in rainfall across western coastline and northeast India and decrease in northern and western India. Adopting statistical downscaling technique, Shashikanth and Sukumar (2017) evaluated three GCMs from the CMIP5 suite to project Indian monsoon monthly rainfall at a resolution of 0.25°. They projected an increase in the monthly mean rainfall all over India. Although statistical downscaling technique is adopted in various studies to project ISMR, several limitations in this technique hamper the results. Statistical downscaling is based on the historically observed empirical relationships between predictors and predicts and. Assuming that these relationships stay unaltered, the regional scale precipitation is projected by applying these empirical relationships to the GCM simulated climate predictors.

However, the change in climate is non-stationary and the reliability of precipitation projected from these empirical relationships is questionable and requires further investigation. The assumption of stationary climate leads to failure of projecting precipitation extremes. In addition, the effect of changing land and sea surface temperatures on intensification of precipitation extremes (Vittal et al., 2016) is not well represented in statistical downscaling. Furthermore, statistical downscaling techniques do not account for the changes due to more regional effects including deforestation or urbanisation. Although statistical downscaling is known to further induce uncertainty in regional scale precipitation projections, improvements in GCM setup and downscaling techniques have led to reduction in this uncertainty (e.g. Shashikanthet al., 2013).

4.3.3. Precipitation Extremes

Precipitation extremes are rare events and hence the reliability of the projected changes in their characteristics, in terms of intensity and frequency, depend predominantly on the amount and quality of historically observed data. In addition, the knowledge of fundamental processes and the reliability of their simulations from a GCM influence the confidence of the projected changes. Historically, the changes (trends) in observed precipitation extremes (heavy precipitation) across India were inconsistent and the magnitude and significance of trend differed across the subcontinent. However, the global scale precipitation extremes were intensified over the past century due to the anthropogenic influences (IPCC, 2012). Hence the projected increases in GHG concentrations along with other anthropogenic influences could lead to further intensification of precipitation extremes. In particular, the projected increases in the characteristics of precipitation extremes (e.g. Woo et al., 2018; Mukherjee et al., 2018) could lead to disastrous impacts, with significant implications on infrastructure, agriculture and water resources across India. Therefore, reliable and credible plausible scenarios of extreme climate can help us in better planning of adaptation strategies.

Intensity of extreme precipitation events are projected to increase in the 21st century across the globe (IPCC, 2013), specifically indicating an increase in heavy daily precipitation in many regions. For instance, the Hadley Centre coupled model HadCM3, when run with the doubled CO_2 emissions scenario, projected as in the magnitude of heaviest rainfall across India (Turner and Slingo, 2009). Another GCM from Meteorological Research Institute and Japan Meteorological Agency also projected and increase in heavy precipitation across south Asia (Kamiguchi et al., 2006). Although GCM projections provide an overview of the changes in climatic variables at a larger spatial scales, changes at a regional or local scale can be seen by downscaling the GCM projected climate. Evaluating the dynamically downscaled precipitation extremes from the Coordinated Regional Climate Downscaling Experiment (CORDEX), driven by CMIP5 models, Mishra et al. (2014) found that the CORDEX-RCMs fail to outperform the GCMs.

Singh et al. (2016) concur with Mishra et al. (2014) and conclude that that the reliability of RCM projected precipitation extremes is not far away from that of the GCM projections. Moreover, Salvi et al. (2013) demonstrated that the statistically downscaled GCM projections also fail to efficiently capture the precipitation extremes (Salvi et al., 2013). Irrespective of this shortcoming of the downscaling techniques, Sanjay et al. (2017) projected an intensified ISMR during 2066 – 2095, in the hilly sub-region within the south-eastern Himalaya and Tibetan Plateau, based on the simulations from several RCMs, from the CORDEX south Asia framework, with the GHG concentration of RCP8.5. In a more recent study, Woo et al. (2018) projected a significant increase in extreme precipitation events (20–50% increase in rainy days) across west-south peninsular India during the far future period (towards end of the century). In addition, Mukherjee et al. (2018) projected an increase in the frequency of precipitation extremes across south and central India and demonstrated that this rise is due to the anthropogenic climate change.

4.4. Concluding Remarks

ISMR is the crucial component for Indian economy, as it plays a major role in the agricultural sector and is the major source of water for domestic and industrial purposes. Also, below or above normal ISMR may lead to disastrous impacts such as droughts and floods respectively. Therefore, knowledge of spatial and temporal variability of ISMR is vital for effective planning and design of any water

resources infrastructure. Thus the quantitative and qualitative assessment of future projected rainfall is vital and provides important information to decision makers in order to assess the impact and plan accordingly for effective adaptation to climate change. There is still a void in understanding the exact influence of several climatic and geographical features on ISMR, for example, ENSO–ISMR relationships require further investigation as these relationships are inconsistent with time (e.g. Yun and Timmermann, 2018) and are hypothesized to be influenced by the low-frequency atmosphere-ocean oscillations including IOD, PDO, etc. (Ashok et al., 2004; Krishnamurthy and Krishnamurthy, 2014).

The uncertainty in the climate change projections remain large, particularly in precipitation projections, despite the increased resolution and better representation of physics in the GCMs. Many of the climate models used in the latest IPCC give estimates of precipitation but the aggregate data at the country level is very hard to find. The CMIP5 data from ESGF data facility can be downloaded but it only provides data at very high spatial resolution. In CORDEX, a number of regional climate models are run as time slice experiments forced by models of the CMIP3 and/or CMIP5 ensemble with the aim to provide climate change relevant data for every land point on Earth, with a spatial resolution of approximately 20km. Currently, the confidence in the projected changes in the regional precipitation patterns, for example ISMR and winter season rainfall across northern India, in India and the uncertainty associated with the RCMs require further refinement. In addition, the unavailability of state-of-the-art regional climate models to simulate extreme events of ISMR makes it a potential area of research.

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CHAPTER 5

IMPACT OF CLIMATE CHANGE ON EVAPORATION AND EVAPOTRANSPIRATION

Suhas D. Khobragade

5.0. Introduction

A steady increase in the green house gases and consequent enhancement of the greenhouse effect has resulted in a phenomenon called "global warming"; causing temperatures to rise globally and associated climatic changes. According to the 5thassessment report of the IPCC, the earth surface temperature exhibited an increase by 0.85°Cover the period 1880-2012 (IPCC, 2015) (Fig. 5.1). Each of the decades has been observed to be relatively warmer than the preceding decade since 1850 and the period from 1983 to 2012 has been observed to be the warmest three decade (30 yrs) period for the Northern Hemisphere during the last 1400 years (IPCC, 2015). Earlier IPCC report (IPCC, 1990) had predicted an increase of 1 to 3.5 ^{0}C in temperature by the year 2100 if greenhouse gas emission is not controlled.

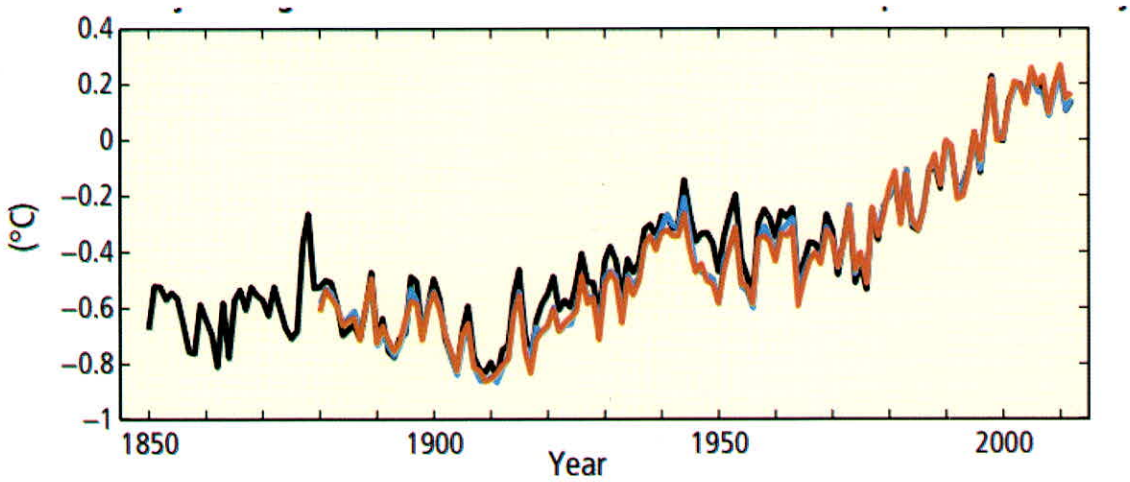


***Figure 5.1**: Globally averaged surface temperature (IPCC, 2014) (different colours indicate different data sets)*

As far as India is concerned, a rising trend in temperature has been reported by many researchers. An increasing trend of 0.57^{0}C for the period 1881-1997 has been reported by Pant and Kumar (1997) while a study by Hingane et al. (1985) had earlier given a rising trend of 0.4 ^{0}C for the period 1901-1982. Arora et al. (2005) investigated the trends in temperature for 125 stations spread all over India using time series data of last hundred years and observed the mean maximum temperature, mean minimum temperature and annual mean temperature to increase at the rate of 0.92, 0.09 and 0.42 ^{0}C respectively. The mean temperature for the post-monsoon season has been observed to increase by 0.94 ^{0}C and that of winter season by 1.1 ^{0}C.GCM based studies by Lal (2001) have indicated a rise of 3.5 to 5.5 ^{0}C for the annual mean surface temperature for the Indian sub-continent by the year 2080, the range of rising for winter and summer monsoon being 4-6 ^{0}C and 2.9-4.6 ^{0}C respectively. Variations have, however, been observed for local scale (for example Das et al., 2008).Amore recent analysis of the surface temperature data for the period of 1901 to 2016 by Ross et al. (2018) indicates a rising trend in daily maximum, minimum and mean temperature for the northwestern and southern India and a

falling trend over the belt spreading from northeastern to central India, from the 1950s to2000s.Annual mean temperature shows increasing trends in most part of the country (Figure. 5.2).

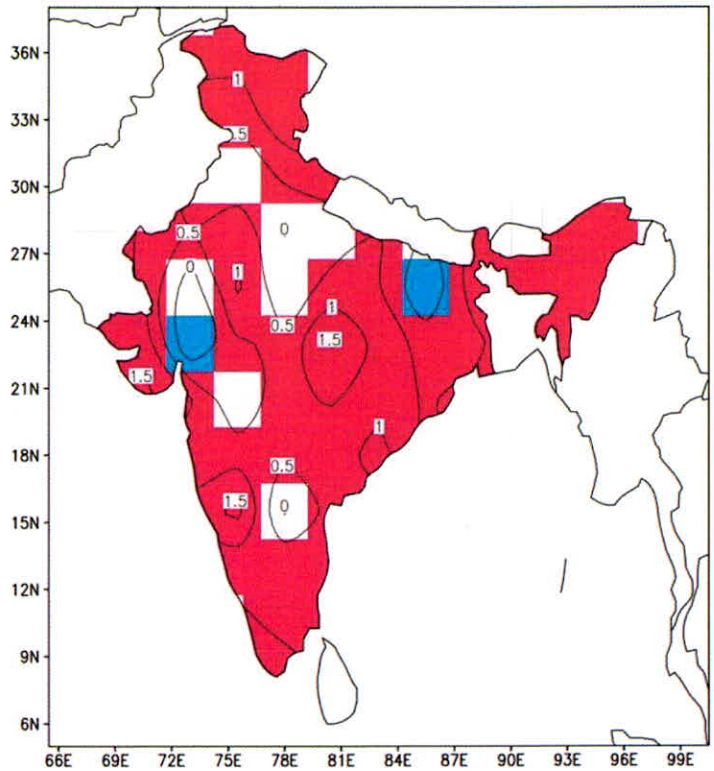


***Figure 5.2**: Trends in annual mean temperature significant at the 95% level over India during 1901–2016(after Ross et al., 2018) (red colour indicates increasing trends while blue colour indicates decreasing trend)*

Evapotranspiration is one of the key components of the hydrologic cycle. Precipitation which falls on the land is subjected to evaporation and evapotranspiration before it reaches back to the oceans, causing a significant loss of the available water. Increasing scarcity of water due to increased ET losses may lead to difficulties in meeting the various demands of the growing population and its development needs. Most of the water bodies in the warm tropical regions undergo heavy evaporation losses. Delclaux et al., 2007, for example, observed that annual evaporation is about 90% of the total output losses from the Lake Titicaca. Annual evaporation losses from reservoirs in Australia have been estimated to be about 40% of the storage capacity (Helfer et al., 2012). As per the CWC (2006) report, average annual evaporation loss from reservoirs/water bodies in India is about 27,000 MCM.

Being a key link between the global water and energy cycles (Yang et al., 2011), any change in evapotranspiration is likely to significantly affect the global hydrologic as well as energy cycle (IPCC, 2013). Being a cause of significant water loss, evapotranspiration plays a major role in determining the stream flow regime (Liu et al., 2013). Therefore, understanding the impact of temperature rise or climate change on evapotranspiration is essential for a proper understanding of the impact of climate change on the hydrological regime of the stream and water availability in the basin or water body. It shall provide a proper assessment of how much more or less water shall be available and, if less water is available, then how much additional water shall be required to meet the various demands.

5.1. The Processes of Evaporation and Evapotranspiration

For a better and proper understanding of the possible impact of climate change on the processes of evaporation and evapotranspiration, it is first important and pertinent to have an understanding of the processes of evaporation and evapotranspiration. Evaporation is a surface phenomenon that takes places from the surface of the various types of water bodies such as the oceans, seas, lakes, reservoirs, ponds, rivers and other surfaces such as wet canopy and moist soils etc. Solar radiation provides the required energy for the process of changing liquid water to gaseous form (vapours). If this form of energy is not available, internal energy stored as heat energy is used by the water body for evaporation. As evaporation continues, vapour molecules get accumulated over the surface leading to an increase in partial vapour pressure, which continues till the saturation level is reached. At saturation vapour pressure, neither evaporation nor condensation occurs (equilibrium state). However, due to the various transport processes occurring in the atmosphere such as the wind, equilibrium never occurs. The other important process that causes loss of water is transpiration by the plants, which involves removal of water from the plant tissues and its subsequent release to the atmosphere. It takes place through the stomata present in the leaves. Most of the water available in plants is lost through the process of transpiration (Allen et al., 1998).Both evaporation and transpiration take place together and distinguishing between the two is not an easy task.

5.2. Factors Affecting Evapotranspiration

Temperature is often thought to be the only causal factor for evaporation. However, this is far from the reality. Evaporation takes place only when there is a vapor pressure deficit and needs a source of energy for removal of water vapours from the evaporating surfaces. Energy, as mentioned above, is supplied by the sun. Higher solar radiation causes higher evaporation rates and vice versa. Wind is another important factor in evaporation which is responsible for creating the evaporative demand by maintaining the vapour pressure deficit. In the absence of wind there would be no evaporation. Increase in wind would increase the evaporation rate till the critical value is reached, beyond which evaporation would not be affected by the wind (Reddy, 1997). Other influencing factors are atmospheric pressure and sunshine hours. Atmospheric pressure has a negative correlation with evaporation. Factors like water quality (turbidity, salinity) may also influence evaporation, although their role is not significant (Reddy, 1997). If one is interested in the volume and not rate of evaporation, then size of the water body could also be an important determinant.

Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other additional factors that need to be considered (Allen et al., 1998).With the depletion in soil moisture in the top soil, evaporation decreases. It ceases completely as the soil becomes void of moisture (Allen et al., 1998).In the cropped area, crop characteristics also influence the transpiration rate, besides the moisture content of the soil and amount of solar radiation reaching the soil surface. This leads to different evapotranspiration rates for different types of plants (Allen et al., 1998).This is further affected by the cultivation practices followed. Since the amount of solar radiation reaching the soil surface is determined by the amount of canopy cover, the role of factors like stages of crop growth and development become an important factor in the process of evapotranspiration from the cropped area (Figure 5.3)ET losses could be almost completely due to evaporation in the initial stages of the crop growth whereas transpiration could become a significant factor at the full crop growth or harvesting time accounting for almost 90% of the total water loss from the cropped area(Allen et al., 1998).

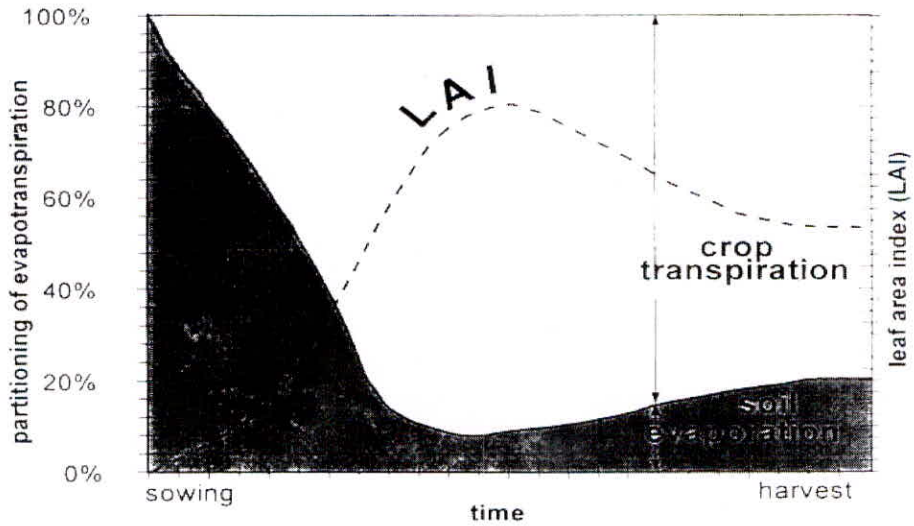


Figure 5.3: *Relative contribution of evaporation and transpiration in evapotranspiration during crop growth period (after Allen et al., 1998)*

5.2.1 Temperature Dependence of the Factors

The most important factors determining the evaporation rates and which are considered in most evaporation and evapotranspiration models are radiation, temperature, humidity, vapour pressure deficit, atmospheric pressure, sunshine hours and wind speed. Many of these factors are temperature dependent. The net radiation is indirectly affected by temperature through its effect on the long-wave radiation. Vapour pressure deficit (VPD) is determined by temperature by determining the vapour pressures of air and water. While vapour pressure of pure water is a function of temperature, the saturation vapour pressure also depends on temperature only (Dingman, 1994). Temperature also determines the latent heat of vaporization. Factors like winds speed and sunshine hours are, however, not directly or significantly dependent on the local temperature variations. The various meteorological factors affecting evaporation and evapotranspiration, which are used in evaporation and evapotranspiration models, can be grouped into three categories: (i) factors affected directly by the temperature changes, for example saturation vapour pressure; (ii) factors affected indirectly by the temperature changes, for example vapour pressure deficit; and (iii) factors not affected by the temperature changes, for example sunshine hours.

5.2.2 Variability of ET and Relative Roles of Different Factors

Evapotranspiration is a very complex process involving complex interactions and interrelationships of a number of meteorological, atmospheric and physical factors. This complexity results in variation of evaporation rates. The pattern of monthly evaporation is also not always consistent from year to year. A variation ranging from 10 to 89% was observed by Rosenberry et al. (1993) for Lake Williams, Minnesota. In many places there are annual variations, seasonal variations, and intra-seasonal variations (Lenters et al., 2005). Even diurnal variations in evaporation have also been observed (Yin and Nicholson, 2000). Studies have also shown that evaporation rate may vary even across a lake, in

case of large lakes (Mahrer and Assouline, 1993) and may also depend on the geometry of the water body (Sacks et al., 1994), with deep and shallow water bodies exhibiting different controlling factors.

The role of different factors controlling evapotranspiration rate vary from place to place and also temporally for the same place. Mohan and Arumugam (1996) based on the study of eight stations of Karnataka and Tamilnadu in India, observed that relative humidity, temperature and wind speed are the most influencing factors controlling the evapotranspiration process, while rainfall and sunshine duration have less influence. Lenters et al. (2005) observed that the seasonal variations are largely due to changes in temperature and net radiation. According to them, the most important individual climatic influence on inter-seasonal variations in evaporation is relative humidity, followed by lake-air temperature difference, wind speed and air temperature. Antonopoulos (2007) from their study on Lake Vegoritis in Greece observed that evaporation rates are determined mostly by the long-wave radiation regime while for the Lower Mekong River basin in Combodia, Kumiko et al. (2008) observed rainy season to have a high evaporation potential due to large amount of net radiation. Wen et al. (2012) observed that for Chuxiong City in China, annual reference ET is determined by wind speed, sunshine hours, relative humidity and temperature in that order while for Varansi in India Annu Priya et al. (2014) observed that annual reference ET is affected most by mean temperature followed in order of importance by solar radiation, vapour pressure deficit and wind speed. Thus, it is important to have a proper knowledge and understanding of the various factors in causing variations in evaporation in different climatic settings so that proper interpretations are done while studying the impact of climate change on evaporation and evapotranspiration.

5.3 Impact of Climate Change on Evapotranspiration

5.3.1 Evaporation Paradox

It is a general perception that rises in temperature should increase the evapotranspiration rate (Abtew et al., 2015, Fiklin et al., 2015). For example, as per WMO/ICSU/UNEP (1989) report evapotranspiration is expected to increase globally by about 10–20% due to global warming. However, subsequent research has shown it to be not true always ast he rate of evapotranspiration is actually declining in many parts of the world during the last few decades, as indicated by many studies (Stocker et al., 2013). This contradiction of evapotranspiration declining despite the rising temperature is known as the "evaporation paradox" (Xing et al., 2016). It was first noted and reported by Peterson et al. (1995), whose analysis of the 40 years (1950-1990) of pan evaporation data of Russia and USA clearly indicated a declining trend in the pan evaporation time series data. This is referred to as "evaporation paradox" because decrease in evapotranspiration means decrease in water vapours generated. This should lead to decrease in precipitation. But this has not been observed ingeneral. Scientists have, therefore, been wondering about the possible causes of this "evaporation paradox". The answer, according to some researchers, lies in the fact that evaporation and evapotranspiration are consequence of the complex interactions of the various atmospheric, meteorological and physical processes, as discussed earlier. The same argument is put forward by Mcvicar et al. (2012). Jiménez Cisneros et al. (2014) based on the review of the various reported studies have attributed the steady decreases in global and regional actual evapotranspiration and pan evaporation since the 1960s to changes in precipitation, diurnal temperature range, aerosol concentration, (net) solar radiation, vapor pressure deficit and wind speed. Earlier, studies by Dankers and Christensen (2005) for Finland and Norway indicated that impact of climate change on evapotranspiration even varies with altitude. Chattopadhyay and Hulme (1997) identified increases in the vapor pressure deficit regime as the cause of the paradox

while Bandopadhyay et al. (2009) observed increase in the relative humidity and decrease in wind speed as the major reason for the declining trends in reference evapotranspiration throughout India. Studies by Khobragade (2009) brings out that for the semi arid region of Udaipur in India, evaporation regime is likely to be affected most by the changes in vapor pressure deficit regime followed by the changes in the regimes of maximum temperature, net long-wave radiation, saturation vapour pressure and net radiation in that order, when the mean temperature is increased by 1^0C. According to the sensitivity study of Serrano et al. (2014), relative humidity, wind speed and maximum temperature have higher correlation with changes in reference evapotranspiration whereas minimum temperature and duration of sunshine have a lower correlation. Sharifi and Dinpashoh (2014), from their study on eight stations in Iran observed the reference evapotranspiration to be related most to the changes in mean temperature for the six of the eight stations while it was least related to the change in vapour pressure regime for most of the stations. Studies for Tibetan Plateau by Xie and Zhu (2012) produced totally different set of inferences with the wind being indicative as the major factor responsible for the declining reference evapotranspiration followed by changes in vapour pressure and net radiation which together negate the increase in rates of reference evapotranspiration caused by the increase in mean temperature. Studies by Liu et al. (2017) for the 3H plains in China bring out that the combined effects of relative humidity and insolation dictate declines in reference evapotranspiration during the summer, autumn and spring while in winter the changes in the wind velocity together with the decrease in relative humidity are responsible for the declines. However, although most of these studies indicate a consistent decline in potential evapotranspiration or reference evapotranspiration rates, yet there are many studies which indicate otherwise. This means that the evaporation paradox is not observed at every place. Serrano et al. (2014), for example, observed increasing trends in monthly reference evapotranspiration for 46 meteorological stations in Spain based on the data of 1961 to 2011.

Based on the findings of the various studies it is apparent that the reasons for the evaporation paradox being not observed at every place in the world is the varying nature of the various controlling factors of evapotranspiration and their varying relative significance at different places and times. However, it surely does not clearly explain as to why there is no decreasing trend in rainfall in most parts of the world if there is a declining trend in evaporation? How could there be same or more rainfall if the amount of total air moisture is decreasing? Scientists are still pondering over this mystery. Brutsaert and Parlange (1998) have come up with an explanation to resolve the mystery. According to them, the paradox arose because of misinterpretation of the pan evaporation measurements which does not account for the role of humidity already present in the air. They claim that the declining trends in the pan evaporation data in many cases are actually indicative of the global warming, if we are able to factorize the land surface moisture and properly process and interpret the raw data of pan evaporation time series. Although the theory has not been rejected by any researcher, not many researchers seem to have accepted the explanation too and the paradox still appears to have remained an unresolved mystery.

5.3.2 Impact Indicators from Different Parts of the World

A plethora of literature is available now from the numerous studies carried in different parts of the world on the possible impacts of temperature rise and climate change on the hydrologic cycle and its consequences for the water resources of the world. Unfortunately only a limited number of these studies are related to the assessment of the impact specifically on the process of evapotranspiration. Itcan be illustrated from the fact that IPCC (2001) report provided only a handful of references on

evapotranspiration although it provided a long list of references on the studies related various aspects of impact of global warming and climate change. Although, the IPCC report (2001) is almost two decades old now, one would be surprised to know that not too many studies have been reported on this aspect thereafter. Even the 5th assessment report of IPCC does not contain many references. Many of the reported studies related to climate change impact are based on trend analysis of the evaporation data, particularly the pan evaporation data. These studies report mixed findings with increase predicted for some regions and decrease for some other. Decline in evaporation has been reported for USA, Russia, Eurasia, China, Australia and New Zealand (Peterson et al., 1995; Thomas, 2000; Golubev et al., 2001; Liu et al., 2004; Roderick and Farquhar, 2004;Roderick and Farquhar , 2005; Huo et al., 2013;Jiao and Wang, 2018) while increasing trend has been reported for some parts. Dinpashoh et al. (2018), for example, observed increasing trend in monthly ET_0 for 86% stations out of 36 stations studied in NW Iran. Statistically significant increasing trends in Evapotranspiration have also been found for the Okavango Delta in Botswanaby Moses and Hambira (2018). Some mixed trends have been observed in East Asia, northeast Brazil, Israel and Togo (Xu, 2001; Cohen et al., 2002, da Silva, 2004, Djaman et al., 2017). No specific trend was observed for the study site in Cyprus by Christou et al. (2017).

Most of these studies are based on the trend analysis of reference or potential evapotranspiration. Few studies have also been reported using the output from the global or regional circulation models and coupling it with the hydrological models. In one of the earliest such attempts, Rind and Lebedeff (1984) investigated the effect of doubling the CO_2 content on evaporation rates and reported that it would increase proportionately, although it is otherwise reported that increase in CO_2 content decreases stomatal density (Woodward, 1987) which should result in decrease in transpiration rates. Ramirez and Finnerty (1996) from their sensitivity analysis for the San Luis Valley of Colorado carried out considering both theCO_2 and temperature changes, observed a decrease of 18.5 % in potential evapotranspiration when a combination of 100% increase in CO_2concentration and a 3^0C rise in temperature is considered. Dankers and Christensen (2005) predicted increased rates of evapotranspiration for a sub-arctic basin with RCM. Lenderink et al. (2007) also predicted significant increase in evaporation for central Europefor the period of 2071-2100 based on their analysis carried out using the regional circulation models. Based on their analysis of the data of 20 stations in Egypt, carried out using GCM (HadCM3) considering the four emission Scenarios (A1, A2, B1 and B2), Khalil (2013) predicted an increase in ET for the future periods of 2040, 2060, 2080 and 2100 when compared to the present (normal)values obtained based on the period of 2000-2009. Jarabicová et al (2015) analyzed the impact of climate change on actual soil evaporation using CGCM3.1 global model (considering SRES A2 andB1 scenarios) and, KNMI and MPI regional models for the Poiplie wetland ecosystem in Slovakia and predicted an increase in the range of 19-24% for the future periods of 2020, 2050 and 2080 based on the reference data period of 1977–1996. Similarly, Dahal et al. (2016) projected an increase in evapotranspiration for southern plains of Nagmati river basin in Nepal using GCM analysis. More recently, Liu et al (2017) investigated the impact on reference evapotranspiration for 40 weather stations of Huang-Huai-Hai Plain (3H Plain) in China along with the RCP 8.5 scenario. Their results indicate a statistically significant decreasing trend in reference evapotranspiration for only the summer season as well as annual time scale, when historical data are used. However, using the RCP8.5 scenario an increasing trend was observed for all the seasons as well as the annual time scale. The annual increase in reference evaporation has been projected to be 3.37 mm/annum.

Temperature determines the vapour pressure deficit (VPD) by determining the vapour pressures of air and water. As long as this deficit exists evaporation takes place. However, since water temperature data are generally not available, saturation vapour pressure of air is assumed as equivalent of vapour pressure of water and used in most evaporation models. However, for water bodies, a more realistic assessment of the impact of climate change can be arrived at by analyzing the possible impact of global warming on the temperature of the water body which is not feasible using the Penman-Monteith model or other evaporation models, if water temperature data are not available. Analysis of the energy budget of the water body is, therefore, required for such a purpose. Such an attempt has been made by Helfer et al (2012) who investigated the impact of climate change on the water temperature of the lake and its subsequent impact on lake evaporation for the Wivenhoe Dam which is a big reservoir in Australia. Their results show that the reservoir evaporation rate shall increase by about 8 percent during 2030-2050 and by about 15 % during 2070-2090 (Helfer et al.,2012) (Fig. 5.4).

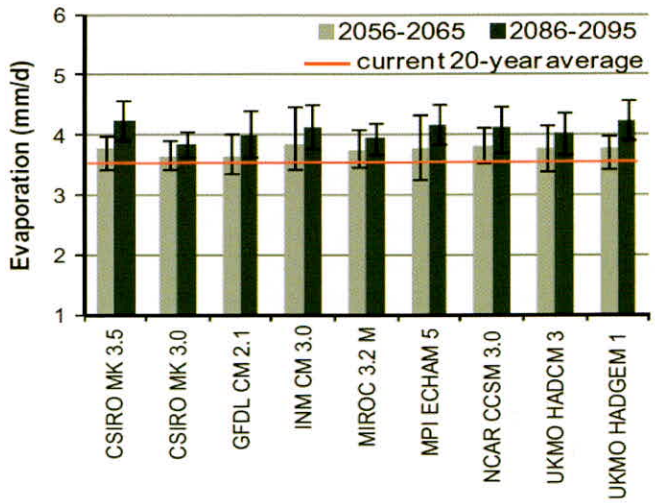


***Figure 5.4**. Projected average daily evaporation for Wivenhoe Dam, Australia (after Helfer et al., 2012)*

5.3.3 The Indian Scenario

As far as India is concerned, although one of the initial studies on climate change impact on evaporation using GCM simulations was reported in the last decade of the previous millennium by Chattopadhyay and Hulme (1997), which projected a decrease in the potential evapotranspiration, not may studies using GCM or RCM data have been reported since then. Most impact studies related to evaporation or evapotranspiration deal with analysis of trends in pan evaporation or reference evaporation data. Verma et al. (2008) from their studies on trend analysis of evapotranspiration data of the period 1971-2000 for 22 stations from different parts of India observed a significant decreasing trend in 17 stations. Jaswal et al. (2008) also observed a significant decrease in pan evaporation for most of the 58 stations from all over India analyzed using the pan data of 1971-2008. Jhajharia et al. (2009) also got similar results for eight out of the nine stations from the humid climatic regions of north-east India analyzed for trends in annual pan evaporation. Results of trends analysis carried out by Bandopadhyay et al. (2009) for 32 years data of reference evapotranspiration for 133 locations spread all over India belonging to the period 1971–2002 also gave a decreasing trend. A significant declining trend in pan evaporation data has also been reported by Padmakumari et al. (2013) for 58 locations

spread all over India based on the data of 1971-2010, with annual declining rate in dry months of October to May being significantly higher (about 9 mm/yr) compared to the humid monsoon months of June to September (about 6 mm/yr)(Fig. 5.5). More recently, Goroshi et al. (2017), based on the trend analysis carried out using NOAA satellite derived gridded average ET data for India, for the period of 1983-2006, have observed a decrease in average evapotranspiration at a rate of 0.22 mm/yr, with the decrease being much higher at 1.75/yr for the semi arid and arid regions. Studies based on climatic variability approach by Khobragade (2009) indicate that 1^0C rise in temperature is likely to increase the daily evaporation rates for the semi arid Udaipur region in India by about 30% during monsoon and about 8% in winter while it is likely to decrease by about 5% during summer. Annu priya et al. (2014) from their analysis using climatic variability approach observed an increase of 2.3% in annual reference ET for every 1 degree rise in mean temperature for Varansi, if CO_2 concentration is not considered. However, they have observed that if temperature remains constant, there is a decrease in reference evapotranspiration with increases in CO_2 concentration, which according to them is due to the decrease in stomatal conductance and increase in stomatal resistance caused by the increase in CO_2 concentration. Thus, combined effects of increase in temperature and CO_2 concentration does not result in any significant rise in evapotranspiration.

From the above review, it can be clearly seen than evaporation paradox has been observed in most parts of India, if we go by the analysis of evaporation trends as reported by the various studies. More and more studies using the projected outputs from the atmospheric circulation models and using them as input in the Penman-Monteith model and considering also the impacts of increasing CO_2 concentration, are required for the picture to become clearer.

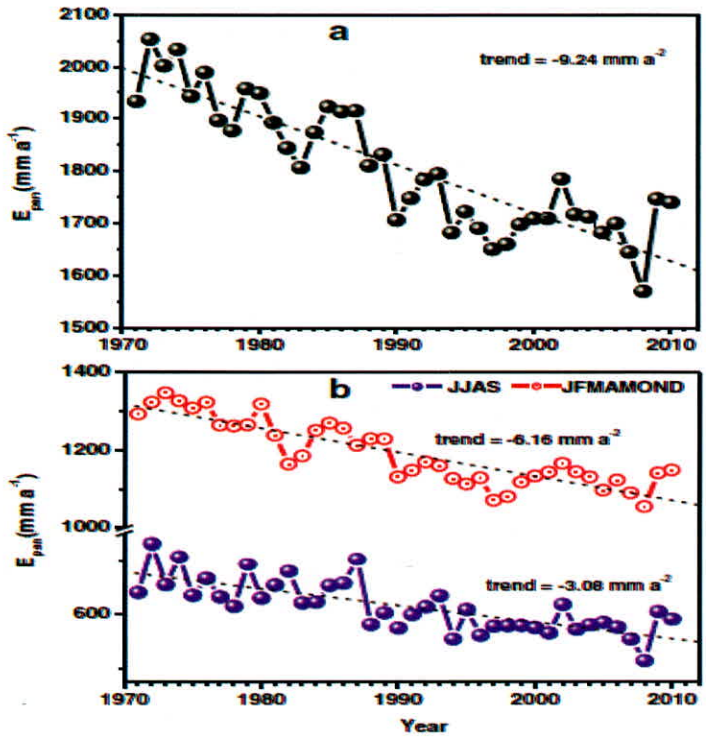


Figure 5.5: *Declining trends in pan evaporation averaged over India (after Padmakumari et al., 2013).*

5.4 Some Issues in Assessment of the Impact

Unlike other components of the hydrologic cycle such as stream discharge or change in ground water levels or magnitude of precipitation, evapotranspiration is not measured directly but estimated indirectly using the various available models, the calibration of many of which for local conditions is not easy. The same is, therefore, true for the assessment or quantification of the impact of climate change on evaporation or evapotranspiration. The various approaches which are in use such as use of atmospheric circulation models or coupling the outputs of the atmospheric models to hydrologic models or use of an assumed hypothetical climatic variability as input to the hydrological models (Ramirez and Finnerty, 1996; Singh and Bengtsson, 2005) have their own limitations, as discussed by Khobragade (2009). The representative character of the data downscaled from the atmospheric models for a local scale is also in question (Wigley et al., 1990). Furthermore, all the variables that are required as input to the evapotranspiration model such as the Penman-Monteith are not made available by the various atmospheric models as rightly pointed out by Kay and Davies (2008).One should keep these limitations in mind while interpreting the results obtained from the various impact analyses.

Another important factor that needs to be considered is the type of model used for data projection. According to Graham et al. (2007) the type of circulation model used is more important than the emissions scenarios selected in projecting the impact.The impact assessment is likely to be different with different models used. The same may be true for the choice of hydrological models or ET models. Similar observations are also made by Dallaire et al. (2019). Guo et al. (2017) from their study of 30 locations in Australia carried out using two different PET models namely Penman-Monteith and Priestley-Taylor observed that while both the models consistently indicated temperature to be the most important variable for PET, they showed large differences in the relative importance of the remaining climate variables. For the Penman-Monteith model, wind and relative humidity were the second-most important variables for dry and humid catchments, respectively, whereas for the Priestley-Taylor model solar radiation was the second-most important variable, with the greatest influence in warmer catchments. Studies by Delghandi et al. (2017) and Lin et al. (2018) show that even the selection of scenarios can be important.

A number of simple models of ET such as those which use only temperature data are available and have been used with fair degree of satisfaction in some studies (Oudin et al., 2005; Kannan et al., 2007). However, the use of simple models that use only a single or limited number of input parameters is not desirable, particularly for climate change impact assessment on evaporation or evapotranspiration because in many places other atmospheric factors may be more important than temperature (Kay and Davis, 2008). Also, it is reported that the sensitivity of the same evaporation and evapotranspiration models to different input parameters varies from region to region depending upon the relative significance of other causal factors (Irmark et al., 2006; Gong et al. 2006) which cannot be duly accounted for by the simpler models. It is for this reason that the IPCC (2001) report explicitly advises the use of such models that consider as many controlling meteorological factors as possible. For the same reason Kay and Davis (2008) suggest the preference of Penman-Monteith model over other ET models for assessment of climate change impact on evapotranspiration, as it considers most of the atmospheric variable that affect the process of evapotranspiration. However, it must also be noted that the models like Penman-Monteith are more suitable for evapotranspiration for the cropped area or potential evapotranspiration from shallow water bodies. In deep water bodies like a deep and large lake or reservoir which undergoes thermal stratification and mixing, the better choice would be energy

balance model which would take into account the impact of temperature rise on lake water temperature and thermal regime, and its subsequent impact on lake evaporation which the Penman-Monteith model cannot do if the water temperature data are not available.

It should further be noted that while analyzing the effects of climate change on evapotranspiration, the combined effects of temperature and CO_2 concentration must be taken into account. This is because studies indicate that the effect of increasing evapotranspiration due to temperature rise may be compensated by the effect of increasing CO_2(Snyder et al., 2011) which may result in low stomatal conductance thereby decreasing the transpiration losses (Annu Priya et al., 2014). The development of stomata is known to be repressed by elevated CO_2 in diverse plant species (Engineer et al., 2016). However, more detailed review of investigations on physiological response of plant to elevated levels of CO_2 are required to understand the nature and magnitude of uncertainties involved as pointed out by Annu Priya et al. (2014).

Although significant changes in land use and land cover have occurred all over the world in recent decades, there are few studies on separating their impacts on ET from the impacts of climate change. A review of paired catchment studies on impacts of vegetation changes on water yield, does indicate changes in ET regime (Brown et al., 2005). Teuling et al. (2019) have reported strong shifts in the continental-scale patterns of evapotranspiration during 1950 to 2010 for Europe on account of changes in climate and land use land cover. Hamilton et al. (2018), however, observed that ET losses in the upland portion of the Augusta Creek catchment in southwest Michigan has been remarkably resilient across a 50-year period despite decreasing cropland, increasing perennial vegetation cover and warming temperatures. But they do not rule out the possibility that changes in the meteorological parameters could have offset the effects of land cover changes on ET. Further, as pointed out by Hamilton et al. (2018) it should be remembered that extrapolation of observations from small catchments that are entirely covered by one kind of vegetation to complex mixtures of vegetation may not be as straightforward as it would seem. In one of the few reported studies on separation of the impacts, Yang et al. (2018) have tried to separate the impacts of climate change and human activities on actual evapotranspiration in Aksu River Basin ecosystems, Northwest China based on the spatiotemporal distribution of actual ET during2000-2015, using the Vegetation Interfaces Processes model and Moderate Resolution Imaging Spectroradiometer-Normalized Difference Vegetation Index. They concluded that human activity caused 89%, 98%, and 80% of the changes in actual ET of forest, grass, and arable land, respectively, while climate change caused 11%, 2%, and 20% of the changes in actual ET, in the Aksu River Basin. In another such study Zou et al. (2017) observed that for Heihe agricultural region in China, the contribution of human agricultural activities to increased ET was significantly greater than that of climate change. They observed that both human activity (including agronomy and irrigation factors) and climate change (including precipitation and relative humidity) contribute to increases in ET per unit area at rates of 60.93% and 28.01%, respectively. Human activity, including the same factors, and climate change, including factors for relative humidity and wind speed, contribute to increases in total ET at rates of 53.86% and 35.68%, respectively.

Another important issue is related to the type of data used for the impact analysis. Guo et al. (2017) analyzed the implications of baseline climate conditions on the sensitivity of PET to a large range of plausible changes in meteorological parameters using a global sensitivity analysis for 30 Australian locations representing different climatic zones. Their study reveals that baseline climate can have a substantial impact on overall PET sensitivity. In particular, approximately 2-fold greater

changes in PET were observed in cool-climate energy-limited locations compared to other locations in Australia. It hasalso been reported that the role of controlling factors in evaporation variability varies with the time scale of the data(Xu and Singh, 1998; Lenters et al., 2005).The time scale must therefore be invariably considered while drawing inference from the impact analysis. Also, it must not be forgotten that since evapotranspiration is indirectly estimated, so the quality of data shall have a great role to play in the accuracy of the estimation. Besides the issues of accuracy of downscaling to local scales, there are number of uncertainties involved in the investigations particularly due to possible errors of measurement and instrumentation, errors in regionalization from point measurements, errors due to averaging of data. These errors are likely to affect the calibration and validation of the atmospheric circulation models which in turn would affect the output of the models leading to errors in quantification of the impact. The research to quantify the impact of climate change on evaporation and evapotranspiration should, therefore, necessarily endeavour to minimize these uncertainties and model the process, to achieve a more precise impact assessment.

5.5 Concluding Remarks

Climate change and the associated temperature rise is expected to significantly affect the hydrologic cyclein general and its various components in particular, necessarily including evapotranspiration. The knowledge of the possible impact of climate change on evaporation and evapotranspiration is particularly important because in water stressed regions of the world any increase in future ET losses may play a significant or even a deciding role in the water availability and management of such regions. Evapotranspiration is a complex process which depends on the interaction of many physical, meteorological and atmospheric factors, the relative significance of which varies both temporally and spatially. As such, variation in evaporation rates due to variation in various causal factors needs to be understood properly and adequately for a variety of climatic setting so that the results obtained from the impact analysis are properly interpreted.

Although it is a general perception that increasing temperature necessarily leads toan increase in evapotranspiration, this may not always be true as the number of trend analysis of the pan evaporation data and some other studies actually exhibit decreasing trends in many parts of the world. To solve this mystery of "evaporation paradox" more impact studies based on the ET models such as the Penman-Monteith model which use GCM or RCM derived projected data of as many parameters (which affect the process of evapotranspiration) as used in the Penman-Monteith model should be carried out. It is important because many of the causal factors of evapotranspiration are temperature dependent with varying degree of induced variability caused by temperature variations in different climatic settings. This induced variations in them due to change in temperature regime needs to be accounted for properly for a realistic assessment. Studies based on simpler temperature-based models may provide grossly erroneous results as these models do not account for these induced variations in various causal factors. Similarly, assessment of the impact based on trend analysis of pan data is likely to be less realistic as pan data may be affected by the humidity regime of the surrounding area, by a degree which may not be the same when the compared to a scale of a cropped area or a land surface or a water body. However, even using the projected atmospheric data obtained using atmospheric models and using them in ET models or coupling them with hydrologic models, one should remember the various limitations of such models while interpreting the results. It is also important consider the impacts of increase in CO_2 concentration as they are likely to reduce transpiration losses thereby affecting the overall impacts due to temperature rise. It should not be forgotten that not all observed

impact in ET regime may be due to climate change alone and there may be some impact of the land use changes such as changes in vegetation type and cover, and human activities such as agronomic practices and irrigation. Efforts be made to separate these impacts for the impact analysis to be more realistic.

As far as water bodies such as lakes and reservoirs are concerned, it is advised that impact of climate change on the water temperature of these water bodies should be taken into account for assessing the impact. Assessment based on the assumption of considering vapour pressure of water surface as equivalent of saturation vapour pressure of air may lead to unrealistic assessment of the impact. Also, for large and deep lakes and reservoirs that exhibit stratifications and mixing, these aspects must be considered and impact of climate change on the thermodynamics of these water bodies may be assessed through analysis of the impact on their energy budgets, for a more precise assessment of the impact.

While considering the various issues discussed above it must also be remembered that any conclusions on the climate change impact assessment on evaporation and evapotranspiration must be invariably stated in terms of the time scale of the data used, as the role of controlling factors in evapotranspiration variability has been found to vary with the time scale considered.

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CHAPTER 6

IMPACT OF CLIMATE CHANGE ON HIMALAYAN CRYOSPHERE

Sanjay K. Jain and Vishal Singh

6.0 Introduction

The mountains cover about 35% geographical area of India, out of which 58% is envelopes by mighty Himalayas, which is almost 21% of India's total geographical area. The permanent snow and glacier fields of the Himalaya act as a critical fresh water reservoir that release large quantity of freshwater throughout the year. The water yield from high Himalayan basin is considered as a dependable source of water supply for drinking, irrigation, hydroelectric power generation and for other miscellaneous purposes like recreation etc. All the major south Asian rivers originating from the Himalayas are fed by the snow and glaciers melt water. Geographically from west to east, the Himalaya has been categorized in three parts, i.e., Western Himalayas, the Central Himalayas and the Eastern Himalayas, on the basis of their latitudes and topographic features. The Indian part of Himalaya has three main river systems namely; Ganges, Indus and Brahmaputra, which are the lifeline of millions of people of northern India. The streamflow in these rivers is induced by a combined form of rainfall and snowfall and glacier-melt runoff. The brief description of these river systems is stated later in this note.

Himalaya has a large area under seasonal snow cover during wintertime which plays a significant role to sustain the regional ecology. The snow cover in the Himalaya varies from western to eastern Himalaya and subsequently affect the flow regime of the rivers. The northern part of western Himalaya receives more snowfall and less rainfall as compared to eastern Himalaya, where the rainfall contribution is significant. Along with the seasonal snow Himalayan glaciers are also have huge storage and very important source of fresh water. In the Himalaya, approximately 33,000 km^2 area is covered by the glaciers (Dyurgerov and Meier, 1997, GSI, 2009) of varying shapes and sizes. With a total number of 9,600 glaciers, the Indian Himalaya (Raina and Srivastava, 2008) has one of the largest concentrations of glaciers after the Polar Regions (Bolch et al., 2001). Such a high concentration of ice has aptly designated the Himalayan region as the 'Third Pole' (Dyhrenfurth, 1955).

Melting from high Himalaya snow cover during early summer is a paramount source of water for many rivers originating from the Himalaya. It is roughly estimated that approximately 10 to 20% Himalayan area is covered by glacier ice, and about 30 to 40% area is covered by seasonal snow cover (Singh and Singh 2001; Singh et al. 2011, Thakur et al., 2013). The runoff from partially glaciered basin is characterized by extended lean flow season from October to February. The flow gradually increases during March and April with the snowmelt and advent of summer, and reaches higher levels of discharge during July and August. The rain and snowmelt contribution for three major basins i.e. Indus, Ganga and Brahmaputra are given in Table 6.1. (Khan et al., 2017)

Table 6.1 Relative percent contributions calculated with respect to sum of Rain (Aphrodite V1101R2), and modeled melt from: snow on land (SOL), snow on ice (SOI), and exposed glacier ice (EGI), for elevations above 2000 m

Basin	Gauge name	Lat (DegN)	Long (DegE)	Elevation (m)	Basin area (km^2)	Basin area>2000 m	Rain %	SOL melt %	SOI melt %	EGI melt (%)

						(km^2)				
Indus	Kotri	25.35	68.33	14	820,659	349,972	23	67	6	3
Ganges	Paksey	24.08	89.02	5	943,244	123,483	52	43	4	<1
Brahma putra	Bahadura bad	25.18	89.70	13	514,383	344,977	26	66	7	1

It is found that the total annual glacier melt contribution from three major rivers namely; Ganges, Indus and Brahmaputra comes out to be about 16 km3, 41 km3 and 17 km3, respectively for the period of 1961-1990.However, the total glacier melt runoff was decreased to 15 km3, 36 km3 and 16 km3, respectively for these three basins, recent last decade (2001-2010)and shown in Table 6.2 (IWMI report, 2013).Table 6.2 shows that the Indus and Brahmaputra basins have similar percentage of snow and glaciered area, however the decrease in the snow and glacier area are more prominent in Indus basin. Also, the decrease in glacier area in all the three basins is more prominent than the snow cover area. However, the contribution from snow and glacier melt to the total run-off of Indus basin is much higher than the Brahmaputra basin, this is because of the higher contribution of monsoonal rainfall in Brahmaputra basin. Seasonal snow covers about 28% of the total basin area in case of Indus basin, which is much greater than the 2.6% occupied by the glaciers during 1961-90, the contribution of two sources to Mean Annual Flow is more or less same.

Table 6.2: Recent changes in the glaciers and seasonal snow and their contributions to MAF

Basin	**Part of basin area (%) covered by**		**Contribution to MAF (%)**	
	Glaciers	Seasonal Snow	Glacier runoff	Seasonal Snowmelt
1961-1990				
Indus	2.6	28	18	19
Ganges	1.2	6	4	2
Brahmaputra	2.7	27	2	2
2001 -2010				
Indus	1.8	25	15	16
Ganges	0.9	6	3	1
Brahmaputra	2.2	26	2	2

For the Ganges basin, as per the report high precipitation in summer season solely determines MAF volume for the basin. It is almost similar in the Brahmaputra basin while the lower parts of the basin i.e., Southeastern Tibet and Eastern Himalayas, observes the high monsoon rains. The report does an analysis of assessments done on impact of climate change on water availability in Himalayas and concludes that many assessments rely on poorly verified sources.

Using the Table 6.2 given above, the report states that the contribution from the glaciered region in the Ganges and Brahmaputra basins is very low to the annual water budgets. The report says, "The climate change impact was found to be more prominent on seasonal rather than annual water availability". Also, the increase percentage in nonrenewable glacier runoff components is highest among all three basins during the years 2001-2010, which imply that the glaciers of Ganga basin are melting rapidly

Table 6.3: Contribution of renewable and non-renewable components to glacial runoff.

Basin	Glacier runoff components		Total Glacier runoff (km^3)	Total Glacier runoff contribution to MAF (%)
	Renewable (km^3)	Nonrenewable (km^3)		
1961-1990				
Indus	33	8.14	41.2	18
Ganges	11	4.74	15.7	4
Brahmaputra	12.7	4.29	17	2
2001 -2010				
Indus	24.5	11.62	36.1	15
Ganges	8.1	6.95	15	3
Brahmaputra	10.6	5.05	15.7	2

6.1 Climate Change

Mountainous regions in general and Himalayas in particular have been identified as one of the most vulnerable regions to climate change (Bajracharya et al., 2015). Himalayas have varied climate from one region to another with elevation ranges varying from 1000 m to 8000 m above mean sea level (Azam et al., 2018). The complex terrain and general inter-dependency of mountain environment and socio-economic systems offer significant difficulties for climate change impacts studies. Different climate models such as General Circulation Model (GCM) and Regional Climate Model (RCM) are used to highlight the climate change impacts on Himalayas (Singh and Goyal, 2016; Bajracharya et al., 2015; Chang I. C., 2013; Jain et al., 2010), however, they are characterized by large amount of uncertainty in their projections. GCMs and RCMs may carry uncertainties due to coarser spatial resolutions and uncertainty involved with their complex physical processes and therefore, sometimes they are less applicable.

Global surface air temperature is projected to keep rising, while the snow and ice fields are reducing, in all assessed climatic scenarios during the 21st century (IPCC, 2014). Therefore, glacier component in the annual runoff in glacier-dominated catchments is increasing to a certain maximum and then starts dropping as the glacier surfaces start shrinking. The timing of the peak of the glacier component depends on the characteristics and location of the catchment. During the past 100 years, the Himalayan region (including Tibetan Plateau) has shown a constant trend in the global warming (Yao et al. 2007). Several studies suggest that warming in the Himalayas is much greater than the global average of 0.74°C over the last 100 years (IPCC, 2007). During 20th century, Bhutiyani et. al. (2007) carried out a detailed study on long-term trends in the minimum, maximum and mean temperatures over the north western Himalaya and reported a significant rise in air temperature with a faster rate of winter warming. Future changes in precipitation are more uncertain and of varying nature across the Himalayas depending on the climate model, season and sub-region, with a general indication of increasing annual precipitation (Nepal and Shrestha, 2015). Long term projections indicate increased precipitation during monsoon season by up to 17%, with precipitation rising up to 12% in winter (Christensen et al., 2013).

The temperature warming due to climate change has brought significant changes in monsoon and precipitation over Asia and other parts of the world. Himalayan ranges are the youngest and belong to extreme high elevation ranges. Himalayas consisted with large amount of fresh water reserves in the form of glaciers, temporary and permanent snow covers, permafrost, lakes, wetlands, and hence it is called as "the water tower of India" (Bolch et al., 2012). The high mountainous regions, especially under Indian Territory, also named as Indian Himalayan Regions (IHR), are under the threat of accelerated anthropogenic greenhouse gas emissions as well as climate change (Singh et al., 2016). The effect of climate change over Himalayas has not only affected its physical processes but it also affects the economy and livelihood of the local communities (Azam et al., 2018). Due to poor availability of quality climatological datasets for IHR, a very few studies highlighted the effect of climate change for the region (Singh and Goyal, 2016; Jain et al., 2010). This has led to number of uncertainties and thus sometime climatic observations are less helpful in this region (Goyal, 2016; Jain et al., 2010).

A study done by Minder et al. (2018) discovered the characteristics and causes of elevation dependent warming in the high hilly Rocky Mountains using high resolution Weather Research and Forecasting Model (WRF) and observed a very complex patterns of warming with elevation, together with cases of warming nearly independent of height. In this study it is found that warming was maximum in regions of maximum snow loss and albedo reduction. As per the study conducted by Jain et al. (2009), the elevation-based fluctuations in temperature may affect the snowmelt process, especially over Himalayan regions. The elevation dependent warming may have significant influence for the mass balance of the high altitude and low altitude glacial areas. Himalayas have complex topography and climate variations and thus many factors make it difficult to analyse the rate of warming in high elevation areas (Pepin et al., 2015). Many studies suggested that warming is higher at higher elevations, but most of studies failed to provide a relationship or showed complex situation (Singh and Goyal, 2016; Jain et al., 2009). The reason could be lack of consistency in the data and methods utilized to determine the rate and patterns of warming. Yan and Liu (2014) showed a striking evidence of elevation dependent warming trends over Tibetan Plateau while using observations from 139 stations. Any temperature change to earth's surface affects the energy balance and along with other

climate factors it may increase the net flux of energy; with an elevation changes it may further lead to accelerate warming as a function of elevation (Pepin et al., 2015).

Several studies highlighted that shifting of the permanent snow line across many glaciers in Himalayas are due to climate change (Das and Sharma, 2018; Salerno et al., 2017). The relationship between snow cover duration and elevation is nonlinear; therefore, snowline may change/retreat as temperature increase. This will enhance the absorption of solar radiation over the retreated snow line areas and the warming will be enhanced at that elevation region (Hantel et al., 2000). You et al. (2017) summarized the factors which could be responsible for the recent climate warming in the Himalayas such as acceleration in anthropogenic greenhouse gas emissions, the snow/ice-albedo feedback, and changes of environmental elements (e.g. cloud amount, Asian brown clouds, land use changes and specific humidity etc.). However, the perfect explanation for driving mechanisms accountable for elevation dependent warming need further investigation. The GCM and RCM outputs are found helpful to build a mechanism deriving elevation dependent warming, asmodel outputs can be run to produce both past and future climatic variables (Palazzi et al., 2018).

A study over Tibetan Plateau Himalayas (Palazzi et. al, 2018) identifies the thermal radiation as the most influencing factor for elevation dependent warming. Another study based on Sikkim eastern Himalayas, Singh and Goyal (2016) reported a strong correlation in elevation dependent warming and elevations, this relationship can be either positive or negative. Singh and Goyal (2016) utilized CMIP5 GCMs and computed precipitation lapse rates (gradient changes) based on elevation difference over Sikkim Himalayan catchments and found significant changes in precipitation lapse rates (during 2006-2100) due to the effect of climate change. Precipitation lapse rate has been recognized as an important component for determining snowmelt under varying conditions (Singh and Goyal, 2016; Jain et al., 2008). Though the GCMs and RCMs provide an effective way to examine the mechanisms by which elevation dependent warming occurs in response to increased CO_2 and climate change; an improved and finer resolutions parameterization schemes in climate models are essential to provide accurate observations.

6.2 Snow-Glacier Induced Himalayan Hydrology under Changing Climate

The above-mentioned changes will affect the water resources generated in the Himalayan catchments, modifying flow extremes and seasonal discharge patterns due to changes in rainfall amounts and seasonality, as well as snow and glacier accumulation and melt (Bolch et al., 2012). Thus, a robust spatio-temporal understanding of impacts on water requirements and availability is necessary for informed adaptation planning, which is of crucial importance for the regional economy and the livelihoods and well-being of the inhabitants (Kumar et al., 2015; Soundharajan et al., 2016). Hydrological models are a vital tool to support this analysis (Kour et al., 2016), as they translate the understanding of future climate and land use changes into impacts on river discharge and water availability in time and space.

Runoff at the basin scale is mainly sensitive to precipitation and temperature. Few studies have shown that due to increase in temperature, streamflow in melt season is reduced (Pelto, 1996, 2008; Barnett et al., 2005; Nolin et al., 2010); whereas other studies report that increasing temperature tends to induce glacier retreat and increased runoff through a rise in snow melt amount (Liu et al., 2003; Li et al., 2010; Zhang et al., 2011). The opposite conclusions can be attributed to the different length of analysis periods as the change in runoff volume is not correlated with increasing temperatures. In a

warmer climate, runoff will increase first due to higher temperatures and more snowmelt. However, this phenomenon will reduced gradually as the glacier area will begin to decline as a result of continued glacier mass loss (Ye et al., 2003; Rango et al., 2007; Huss, 2011) causing streamflow to initially increase for a given period before declining in glacier basins.

According to the Fifth Assessment Report of Intergovernmental Panel on Climate Change(IPCC), the earth will be warmer by 1.5°C to 4.5°C by the end of 21st century (IPCC 2013), this would accelerate the melting of glaciers and snow covers and will also affect the natural equilibrium from precipitation-to-rain and precipitation-to-snow in mountains. There are two drivers identified by Foster et al. (2016) that can be affected by temperature increase and will have significant impact on snow hydrology over mountains: (i) precipitation phase that can be shifted and (ii) available energy at the land surface which may increase. Foster et al. (2016) also showed the reduction in streamflow between 11 to 18% over semi-arid mountains due to shift in precipitation pattern from snowfall to rainfall. Similar observations were made by Liu et al. (2018) in Upper Yellow River Basin (USA) where due to enhanced warming and wetter conditions, more precipitation was reported in the form of rainfall and thus more flow added in the total runoff. Nevertheless, several studies found that it is critical to understand the impact of these two drivers (shift in precipitation phase and changes in available energy at the land surface) on hydrologic partitioning vis-à-vis preparedness against climate change in snow-dominated regions (Liu et al. 2018; Foster et al. 2016). Several efforts have been made in this direction reveal the relative sensitivity of mountains to changes in precipitation phase and surface energy fluxes (Barnhart, 2018; Foster et al. 2016).

Snow cover and glaciers are important components of Himalayan hydrology and are expected to be vulnerable to accelerated global warming and climate change (IPCC 2013). These are the key hydrological components that benefit various sectors such as agriculture, hydropower production, sanitation and drinking water supply, especially in IHR. Many studies have highlighted that temperature and precipitation significantly changed over Himalayan regions due to climate change (Singh and Goyal, 2016; Bolch et al., 2012). The permanent snowpack (or snowfall) and glaciers are reported to be reducing their masses and more snowmelt is entering the streams (Shukla et al., 2017; Jain et al., 2009). Many studies utilized remote sensing applications for the characterization of glaciers (Singh and Goyal, 2018) and calculation of snow cover areas and their changes (Shukla et al., 2017; Jain et al., 2010; Jain et al., 2009; Kulkarni et al., 2007), however, due to the limitation of the temporal data availability from remote sensing it is found less applicable for analysing long term changes. An increased global annual average temperature is reported as the primary cause of changes in precipitation pattern and magnitude in the Himalayas (IPCC, 2013; Bolch et al., 2012). The retreat in glacier and variations in snowmelt due to climate change may influence water storage and, thus, affecting the sustainability of human activities. The equilibrium between precipitation-to-rain/snow is changing. Spatial distribution and temporal variability of rainfall and snowfall across the Himalayas in spatio-temporal domain is attributed to climate change (Jain et al., 2008). While snowpack and glaciers influence stream flows in high elevation, rainfall is considered a predominant factor in low elevations (Jain et al., 2009). As an example, Satluj River, one of tributaries of Indus. Higher melting will result in an increase in runoff downstream before the monsoon season (Jain et al., 2010) leading to increased vulnerability to floods in downstream channel. The variability in Temperature Lapse Rate (TLR) and Precipitation Lapse Rate (PLR) due to observed climate change can be the major cause of reduced snowpack at high elevations of the Himalayas (Singh and Goyal, 2016).

Snowmelt which is highly sensitive to temperature change and precipitation pattern is particularly significant for flow in the Himalayan basins. Immerzeel et al. (2013) forecasted reduction in glacier area and volume by 33% and 50% by 2100 with peak glacier melt in 2044 or 2065 in the Baltoro catchment of upper Indus basin. It will lead to 7-12% increase in annual runoff by 2050 due to accelerated melt with increase in precipitation (Lutz et al., 2014). At present Snow and glacier melt contributes 10% and 27% to upstream water flow overall in the Ganges and Brahmaputra basin, respectively. It may decrease by ~17% in Gnaga and ~20% in Brahmaputra basin by 2046-2065 as per the projections made in A1B emission scenario (Immerzeel et al., 2010). This reduction in upstream melt runoff may partially compensated by the increased upstream rainfall by more than 8% and 25% in upstream of Ganges and Brahmaputra. Immerzeel et al., (2013) forecasted 54% reduction in glacier area by the end of the century in Lang tang catchment of Ganga basin under projected climate change scenario.

The capability or strength of any hydrological model to simulate and project snowmelt and glacier melt runoff depends on how well the model accounts the complexities that are associated with multiple snow-hydrology parameters and their processes (Fontaine et al., 2002). Many studies incorporated the temperature index model based on the degree-day-factor (e.g. SWAT Model, HMS Model, NAM model, HBV model etc.) for the assessment of snowmelt runoff (Goyal and Goswami, 2018; Kumar et al., 2017; Azamat et al., 2016). Temperature index model generates snow water equivalent (SWE) or the amount of snowmelt (liquid water) using a constant snowmelt factor which is a function of mean surface air temperature (Fontaine et al., 2002), however, in unstable climate conditions like Himalayas where elevation variations are frequent this approach is found less acceptable (Kumar et al., 2017; Fontaine et al., 2002). The snowmelt factor or degree-day factor directs the snow-glacier melt process, and it is defined as the function of temperature. The temperature is dependent on elevation, and thus, it alters the degree-day parameter significantly (Fontaine et al., 2002), however, an elevation dependent warming in Himalayas due to climate change can enhance uncertainties in their simulations (Kumar et al., 2017; Azamat et al., 2016). Therefore, the role of elevation bands must be addressed when computing snowmelt and snowpack, especially over Himalayan catchments.

Stigter et al. (2017) utilized remotely sensed snow cover with the seNorge snow model to estimate snow water equivalent and snowmelt runoff over Nepalese Himalayan catchment and a decrease in snow water equivalent (SWE) due to higher air temperature at high elevations is observed. Shukla et al. (2016) utilized remotely sensed MODIS snow cover dataset to find out the snow cover area-based changes in western Himalaya and revealed 44% to 56% variations in snow cover area over Satluj river Himalayan catchment during 2001 to 2014. Several studies highlighted that since last two decades Himalaya has warmed greatly (IPCC 2013). Engelhardt et al. (2017) utilized mass balance model for the computation of meltwater runoff from a glaciered catchment of western Himalaya and revealed that mass balance approaches are more compatible for accounting melt contributions especially from glaciers. Jain et al. (2010) used elevation band approach for accounting snowmelt runoff from satellite snow covers in Satluj river Himalayan catchment and incorporated GCMs for analysing snowmelt runoff changes in future time domain. The results showed that snowmelt runoff occurred earlier due to increased snow melting, a shift is observed, however, reduced in the monsoon months. Ahluwalia et al. (2017) utilized hydrological model SNOWMOD coupled with isotope analysis to characterize and compute the snowmelt runoff in western Himalayan catchment. The

coupled approach is found more suitable to analyse snowmelt and glacier melt runoff separately. A very few studies applied energy balance approach for the computation of snowmelt runoff over Himalaya due to less data available and harsh climatology of Himalaya. Energy balance approach could be more accurate but it requires large amount of dataset. However, a study done by Datt et al. (2008) used energy balance approach over North-West Himalaya for snowmelt runoff computations show significant improvements in the results.

Apurv et al. (2015) studied over eastern Himalayas and reported a significant increase in the amount of discharge from the Brahmaputra River utilizing CMIP5 GCMs. Most of the modeling-based approaches incorporated the melt contributions in streamflow only from the snowfalls (or snow cover areas). Studies using GCMs revealed the impact of climate change on the variability of precipitation over the Himalayas (Singh and Goyal, 2016; Apurv et al., 2015; Jain et al., 2010). Several studies utilized GCMs and RCMs for the assessment and projections of snowmelt and snowpack in Himalayas and revealed that in future snowpack will be reduced, while snowmelt volume will be enhanced due to warming (Palazzi et al., 2017; Jain et al., 2010). However, the accuracy of these predictions is still not very clear because of the uncertainty involved in coarser resolution GCMs and RCMs and also due to uncertainties associated with hydrological models (Singh and Goyal, 2016; Apurv et al., 2015; Jain et al., 2010).

Observed discharge variations in the Himalayan head Water Rivers and tributaries, with substantial snow and glacier ice contribution show a mixed response with majority of them showing a declining or a steady trend. In the Ganga basin, flow of the Kali Gandaki at Setibeni declined by 12% over 20 years, while the runoff from the bigger Narayani basin basin remained stable. Discharge of Sutlej at Khab decreased by 32% over 20 years, influenced by declining monsoon precipitation over the north-west watershed of the Ganges basin (Collins et al., 2013). Reducing discharge in the Sutlej in the downstream reaches, at the Bhakra dam, confirms weakening monsoon conditions reducing summer precipitation in the late twentieth century (Thayyen and Gergan, 2010). Similar to the Sutlej river, Beas river also shows declining trend in the discharge (Bhutiyani et al., 2008). Moving further west, Chenab, Jhelum and Indus, rivers show lower discharge during 2000-2016 period as compared to 1985-1998 period (Wescoat et al., 2017). The observed discharge variations of western Himalayan rivers have an overriding trend of reducing discharge which is not entirely in tune with the results obtained from modelling studies. This points towards large uncertainty of modelling studies which call for greater improvement in climate modelling of Himalayan region.

6.3 Status and Mass Changes of Indian Himalayan Glaciers

A considerable impact on the glaciers of Himalayan Region has been seen due to change in climate in recent decades. It is believed that the changes in glaciers are a consequence of climatic changes. The response of climate change on glacier is different which depends on size, area-altitude distribution, orientation, and moraine cover. Change is glacier extent is important to study as it will have profound effect on water availability. For estimation of retreat it is important to identification and mapping of glacier boundary and terminus. The identification of snow, ice and rock on satellite images is possible in case there is no debris because of the difference in spectral reflectance signature of different surfaces. A map of glacier in three major basins of Himalayan region i.e. Indus, Ganges and Brahmputra are shown in Figure 6.1 (Sharma et al., 2013)

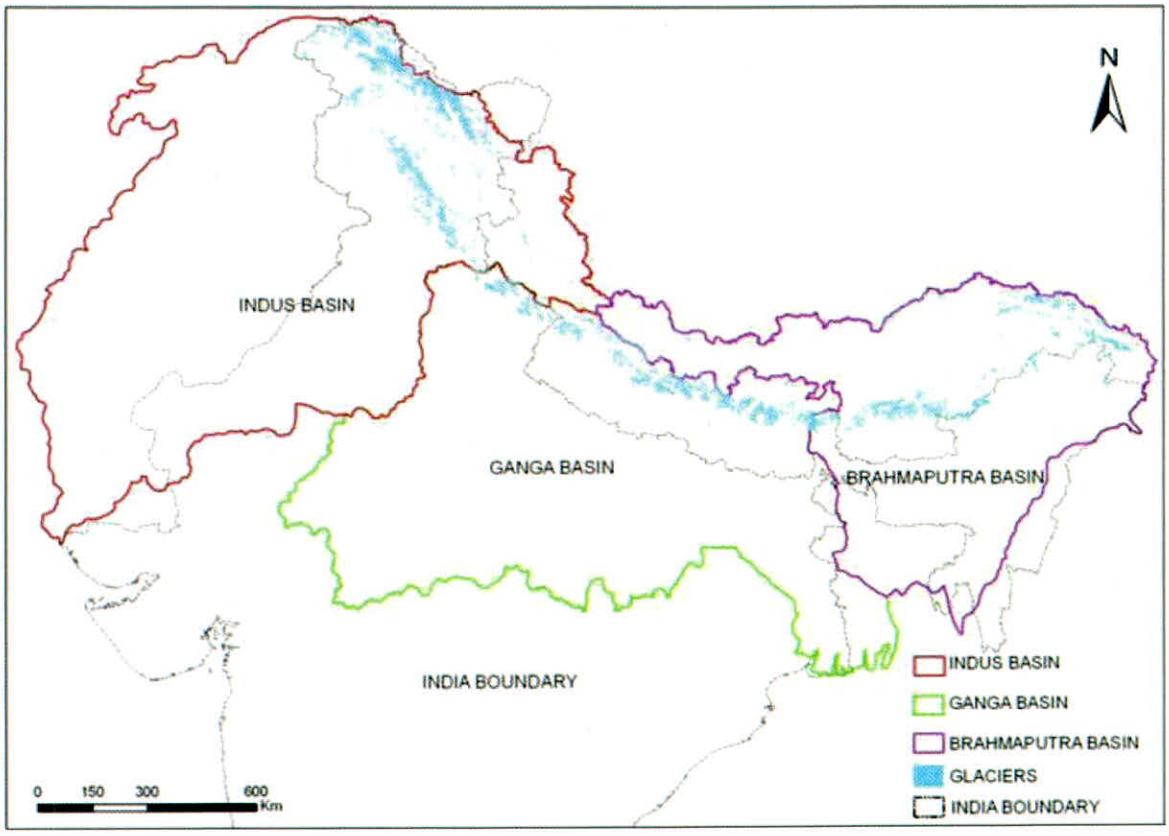


Figure.6.1 *Indus, Ganges and Brahmputra with glacier covered area*

Studies highlighted that glaciers in Himalayan regions are retreating since 1850s (Azam et al., 2018), however, a very few studies highlighted opposite trends such as Karakoram glaciers gained mass and found stable during 1998-2008 (Gardelle et al. 2012). Several studies based on field measurements highlighted that ice flow of land-terminating glaciers varies with mass changes at decadal scales (Dehecq et al., 2018; Vincent et al., 2009; Span and Kuhn, 2003). In other study, ice velocity changes analysed in recent decades using single satellite image pairs from few numbers of glaciered regions in the world (Heid and Kaab, 2012). In these studies, with negative mass balance ice flow found slower in regions but also represented no clear relation between mass balance and velocity change. A study by Wagon et al. (2007) over Chhota Shigri Glacier, a part of western Himalaya, found evidences of retreat which could be influencing by the effect of incoming solar radiation. It was further observed that melting rate varies as per elevation variations and thus, they suggested an energy-balance approach to analyse the effects of heat fluxes. More recent studies clearly highlighted that most of glaciers in Himalayas including large size glaciers are under threat to climate change (Azam et al., 2018; Kaushik et al., 2018; Mukhopadhyay, 2012). Kaushik et al. (2018) studied western Himalayan ranges and analyse the climate change driven impacts on glaciers. Bhaga river basin demonstrated that the total area of glaciers was lost by reduction rate of 12 m/year from 1979 to 2017. Glaciers situated at low elevations and smaller in sizes are reducing faster than large size glaciers (Kaushik et al., 2018; Mukhopadhyay, 2012).

Most of studies conducted over smaller size of glaciers showed enormous changes, while only few studies showed significant retreating in large size of glaciers (Thakuri et al., 2013; Nainwal et al., 2008). Several site-specific studies provided significant information about various glacial parameters

such as glacier orientation, hypsometry, topography, morphology and other glacier dynamics (Mukhopadhyay, 2012; Kulkarni and others, 2007). Debris cover is an important factor for analysing glacier retreating and studies highlighted that glaciers having thick debris covers which are responsible to reduce melting rates found less prone to retreat (Singh and Goyal, 2018; Huss et al., 2011). However, the thickness of debris covers is mainly controlled by elevation (Singh and Goyal, 2018) and therefore, elevation dependent warming could be crucial to understand the glacier retreating (Murtaza and Romshoo, 2017). The ice-covered area of Satopanth Glacier part of Alaknanda basin reduced by 313.9 m^2 mainly at the snout area from 1962 to 2006.In other glacier such as Bhagirathi Kharak Glacier around 129.4 m^2 area has been during a similar time period (Nainwal et al., 2008). While these two glaciers having same climatic and topographical conditions and also situated in the same river basin, their recession rates were recorded to be different. This could be happened because of the sensitivity of the thickness of debris covers with respect to elevation changes. Bhambri et al. (2011) concluded that the south- and southwest facing glaciers shrank at higher rates and average shrinkage rate mainly is influenced by glacier size. Huss (2011) noticed that when glaciers shrunk, their relative contribution decreased and the annual runoff peak shifted toward spring. However, shifting in the runoff is expected to be higher in the western Himalaya than the eastern Himalayas due to shifts in snowmelt, where monsoon and melt seasons overlapped (Azam et al., 2018).

Glacier change studies have been carried out in two sub-basins of Satluj basin and Beas basin by National Institute of Hydrology (NIH), Roorkee. A glacier inventory has been prepared using Survey of India (SOI) topographical maps (1966) and Landsat datasets as ETM+ (2000, 2006) and TM (2011) to study glacier changes in Tirungkhad basin (Fig. 6.1a). This basin, a part of Satluj basin, is located in western Himalaya. Glacier areal changes showed a deglaciation of 26.1% (29.1 km^2) from 1966 to 2011. Smaller glaciers (area <1 km^2) lost more ice (34%) compared to large glaciers (area >10 km^2) for which the ice loss is reported around 20%. Glacier volume loss was found to be 32% (2.9 km^3) from 1966 to 2011. The north facing and low altitude glaciers showed high percentage of loss. A trend analysis of temperature, rainfall and snow water equivalent (SWE) was also carried out. During a period of 24 years (1984 to 2008), the mean annual maximum temperature has increased by 1.1°C and minimum temperature has increased by 1°C, whereas snowpack and rainfall has decreased. SWE data from Purbani meteorological station within the basin also showed a decreasing trend. This observation indicates that the warming of the climate is probably one of the reasons for the glacier retreat in the basin.

Using the Landsat data (MSS, ETM+ and TM), the changes in glacier area, length and debris cover have been delineated in the Baspa basin (Fig. 6.2)., which is a highly glacierised sub-basin of Satluj River in the western Himalaya. A total of 109 glaciers have been inventoried and it is found that 36 glaciers were found to be heavily debris covered. The clean, small sized, low altitude glaciers with south to southwest aspect and relatively steep slope have lost maximum area which indicates a major control of these factors on the glacier changes.

The mass balance of glaciers has been determined using the geodetic method (Pratap et al., 2016; Zemp et al., 2013), glaciological method (Pratap et al., 2016; Dobhal et al., 2013; Paterson 1994), accumulation-area ratio (AAR)/equilibrium line altitude (ELA) method (Pratap et al., 2016; Brahmbhatt et al., 2012; Kulkarni 2004) and hydrological method (Pratap et al., 2016; Bhutiyani et al., 1999). Glaciological mass balance is an in-situ measurement of ablation and accumulation for the entire glacier in a balance year which generally utilize to compute glacier mass and volume changes

(Pratap et al., 2016; Paterson 1994). Geodetic method mostly utilizes to compute glacier thickness by generating Digital Elevation Model (DEM) of the glacier in two different times (Zemp et al., 2013). In the early seventeenth century, glacier boundaries and their characteristics (parameters) were denoted as rough sketches. Raina and Srivastava (2008) provided a glacier inventory and historical documentation of the glacier related studies in India, which gives detail for only few selected glaciers. The Survey of India (SOI) is the nodal agency in India involved in surveying the Himalayan regions and mapping glaciers since year 1767 when it was established. Few glacier inventories have been prepared for world glaciers and specific to Himalayan glaciers (Frey et al., 2012; Cogley, 2009).

A study by Bhushan et al. (2018) over Zanskar River basin analysed the prevent mass loss in glaciers, and emphasizes that mass budget and surface velocity of glaciers is important for characterizing heterogeneity in glacier dynamics. Thayyen and Gergan (2010) also reported that most of the glaciers are retreating due to warming, whereas glacier growth is also observed over few glaciers due to strong monsoon. In other study over central Himalaya, Xiang et al. (2018) utilized remote sensing techniques for the assessing glacier mass-balance (1975-2010) and reported that debris covered glaciers having area > $5km^2$ retreated faster than debris free glaciers ofsame sizes. A study conducted by Mir et al. (2018) over Dalung Glacier and Padam Glacier, western Himalaya utilizing remote sensing satellite datasets of different temporal resolutions found significant reduction in the mass of both glaciers with different recession rates. Garg et al. (2018) found a degeneration of the frontal part of the Kangriz glacier situated in Jammu and Kashmir, western Himalaya, and resulted accelerated surface melting, thinning of debris cover and snout areas. The ablation data assimilated for 2016–2017 displays the lowering of the frontal part of the glacier to be ~148 ± 34 cm (mean). Thinning rates of the debris flows of Gangotri glacier have seen during the period 1968-2014. In many studies like for Gangotri glacier the reduction of length of glaciers is identified as a delayed response of climate change, while glacier mass balance is identified as a more direct and immediate response (Bhattacharya et al., 2016).

6.4 Status of Permafrost in the Himalaya

Permafrost is another cryospheric component critical for the Himalayan environment. Permafrost is unconsolidated sediment or bedrock that remains frozen for at least two consecutive years. Permafrost mainly occurs in the arctic (Westermann et al.,2015, Gartner-Roer et al.,2010) and high mountain areas (Haeberli et al., 1993; Cremonse et al.,2011, Gruber et al.,2012) and impact around 25% of the landmass of the northern hemisphere. Number of studies have shown permafrost thawing in the Northern Hemisphere during the past couple of decades (Nelson, 2003; Hinzman et al., 2005, Zhang et al., 2005; Romanovsky et al., 2010). However, Permafrost studies are sparse in the Hindu Kush Himalaya (HKH) region in general and IHR in particular (Gruber et al., 2017).

As water resources in the IHR region showing signs of stress, with the increasing population and unpredictable climate; there is a need to look into the finer details of the water resources dynamics in the Himalayas. Conclusive evidence of permafrost in the IHR was available from Tso Kar lake area way back in 1975-76 from a study conducted by the Geological Survey of India (GSI) (Rastogi and Narayan, 1999). Boreholes drilled up to 29m had many ice layers interspersed with sandy gravel layers with a temperature of -2°C indicated permafrost area about 20 km^2. Initial modelling assessment on a regional scale suggests that the permafrost area in the HKH region could extent up to 1 million km^2, which roughly translate into 14 times the area of glacier cover of the region (Gruber et al., 2017).

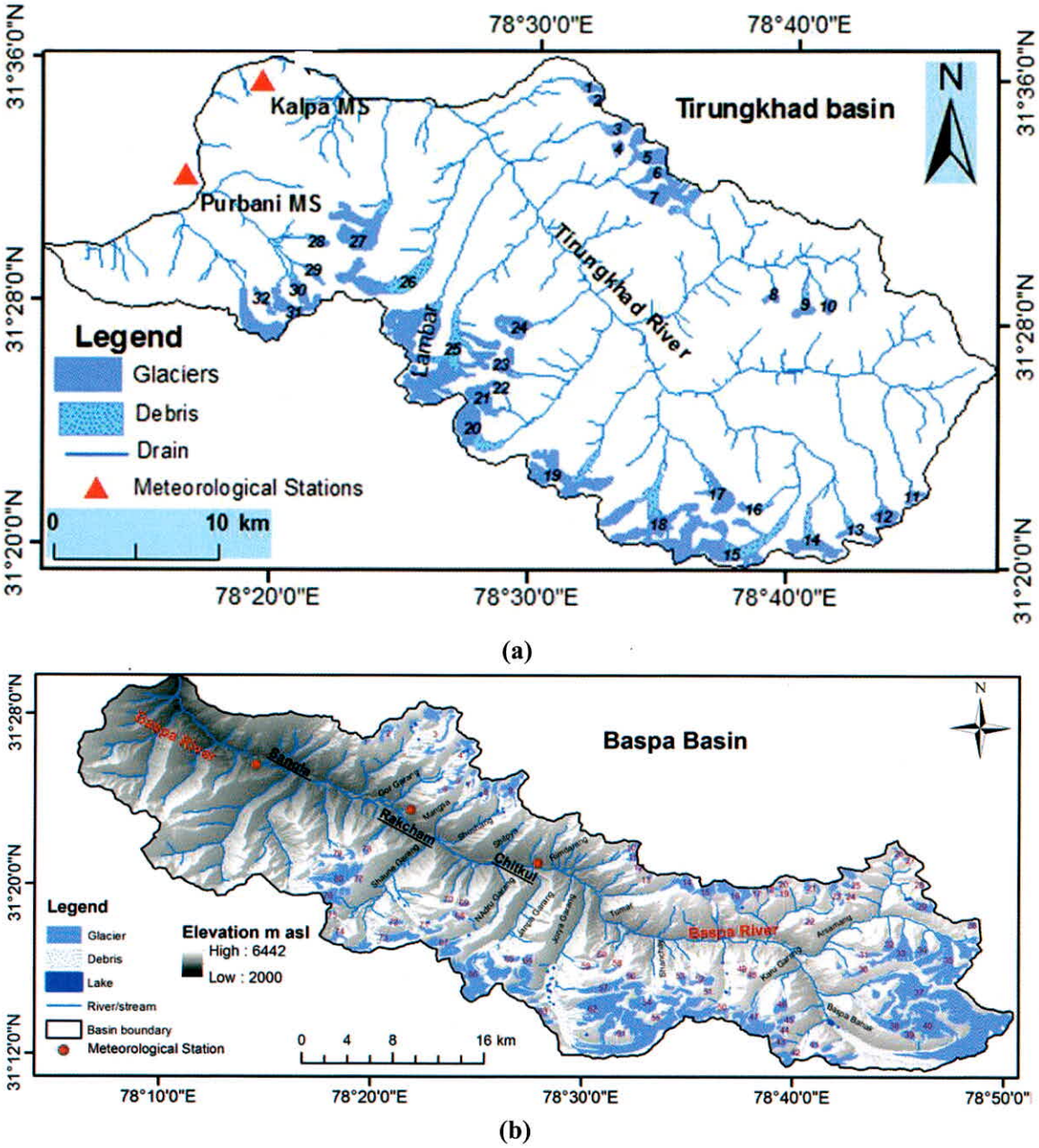


Figure 6.2 *Location and glacier maps of the (a) Tirungkhad and (b) Baspa basins, which are sub-basins of the Satluj river basin. On the maps, the glaciers are labeled by numerical numbers only where as in the text; the prefix G is also indicated before the numerical number (such as G-1, G-2).*

As water resources in the IHR region showing signs of stress, with the increasing population and unpredictable climate; there is a need to look into the finer details of the water resources dynamics in the Himalayas. Conclusive evidence of permafrost in the IHR was available from Tso Kar lake area way back in 1975-76 from a study conducted by the Geological Survey of India (GSI) (Rastogi and Narayan, 1999). Boreholes drilled up to 29m had many ice layers interspersed with sandy gravel layers with a temperature of -2°C indicated permafrost area about 20 km^2. Initial modelling assessment on a

regional scale suggests that the permafrost area in the HKH region could extent up to 1 million km^2, which roughly translate into 14 times the area of glacier cover of the region (Gruber et al., 2017). Studies on the rock glaciers were also carried out in recent past suggested that the lower limit of permafrost in the region may lies within 3500-5500 m a.s.l. (Schmid et al., 2015). Allen et al., (2016) suggested a permafrost spread of 420 km^2 in Kullu district of Himachal Pradesh covering 9% of the district area.The cold-arid region of Ladakh has reported sporadic occurrence of permafrost and associated landforms (Gruber et al., 2017) with sorted patterned ground and other periglacial landforms such as ice-cored moraines. Catchment scale studies suggest that ground ice melt component may be a critical water source during dry years in the cold-arid regions of Ladakh (Thayyen et al., 2015). Ladakh has large areas of high altitude wetlands and lakes and the studies indicated phases of permafrost growth during low lake levels, especially after 5 kyr BP. Continuous development of permafrost mounds and thermokarst features are also inferred during the last 60 years as well (Wünnemann et al.2008). These studies have firmly established significant permafrost coverage in the high mountain areas of IHR. As glaciers and snow cover are shrinking in the most part of the IHR (Bolch et al., 2012, Immerzeel et al., 2013) in response to changing climate, the permafrost areas are also expected to respond in a comparable manner as evident from other similar cryospheric areas globally. Possible permafrost thaw related impacts also can be inferred from other areas which include changed frequency and unexpected location of landslides, changes to vegetation and runoff patterns, change in the water quality and sediment load in the rivers and could impact more on the population depended on these high altitude ecosystems (Gruber et al., 2017). World Meteorological Organization (WMO) describes the permafrost as an essential climate variable and growing appreciation of the permafrost thaw related issues are visible in the region during the recent past. Some firm steps are taken by the national and International agencies (Stumm et al., 2016; Thayyen et al., 2016) to promote permafrost research in the IHR.

6.5 Climate Change and Extreme Events

A study conducted over eastern Himalaya and western Himalaya based on CMIP3 and CMIP5 models showed a significant increase in Temperature (Panday et al., 2015). Singh and Goyal (2016) developed standard precipitation extreme indices over Sikkim Himalayas utilizing CMIP5 GCMs and revealed that extreme high intensity events and wet spells will increase after 2040s. In a similar area (Sikkim Himalayan catchments), Goswami et al. (2017) generated temperature extreme indices applying copula-based approach under CMIP5 GCMs and revealed that warmest night and day temperature are increased by 1.41°C to 1.83°C, respectively. Every of the main features of the Himalayan regions induced by snow, glaciers and ice-sheets may carry conditions that can pose threats to society under extreme climate conditions (Xu et al., 2007). For example; a large fluctuation in the melting of snow and ice may result in extreme or inadequate water supplies, heavy snowfalls can obstruct roads and other structures. Heavy snowfall on steep slopes, which are so frequent in Himalayan regions, and related conditions give rise to avalanches etc.

Nandargi and Dhar (2011) analysed precipitation extremes over Himalayan regions during 1871 to 2007 and concluded that the frequency of rainfall events has been significantly enhanced during 1951-2000 followed by a sudden decrease from 2001 to 2007. Another study based on precipitation extreme indices performed over HKH regions showed that light and moderate precipitation events have increased during 1961-2012 over Indian and Tibetan Plateau (Zhan et al., 2017). Several other studies have also shown an increase in precipitation over Tibetan Plateau (You et

al., 2017; Singh and Goyal, 2016). Several precipitation gauges over the Karakoram regions have also measured a clear increase in the number of wet days and extreme precipitation events during the last few decades (Choi et al., 2009; Klein Tank et al., 2006). Studies highlighted that because of the positive correlation between changes in potential velocity of air near surface and precipitation along with the flow of western disturbances and topography of the western Himalaya complicated extreme weather events (e.g. Leh floods in 2010, Uttarakhand floods in 2013; Kashmir floods in 2014) (Zaz et al., 2019). As per IPCC (2013), in the Himalayas, every year there will be at least one extreme event. It may range from north-eastern India to Pakistan in the west. A glaicla lake inventory of three major basins is given in Table 6.4. (Maharjan et al., 2018)

A continuous glacier recession due to climate change and due to which formation of glacial lakes have been found behind the newly exposed unstable moraines in most of the glaciated regions of the world (Kaser et al., 2006; Zemp et al., 2009; Bolch et al., 2012; Mir et al., 2015).These lakes are made of poorly consolidated unstable glacial material and formed behind consolidated end-moraine dams. During recent past, a number of glacial lakes have been identified and found expanding in response to climate change and glacier thinning (Reynolds, 2000; Ageta et al., 2000; Benn et al., 2000). The moraines provide a physical barrier to glacial melt water drainage resulting in the creation of a moraine-dammed glacial lakes (Costa and Schuster, 1988) with a potential for a glacial lake outburst flood (GLOF) hazard (Benn et al., 2012; Westoby et al., 2014; Worni et al., 2014).

Table 6.4: Number, area (in km^2), and types of glacial lakes in three major river basins of Himalayan region

Major basin			Indus		Ganges		Brahmaputra	
Type			Number	Area (km^2)	Number	Area (km^2)	Number	Area (km^2)
Moraine-dammed lake (M)	End-Moraine	M(e)	587	25.02	587	103.28	1,241	170.93
	Lateral Moraine	M(l)	121	4.28	97	11.15	43	4.07
	Other Moraine-dammed lake	M(o)	1,215	39.07	1,482	31.00	1,973	51.48
Ice-dammed lake (I)	Supra-glacial lake	I(s)	461	4.75	539	5.58	196	2.07
	Glacier ice-dammed lake	I(v)	13	0.56	7	0.10	5	0.10
Bedrock-dammed lake (B)	Cirque	B(c)	378	40.83	299	14.70	1,976	173.48
	Other bedrock-dammed lake	B(o)	2,611	107.86	1,045	34.35	7,809	351.52
Others		0	303	38.17	26	8.43	399	129.90
Total			5,689	260.54	4,082	208.59	13,642	883.55

The glacial lakes closer to the glaciers are mostly fed by glacial melt and continuously changing size. The lakes that lie for ahead of the glaciers may or may not be fed by glacial melt but are instead formed in the paleo-glaciation landforms and are mostly constant in size. The lakes are categorized into 10 classes in terms of distance from the glaciers. Lakes on the glaciers comprise 4.8% of the total number of lakes and are mostly ice-dammed. The size and number of these lakes change frequently depending on seasons and time, and supra-glacial lakes especially appear to merge with maraine-dammed lakes or may develop contemporaneously as composite forms. Lakes in contact with the glaciers are mostly maraine-dammed and comprise about 2.5% of all lakes. The size of these lakes changes rapidly due to melting of glaciers, and so need to be monitored. Maharjan et al., 2018)

A first step for the assessment of GLOF hazards is the identification of Potentially Dangerous Glacial Lakes (PDGLs). However, this is difficult, cumbersome and time-consuming by conventional methods due to inaccessibility and harsh weather condition prevailing at high-altitude region such as Himalayas. Therefore, RS and GIS techniques are highly suitable as it allow rapid analysis of large areas and large number number of sites in economical way (Huggel et al., 2002; Kääb et al., 2005). Using such techniques, the vulnerable lakes can be easily identified and detailed studies (e.g., GLOF modeling) can be carried out if found to pose any potential risk to down lake communities or infrastructure (Bajracharya et al., 2007; Mergili and Schneider, 2011; Worni et al., 2012). It is to keep in mind that the modeling of GLOF is similar to the dam break study of the moraine dams (Jain et al., 2012, 2015).

The first GLOF event in the Indian Himalaya; has been reported in 1926 in which a flood was released from the Shyok glacier, Jammu and Kashmir destroying the Abudan village and the surrounding land at a distance of 400 km from the outburst source (Mason, 1929). Sangewar et al., (1999) has also reported sudden emptying of some of the moraine dammed lakes of Shaune Garang glacier in the Indian Himalayas based on high discharge measurements downstream during 1981 to 1988. During June, 2005 an outburst of landslide dammed lake at Parechu River (China) caused a transboundary flood in Himachal Pradesh, India. Chorabari Lake in Kedarnath was very disastrous event in the year 2013. As reported, the Himalayas have 9000 glacial lakes created from 15,000 glaciers (Bajracharya et al., 2006; ICIMOD, 2011) with total glacierised area around 33,200 km^2. Worni et al., (2012) has provided an inventory of 103 glacial lakes for Indian Himalayan region. In July 2016, a glacial lake outburst flood (GLOF) occurred in the Bhotekoshi/Sunkoshi River, Nepalese Himalaya that resulted insubstantial changes to the River channel bed, banks, and adjacent hill slopes, further causing at least 26 landslides (Cook et al., 2017). Several studies highlighted that Himalayan glacial lakes are under the threat of climate change and they are increasing their sizes and volume mainly due to faster melting of snow-covers and glaciers (Zaz et al., 2019; Mir et al., 2018; Cook et al., 2017, IPCC 2013). The comparatively recurrent occurrence of GLOFs relative to monsoon floods, or may be the effect of global warming causing monsoon disturbances, suggest that GLOFs could dominate the dynamics of fluvial systems.

A number of GLOF studies have been carried out by NIH for river basins of Teesta, Dhauliganga, Twang, and Bhutan. As per these studies, as such no lake is potentially dangerous in Dhaluiganga whereas some lakes are vulnerable in Teesta, Twang and basins in Bhutan. GLOF study has been carried out for two lakes located in Zanskar Himalays (Mir et al., 2018) and shown in Figure 6.3

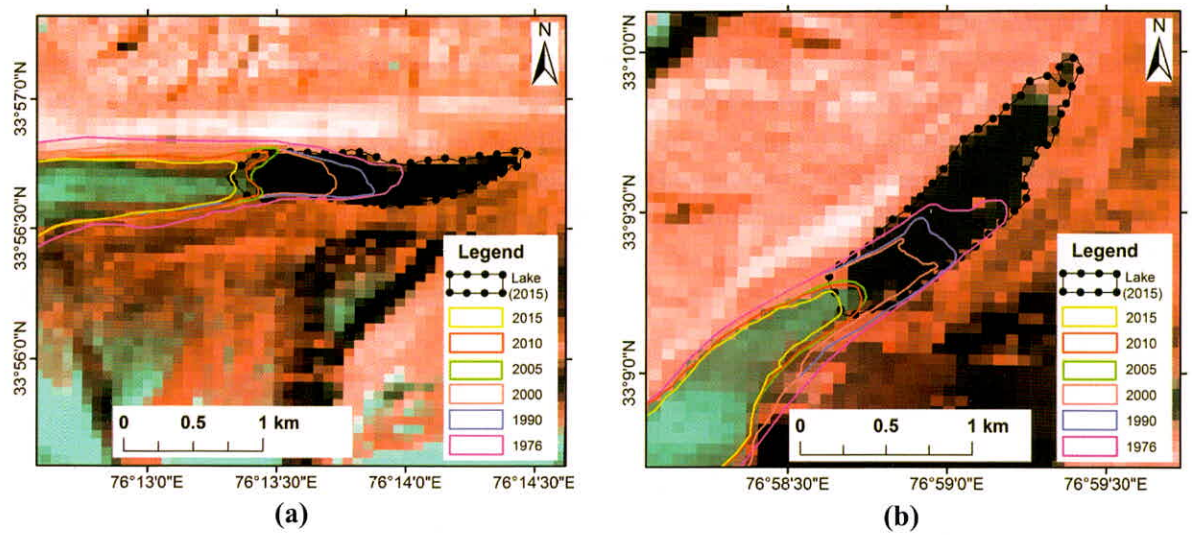


Figure 6.3: *Recession of (a) Dalung glacier (b) Padam glacier during different time periods between 1975-2015 and corresponding expansion of Lakes in Zanskar Himalaya. The back ground is represented by Landsat-TM image of October, 2010.*

6.6 Concluding Remarks and Way Forward

The livelihoods and wellbeing of billions of people rely on the water resources generated in the Himalayas. The above review and discussion clearly highlight that Indian Himalayan Region currently is under the threat of global climate change. Many studies showed that warming over the Himalayas has been enhanced since 1955, which is further accelerated since 1980s. Last two decades are found to be very critical for the Himalayan snow cover and glaciers changes and also for other mountains around the world which are induced by snow cover and glaciers. Studies have shown that though most of the Himalayan glaciers are retreating since 1850s, this retreat has accelerated since last four-five decades. The only reason is enhanced global average annual temperature due to anthropogenic acceleration of greenhouse gases emissions. Studies revealed that large size of glaciers are retreating slower than smaller size glaciers. The temperature and precipitation variations have been increased based on their altitudinal variations. Temperature lapse rate and precipitation lapse rate are changing due to accelerated warming, which may be crucial for accounting snowmelt. Many glaciers have been reduced their masses and permanent snow covers. However, few exceptions are also seen such as for Karakoram glacier which has gained mass and found to be stable. Various methods are successfully employed for the computation of glacier mass balance and snow-glacier induced hydrological modeling.

Based on findings as discussed above, it is assumed that contributions of melt water from glacierized and non-glacierized portions may be affected largely due to the increasing variability in temperature and precipitation. Previous studies did not highlight impacts of climate change and their severity on the snowmelt induced streamflow resulted from glacierized and non-glacierized portions separately. In a variable climatic condition, an accurate projection of snowmelt and snowpack through model-based approaches, especially in Himalayas under lot of data scarcity conditions, is a major challenge. Therefore, the severity of climate change over melting volume of water should be accounted separately for glacierized and non-glacierized portions, especially in Himalayas.

Understanding the evolution of the Himalayan snowpack and glaciers is necessary for projecting the impacts of future climate change on the hydrological behaviour of the major rivers originated in the Himalayas. Hydrological models and their application are a key supporting component for this. The review of relevant hydrological modelling studies applied in the Himalayas show that distributed, process-based hydrological models, coupled with temperature-index snowmelt models, are predominant in simulating the direct impacts of climate change. However, limitations in input data (particularly related to their availability and spatial resolution) lead to significant uncertainty in the ability of all models to confidently project climate change impacts on water resources and hydrological behaviour over medium and long timescales in the region. Therefore, there is a need to have extensive snow/glacier melt runoff modelling under future climate change scenarios in Himalayan region.

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CHAPTER 7

CLIMATE CHANGE AND RIVERFLOW

Swapnali Barman and M. K. Goel

7.0 Introduction

Runoff, a major component of the hydrologic cycle, is composed of surface runoff and interflow/subsurface runoff. Surface runoff is that portion of rainfall, snowmelt, and/or irrigation water that runs over the soil surface towards the stream rather than infiltrating into the soil. Interflow or subsurface flow includes water which moves just below the surface and makes its way relatively quickly to the stream channel. The actual physical processes that convert rainfall to runoff are both complex and highly variable. As such, these processes cannot be replicated mathematically with exact certainty. However, through the use of simplifying assumptions and observed data, there are several mathematical models and equations that can simulate these processes and predict resultant runoff volumes and rates from rainfall occurrence with acceptable accuracy.

The streamflow (or riverflow) refers to the amount of water flowing through a river section in a particular duration. The observed flow at a site may be affected by landuse/land cover changes and the water utilization for different purposes in the contributing basin. Changes in the landuse (say, afforestation/deforestation, urbanization, irrigation development etc.) impacts the timing and quantity of water flow in downstream river sections. Further, the streamflow consists of contributions from melting of snow/ ice and rainfall-induced runoff, all of which are sensitive to changes in climate conditions (Wendel, 2015). In the 21st century, climate change will affect the global hydrological cycle [Figure - 7.1 by Singh and Kumar (2018)] including higher occurrence of extremes (Hisdal et al. 2001; Arnell and Lloyd-Hughes 2014) and magnitude of changes will largely depend on representative concentration pathways (RCPs) (Koirala et al. 2014). Higher precipitation intensities are expected to impact the extreme flow conditions (both, low and high flows). Therefore, assessment of potential impact of climate change on hydrology and water resources of rivers is important for future planning and management of water resources.

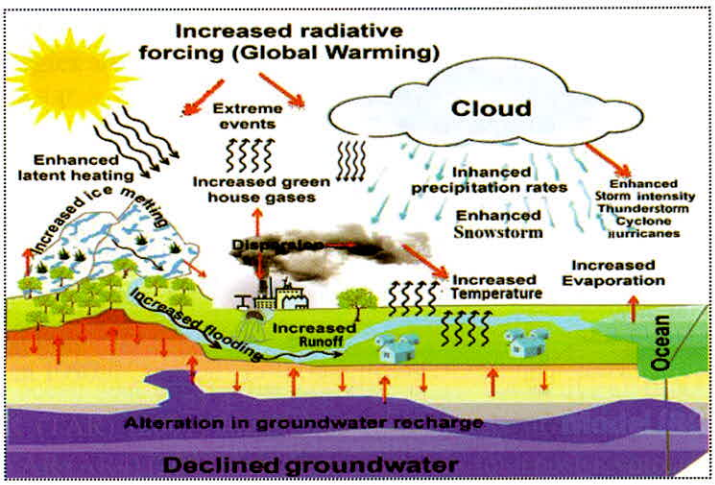


Figure - 7.1: *Influence of global hydrological cycle in context of climate change.*

Climate change is expected to alter the hydrological conditions, posing additional pressure on water resources with different authors having varied opinion. Increase in water stress and alteration of river flows in different parts of the world will be a major consequence of future climate change (Arnell 2004; Musau et al. 2015). With the doubling of CO_2 concentration, global mean runoff may increase by 5% as a result of reduced evapo-transpiration due to CO_2 enrichment (Betts et al. 2007). Stonevicius et al. (2016) opined that simultaneous increase in precipitation and evaporation may produce no overall change in the runoff even with change in both of these parameters. However, it is certain that there will be a significant change in runoff if increase in earth's temperature and change in precipitation take place simultaneously (Mousavi et al. 2018).

Since flow in the river is a result of complex interactions among different hydrological variables, hydrological models are the suitable tools to understand the impact of climate as well as LULC changes on water resources because of their ability to simulate or model such interactions. To establish the impact of climate change on river flows, the outputs of General Circulation Models (GCMs) are coupled with a deterministic hydrological model. By simulating stream flows resulting from precipitation and temperature data derived from GCM outputs corresponding to any specific climate change scenario, it is possible to quantify the impact of corresponding climate change on the hydrology of the basin. However, there is also a need to validate the hydrological model for the baseline time period with the downscaled output of GCMs. Only if the simulation results corresponding to the baseline period have similar streamflow characteristics when compared to the corresponding historical data, the model can be reliably used to simulate possible hydrological impact of future climate change scenarios (Dibike and Coulibaly, 2007). Another approach used in climate change impact studies is based on hypothetical scenarios (Xu, 1999). This approach has four stages:

a) Determine the parameters of a hydrological model in the study basin using current climatic inputs and observed river flows for model validation.

a) Perturb the historical time series of climate data according to some climate change scenario.

b) Simulate the hydrological characteristics of the catchment under the perturbed climate using the calibrated hydrological model.

c) Compare model simulations of the current and possible future hydrological characteristics.

Therefore, studies related to the climate change impacts on the river flows may be broadly categorized into: (i) studies using GCMs to directly predict the impact of climate change scenarios, and (ii) studies that use hydrological models under assumptions of plausible hypothetical climatic inputs. Many studies have investigated the impact of climate change on water resources, especially streamflow, in many parts of the world. In the following sections, impact of climate change on river flows in global as well as Indian context have been discussed.

7.1 Impact of Climate Change on Riverflows– Global Context

Among the early users of GCM approach, Kite in 1993 used mean monthly climatic variable values from Canadian Climate Centre second generation GCM. He found increase in both, high discharge and extreme rainfall, events. Contradictorily, when Arora and Boer (2001) studied the hydrology of some of the world's major river basins using CGCM1 model, they did not observe any such high discharge events.

Based on A2 and B1 scenarios, Van et al. (2013) revealed that the earth will experience decrease in low and increase in high flows in future. A reduction of freshwater may aggravate the water management problems for regions of mid and low-latitude; while higher amount of surface flow will be

experienced in the higher-latitude regions (Nohara et al. 2006; Arnell and Gosling 2013). Arora and Boer (2001) from their study concluded that low-latitude rivers will experience negligible decrease in annual discharge while high- and mid-latitude rivers will face decrease in annual phase and amplitude of streamflow cycle. However, according to Nijssen et al. (2001), the annual streamflow would increase for the high-latitude rivers and would decrease for tropical to mid-latitude rivers.

Wetherald and Manabe (2002) specified that most of the tropical and mid-latitude rivers would experience positive as well as negative changes in runoff, except the Ganges and the Amazon. In these two rivers, the runoff is projected to increase quite substantially. Different researchers concluded that the rivers Mississippi, Brahmaputra, Danube and Lena will experience increased runoff (Jha et al. 2007; Costard et al. 2007; Ye et al. 2009; Bormann 2010; Gain et al. 2011; Ghosh and Dutta 2012). However, for the rivers Nile, Indus and Ganga, the researchers do not have clear consensus about the future runoff (Soliman et al. 2009; Taye et al. 2010). Based on the simulations from different models, the same river basins are projected to have both; high and low runoff states (Bhatt and Mall 2015). Tong et al. (2016) carried out a study in the Las Vegas Wash watershed in the USA and revealed that under B1 climate scenario, discharge in the watershed will decrease during winter and increase during summer. According to a study on future water availability in Bangladesh, Kirby et al. (2016) found that climate change will significantly impact the runoff in the region. He et al. (2013) found annual streamflow variations in the upper San Joaquin basin due to future climate change projections. Tall et al. (2017) witnessed increase in runoff in Senegal by the middle of 21st century due to increase in precipitation, temperature and evaporation.

Senent-Aparicio et al. (2017) reported that in Spain, future climate change will increase temperature by 1.5 to 3.3°C, decrease precipitation by 6 to 32% and decrease runoff by 2 to 54%. Xu and Luo (2015), from their study using GCMs and A1B scenario, found that temperature, precipitation and seasonal discharge will change up to 8.6°C, 139% and 304% respectively in China. Huang et al. (2015) studied the impact of climate variables on runoff in the Minjiang River and showed that variation in precipitation had more impact on simulated runoff than variation in temperature. Boyer et al. (2010) used the hydrological model 'HSAMI', three GCMs, viz. HadCM3, CSIRO-MK2 and ECHAM4, and A2 and B2 emission scenarios to study the impact of projected climate variability on seasonal discharge in the St. Lawrence tributaries, Quebec, Canada. Their results showed that the discharge will increase during wintertime and decrease during springtime. Azari et al. (2016) used climatic projections and hydrologic models to simulate the streamflow in northern Iran and reported that discharge would increase and decrease in the wet and dry seasons respectively and the overall annual discharge will increase. Shahini et al. (2016) also revealed an increase in wintertime runoff and decrease in springtime runoff due to variation in projected future temperature and precipitation.

Based on six different GCMs under three SRES scenarios, a study by Mousavi et al. (2018) on the Dez Dam basin, Iran indicated33% reduction of annual flow in the future. Based on the results of CGCM1 fed into a coupled hydrology-hydraulic model, substantial increase in the runoff volume (with up to 250% in maximum discharge) and water level was predicted in Chateauguay river basin of Quebec, Canada by Roy et al. (2001). To evaluate the impacts of climate change on water resources in the Pungwe river basin, Andersson et al. (2011) linked the Rossby Centre Regional Climate Model (RCA3) and hydrological model HBV. Their experiments indicated a decrease in available water and river flow rate for the entire river basin as a result of combined impact of decrease in precipitation and increase in evaporation and river flow reduces by 50 to 60%during the end of dry season. Stonevicius

et al. (2016) used CMIP5 model outputs for RCP 2.6 and RCP 8.5 and applied water balance model WatBalon in the Nemunas River which is one of the largest tributaries of Baltic Sea. The results revealed a decrease in spring runoff and increase in winter runoff with an overall likely decrease in annual runoff.

Hamid et al. (2010) assessed the impact of climate change on flood-plain and hydrologic ecotones over the Lower Tualatin basin in the Pacific Northwest US using daily downscaled data of precipitation and temperature. They considered the effect of three different GCM climate change emission scenarios (high from the IPSL GCM's A2 scenario, middle from the ECHAM5 GCM's A2 scenario and low from the GISS GCM's B1 scenario) and used SWAT model to predict daily flows in the basin and HEC-RAS model to delineate the flood-plain extents for various climate scenarios. Their study predicted significant decrease in 50-year recurrence interval (RI) flow (between 18,000 to 19,000 cusec) compared to the observed 50 year RI of approximately 26,000 cusec for the low and middle emission scenarios. However, under the high emission scenarios, the 50-year RI flow increases to nearly 33,000 cusec.

*7.1.*1 Combined Impact of Climate Change and LULC Change on River Flows

Various researchers, from their study in different parts of the globe, found that runoff in a basin is sensitive to both, climate change and LULC change. Urbanization leads to changes in precipitation and temperature in a way that surface air temperature increases and precipitation changes in intensity and spatial pattern (Giannaros et al. 2013). Again, due to deforestation, there may be decrease and increase in surface air temperature in temperate and tropical regions respectively (Costa and Piers 2010).

Based on the results from SWAT model, Liu et al. (2003) found that during 1980-1990, the runoff in a region of the Yellow River decreased by 109% due to climate change and increased by 10% due to LULC change. Li et al. (2009), using SWAT model, found that runoff decreased by 9.6% due to LULC change and by 95.8% due to climate change in the Heihe catchment of Loess plateau. Huang and Zhang (2004) studied the impact of LULC change on mean annual runoff in the Jialuhe River catchment and found that runoff decreased by 32% during 1967-1989 due to conservation practices implemented in the catchment.

Mu (2007) reported that runoff will decrease by 29% and 71% due to precipitation change and LULC change respectively in the He Long region of the Yellow River. For the Langat river basin of Malaysia, Noorazuan (2003) found that due to change in LULC, surface runoff increased by 20.35% and 27-31.4% during 1983-1988 and 1988-1994 respectively. Guo et al. (2016) applied SWAT model in the Xiying river basin in China to evaluate the impact of change in climate and LULC on runoff. Their study indicated that during 1990-2008, mean annual runoff increased by 102.8% which was primarily due to climate change. From the future projection study, while comparing the runoff with that for the period 1961-1990, they found that under A2 and B2 scenarios, there will be a decrease in mean annual streamflow by 5.4% and 4.5% respectively for the period 2010-2039. Again, under these two scenarios, runoff will decrease by 21.2% and 16.9% respectively for the period 2040-69. Tan et al. (2015) applied SWAT model to understand the impact of change in climate and LULC in the Johor River basin, Malaysia. They concluded that impact of climate change on streamflow is more significant than LULC change in the study basin. From the Mann-Kendall and Sen's slope test, they found that in contrast to the significant increasing trends of precipitation and temperature, the increasing trend of

streamflow is very insignificant. While considering the combined impact of LULC and climate change, the streamflow increased by 1.2% in the Johor River.

Trang et al. (2017) studied the impact of LULC change and climate change for future three different time periods, viz., 2015-2039, 2045-2069 and 2075-2099 using ensemble of five GCMs for RCP 4.5 and RCP 8.5 for the 3S river basin. Indicating that there will be increase and decrease in discharge in wet and dry seasons respectively for the selected time periods, they concluded that throughout the 21st century, the discharge will increase in the 3S river basin. Using Joint UK Land Environment Simulator (JULES) and Land Surface Model (LSM), Tsarauchi and Buytaert (2018) investigated the impact of future climate and LULC changes on hydrological response in upper Ganga River Basin in northern part of India for the period 2000-2035 using CMIP5 outputs of 21 models for RCP4.5 and 8.5, and 15 land-use pathways. They carried out the experiments for separate as well as combined impact of LULC and climate change and predicted severe increase in high extremes of flows.

7.2 Impact of Climate Change on Flows of Indian Rivers

7.2.1 Current Scenario

There are two major river systems in India. The first system includes all the major rivers and their tributaries that originate in the Himalayas and second system includes the rivers draining the Deccan Peninsula (Rashtriya Barh Ayog, 1980). India has a monsoon type of climate and about 80-90% of the annual river flows occur during four monsoon months (Jain 2017). The aspect related to changes in streamflow due to snow and glacier-melt has been covered in separate chapter in this report and is not elaborated here. Some other studies in the field of hydrologic impacts of climatic change on Indian river basins is presented here.

Table – 1: Basin-wise average flow of major Indian rivers:

S. No.	River	Average annual flow (km^3/yr)
1	Indus	73.31
2	Ganga-Brahmaputra-Meghna Basin	
	2 (a) Ganga	525.02
	2 (b) Brahmaputra sub-basin	629.05
	2 (c) Meghna sub-basin	48.36
3	Brahmni-Baitarani	28.48
4	Mahanadi	66.88
5	Godavari	110.54
6	Krishna	69.81
7	Pennar	6.32
8	Cauvery	21.36
9	Tapti	14.88
10	Narmada	45.64
11	Mahi	11.02
12	Sabarmati	3.81

Source: Kumar et al. 2005

Out of many rivers in India, 12 are classified as the major rivers. Most of the rivers are perennial and few are seasonal. For the Himalayan rivers, the average water yield per unit area is more than that of the south peninsular rivers due to snow and glacier melt contribution from the mountains to the Himalayan rivers (Mall et al. 2006).

Ghosh and Majumdar (2008) carried out a study for Mahanadi River basin and used the vector machine with fuzzy clustering to project the future monsoon streamflow considering the CCSR/NIES GCM with B2 scenario. Their study revealed a decreasing trend in monthly peak flows which may be attributed to high surface warming that leads to significant reduction in occurrence of high flows. Additionally, they used conditional random field (CRF) downscaling model with AR4 projections and found that for most of the future scenarios, there will be a decrease in the mid-level flows. However, for the period 2040-65, for most of the scenarios, significant increase in high flows and slight increase in low flows was predicted.

As recorded by Climate Change Cell of Ministry of Environment, Bangladesh (2009), there was an increase in streamflow at Bahadurabad in the Brahmaputra River during 1956-2007 due to some particular flood occurrences. At the Mundali outlet in the Mahanadi basin, Dadhwal et al. (2010) reported an increase in annual streamflow by 4.53% during the period 1972-2003 due to reduction in forest cover by 5.71%. Panda et al. (2013) reported decreasing streamflow at the rate of 3388 million cubic meter (MCM) per decade for the period 1972-2007 at Tikerpara gauging site of Mahanadi river in Peninsular India, which was attributed to increased upstream usage in the river.

For the Brahmani River basin, Islam et al. (2012a) used the USGS's Precipitation-Runoff Modeling system (PRMS) to study the impact of climate change on streamflow. They found that impact of change in rainfall on annual and seasonal streamflow is more significant than change in temperature in the basin. Abeysingha et al. (2016) observed decreasing trend in annual streamflow of Gomti River for the period of 1982-2012. Anandet al. (2018) used SWAT model along with statistical methods to detect trend and critical changes in streamflow of Ganga river. They found increase in streamflow from the snow-fed areas but significant decline in streamflow in lower reaches which may be attributed to anthropogenic changes.

Saharia et al. (2018) evaluated future climate change impact on hydrologic processes in Bharalu (urban) and Basistha (rural) basins using SWAT model for two different climatic scenarios - RCP 2.6 and RCP 8.5. Various hydrological processes such as precipitation, discharge, water yield, surface runoff, actual and potential evapo-transpiration were examined. In the mid-century and late century, the stream flow, water yield, surface runoff and actual evaporation were found to decrease in urban basin as compared to rural basin. Under RCP 2.6 and RCP 8.5 scenarios, the average annual discharge was found to increase by 1.43 cumec and 2.20 cumec respectively as compared to base line scenario.

Reshmidevi et al. (2017) estimated the impact of climate change on water balance in an Indian catchment using an ensemble of 5 GCMs (MPI-ECHAM5, BCCR-BCM2.0, CSIRO-mk3.5, IPSL-CM4, and MRI-CGCM2). Modified Markov Model-Kernel Density Estimation (MMMKDE) and k-nearest neighbor downscaling models were used. Present and future hydrological simulation was done using SWAT model. They found decreasing trends in runoff ratio, annual stream flow and groundwater recharge by the end of the century. An increasing trend of temperature as well as evapo-transpiration was predicted which in turn, will increase the irrigation demands. Also, there will be an increase in average precipitation towards the end of the century under future climatic projection. The authors

conclude that due to reduction in streamflow and ground water recharge along with increase in irrigation demands, the water stress in the region will be aggravated.

7.2.2 Future Projections

As per IPCC 5th Assessment Report, India in 2080 as compared to 1961-1990, will experience warming of the order of 1.5, 2.4, 2.8 and 4.3°Cunder RCPs 2.6, 4.5, 6.0 and 8.5 respectively (Chaturvedi et al. 2012). There will be a general trend of increase in mean average annual temperature and enhanced precipitation in the Indian subcontinent (Cruz et al. 2007). Mall et al. (2006) reported that the pre-monsoon and monsoon rainfall over the central plains of Indian sub-continent would increase by the end of the century which would result in an increase in the monsoonal and annual runoff. However, due to no substantial change in winter rainfall, the winter runoff over the central plain will not change significantly.

Sharma et al. (2000) and Sharma (2000) studied the impact of potential climate change scenarios on hydrology of the Kosi Basin. Their study revealed that, compared to precipitation, increase in runoff was higher in the basin for all the scenarios. However, the scenario created by considering contemporary precipitation and a rise in temperature by 4°C, caused decrease in runoff by 2 – 8% depending upon the areas considered and the model used.

Gosain and Rao (2003) studied the impact of future climate change on runoff of different river basins and sub-basins in India. For Mahanadi, Brahmani, Ganga, Godavari and Cauvery River basins, the authors predicted that corresponding to increase in precipitation; there will be no increase in the annual runoff because of increase in evapo-transpiration due to increased temperature and variation in precipitation distribution. For the Sabarmati River basin, appreciable decrease in projected precipitation and correspondingly total runoff was predicted which may cause severe drought conditions in the basin in future. Singh and Kumar (1997) used various climate change scenarios to study the impact on runoff in Spiti River, a high altitude Himalayan River in Satluj basin. They found linear increase in snowmelt runoff, glacier-melt runoff and total streamflow due to changes in temperature.

Das and Umamahesh (2018) projected the monthly monsoon streamflow in the Wainganga basin, India using 40 GCM outputs and four RCPs. Relevance vector machine (RVM) was used to simulate future monsoon flows. Their results indicated that upper extremes of monsoon flow will continuously decrease in future while medium and low flows will increase under the different RCPs. Towards the end of the 21st century, the decrease in mean annual monsoon flow was found to be more significant.

Mishra and Lihare (2016) considered 18 Indian major sub-continental basins viz., Indus, Brahmaputra, Ganga, Brahmani, Cauvery, Godavari, North Coast, South Coast,East Coast, West Coast, Mahanadi, Krishna, Narmada, Tapti, Sabarmati, Mahi, Pennar and Subarnarekha to assess the impact of climate change on hydrological processes under RCP 4.5 and RCP 8.5 scenarios using SWAT model. The analysis was performed for three different future time frames, 2010-39, 2040-69 and 2070-99. They reported that under RCP 4.5, there will be significant increase in streamflow for Ganga, Brahmaputra, Narmada and South Coast Rivers, while, there will be decrease in streamflow for Mahi and Tapti Rivers during monsoon season. Under RCP 8.5, Brahmani, Ganges, Godavari, Mahanadi, Narmada, Pennar and Subarnarekha Rivers will experience significant increase in streamflow. The projected change in streamflow during monsoon season for different basins as given by authors are represented in Figure- 7.2. In the mid and end of 21st century, majority of the sub-continental river

basins will experience increase in streamflow by 20-40%. The authors attributed it to increase in precipitation with relatively lesser increase in evapo-transpiration during monsoon season.

For the Barmanghat gauging site in Narmada basin, Sudheer (2016) used six RCMs and two RCPs (4.5 and 8.5) to run the SWAT model and identified dependable flows at 5%, 10%, 20%, 50%, 75%, 90% and 95% dependability. He reported that the 5% dependable flow during 2006-40 varies between 405.6 cumec for ACCESS to 452.2 cumec for MPIESM. During 2041-70, the 5% dependable flow varies between 382 cumec for CNRM to 520.4 cumec for GFDL. However, the 5% dependable flow may increase during 2071-99 varying between 507.9 cumec for MPI-ESM to 607.3 cumec for CNRM indicating possibilities of occurrence of floods towards the end century.

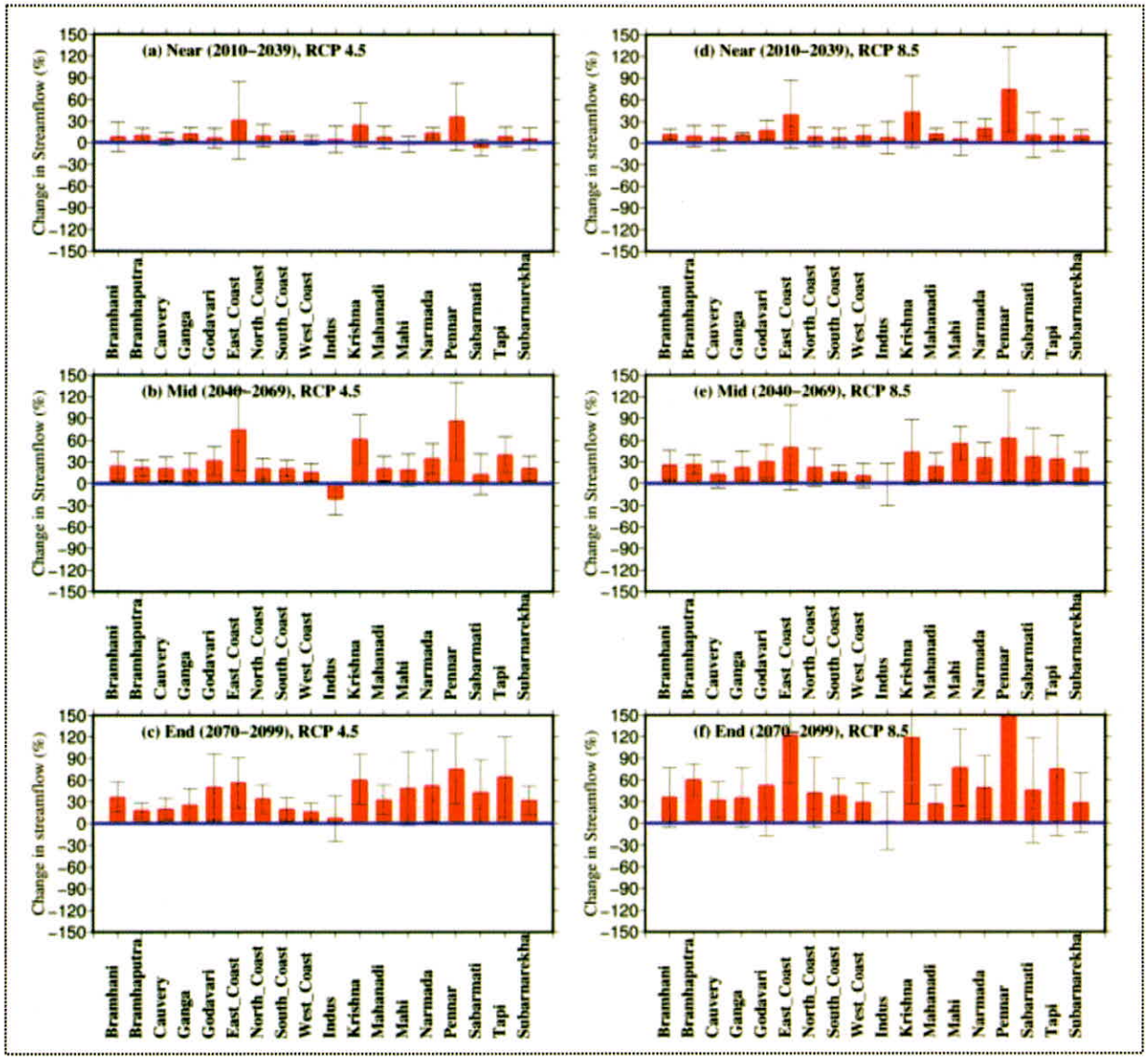


***Figure- 7.2**: Multi-model ensemble mean projected changes (%) in mean monsoon season streamflow under RCP 4.5 and 8.5 scenarios for the Near (2010-2039), Mid (2040-2069), and End (2070-2099) term climate with respect to the historic (1971-2000). Bars show multi model ensemble mean change, while error bars show intermodal variation using one standard deviation (Source: Mishra &Lihare 2016).*

Pervez and Henebry (2015) applied SWAT model using downscaled CGCM3.1 precipitation from CMIP3 and Image-derived LULC to assess impact of climate and LULC change on the hydrology of the Brahmaputra River basin. The impact was analyzed for A1B and A2 scenarios taking 1988-2004 as the base period. The results predicted strong increasing trend of streamflow during August-October (indicating possibility of floods) and strong decreasing trend of streamflow during May-July of 21stcentury (indicating possibility of drought) in the basin.Kamal et al. (2013) studied the seasonal variability of monsoon and dry periods through projected data of the period of 2020s, 2050s and 2080s and found that peak flow of GBM (Ganges, Brahmaputra, Meghna) rivers may enhance by about 4.5 to 39.1% in the monsoon period while in the dry season, the low flows may decline by about 4.1to 26.9%.

Masood et al. (2015) assessed the impacts of climate change (considering high-emission path) on runoff, evapo-transpiration, and soil moisture using five CMIP5 GCMs. Results showed that by the end of 21st Century, these basins will be warmed by ~4.3 °C and changes in mean precipitation (runoff) are projected to be +16.3% (+16.2%), +19.8% (+33.1%), and +29.6% (+39.7%) in the Brahmaputra, Ganges, and Meghna basins respectively. A study by Mahanta et al. (2014), based on 22 GCMs and A1B, B1 and A2 scenarios, revealed that the flow of Brahmaputra River at Chilmari will increase by 5to20% by the end of 21st century. Lutz et al. (2014) used a distributed cryosphere-hydrological model on the upstream basins of the Ganges, Indus and Brahmaputra and predicted a consistent increase in the runoff at least until 2050.

Sharannya et al. (2018) studied impact of climate change on hydrology of river Gurupura, one of the major rivers of Dakshina Kannda district of Karnataka. This is a west flowing river that originates in the Western Ghats of India. CORDEX data was used along with SWAT model. The analysis was performed for both, past and future, scenario. The time period of historical analysis was 1951-2005 and for future they used RCP 4.5 scenario for the period 2006-2060. Their result indicated that the annual streamflow in the river showed decreasing trend at the rate of 1.2 MCM/yr for the past and 2.56 MCM/yr for future scenario. Talib et al. (2017) applied the SWAT model at Bhakra, the major reservoir in the Satluj river basin in India to simulate the streamflow for three different time-frames viz., 1961-1990, 2021-2050 and 2071-2098. Climatic change projections generated under PRECIS for IPCC A1B scenarios were considered. The authors found 12.8% and 19.4% increase in annual streamflow at Bhakra for 2021-2050 and 2071-2098 respectively. The monsoonal streamflow would increase by 10% for both the periods as compared to the base period. However, for January-February, the streamflow were projected to increase by 49% and 21% respectively for 2021-2050 and 2071-2098 periods as compared to the base period.

Kumar et al. (2017) studied the impact of climate change on streamflow of the Upper Kharun Catchment, a part of Seonath sub-basin which is a tributary of Mahanadi river in the Chhattisgarh State of India. They used PRECIS regional climate projections for the period 1961-2098 and simulated the streamflow using SWAT model. The authors found an average decrease of annual discharge by 2.9% for 2020s; average increase of 12.4% for 2050s, and average increase of 39.5% for 2080s. Nilawar and Waikar (2019) used SWAT model, three RCMs, and RCPs 4.5 and 8.5 for future four different time periods viz., 2009-31, 2032-53, 2054-75 and 2076-99 to study climate change impact on streamflow and sediment concentration in the Purna river basin of India compared to the base period 1980-2005. The results showed increase in average monthly streamflow by 24.47 to 115.94 cumec under RCP 4.5 and 8.5 and significant increase in future streamflow from June to September at the outlet of the basin was predicted.

Vandana et al. (2018) used Precipitation Runoff Modelling System (PRMS) to study the impact of climate change in the Brahmani river basin. They generated multi-model ensemble climate change scenarios using Hybrid –Delta ensemble method forA2, A1B, and B1 scenarios. Their results indicated that annual streamflow would increase in the range of 2.2 to 2.5%, 2.4 to 4.7% and 7.3 to 12.6% during 2020s, 2050s and 2080s respectively. Increase in high flows and decrease in low flows in the future periods was also predicted by the authors. Gosain et al. (2006) conducted a simulation on 12 river basins of India with size ranging from 1,668 to 87,180 sq. km for the period 2041-2060 using SWAT model and HadRM2 regional climate model. The results predicted a general decrease in future runoff. However, Gosain et al.(2011) used PRECI Sregional climate modelinA1b emission scenario along with SWAT model and found that for most of the Indian Rivers, the water yield will increase during 2030s and 2050s. According to their study, Godavari, Brahamani and Mahanadi River basins were not found to have water shortage and predicted rather severe flood conditions. However, decrease in peak flow magnitudes was observed for a few sub-basins of Ganga, Brahmaputra, Krishna, Cauvery and Pennar River basins.

Pechlivenidis et al. (2016) used climate projections from CORDEX- South Asia framework which were used to run the HYPE hydrological model to predict the runoff in the Ganga basin of Indian subcontinent. Their study revealed that variations in discharge due to climate change vary from season to season and region's hydro-climatic gradient is responsible for the magnitude of this variation. For Mahanadi River basin, Asokan and Dutta 2008 projected the highest increase in peak runoff (38%) for the period of 2075-2100 and the maximum decrease in average runoff (32.5%) in the month of April during 2050-2075.

Mudhatkal et al. (2017) assessed the climate change impact on the hydrology of the Sub-humid and Per-humid river systems that are originating in the Indian western mountain range (Western Ghats). The authors used modified Mann-Kendall test to evaluate the trend of data observed between 1975 to 2004 and RCP 4.5 data (2006-2070) of climatic variables. The Netravati River showed a decreasing trend of annual flow. In addition, a decreasing trend of high flow was estimated for Netravati, whereas the trend was found to be increasing for Malaprabha River. Thus, the climate change impacts on Western Ghats were very evident, but the flow of each river was found to respond differently.

Meenu et al. (2013), based on their study using HadCM3 GCM and the A2 and B2 scenarios, predicted that the average streamflow of river Tungabhadra will increase by 5.4 to 17.1% in 2050 and by 46% in 2080s. They used the downscaled precipitation and temperature data obtained from SDSM as input to HEC-HMS 3.4 model. Shah and Mishra (2018), evaluated changes in total runoff and streamflow in 18 Indian River basins using Variable Infiltration Capacity (VIC) model for RCPs 2.6 and 8.5. They found that streamflow is expected to rise in majority of the river basins except for the Indus basin under projected future climate (Figure - 7.3). The increase in total runoff and streamflow could be due to extreme precipitation during monsoon season.

7.3 Concluding Remarks

It is now well-established that the global climate change is causing and will continue to have a significant impact on the amount and the timing of river flows. In the present scenario, at the global scale and particularly in the context of the diverse Indian sub-continent, climate change has significant impact on annual flows of rivers, though to a different extent in different regions and in different times of the year.

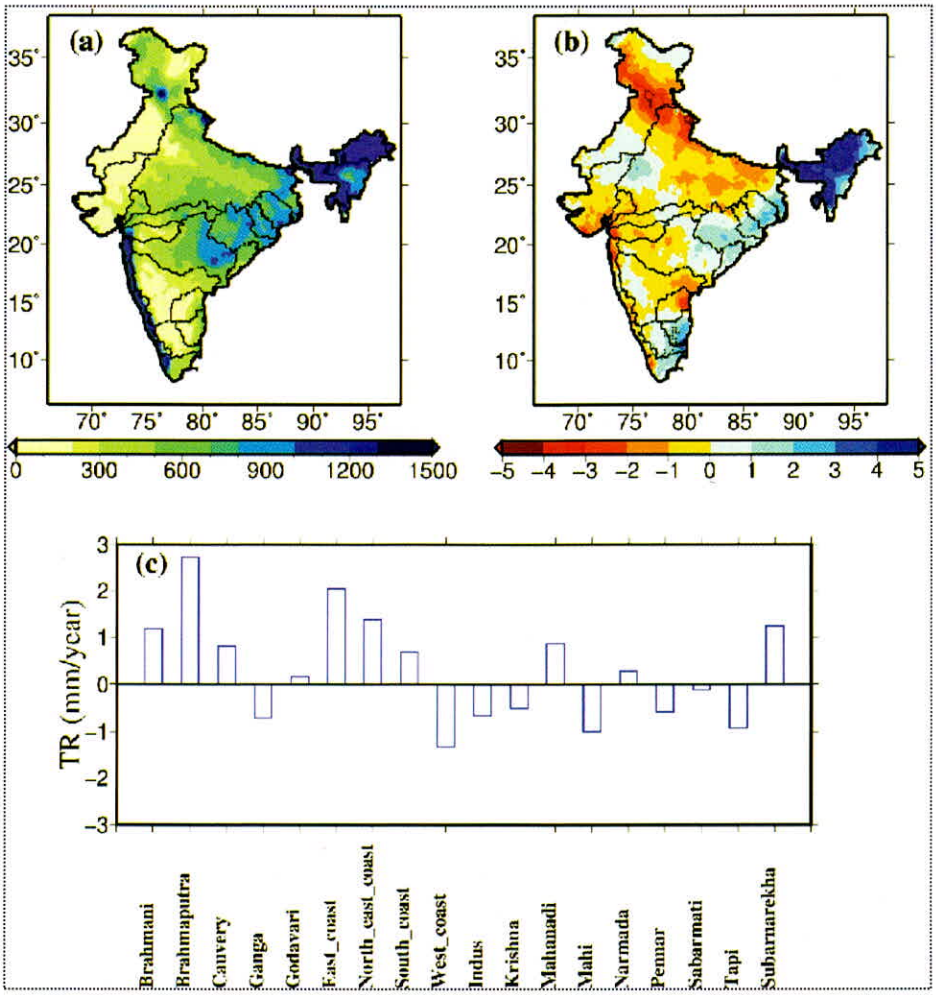


Figure - 7.3: *Ensemble historical mean of five GCMs (a) mean annual runoff (mm), (b) trend in total runoff (mm/year) estimated using Mann-Kendall test; and (c) basin averaged change in total runoff (mm/year) from 1970-99(Source: Shah & Mishra 2018).*

Regional climate dynamics is influenced by both, global climate and LULC changes. However, changes in LULC are often ignored in long-term regional climate projections. In a developing country like India, climate change, LULC change, and fast-pace changes in demography, urbanization, industrialization, and development of surface and groundwater resources have triggered major impact on water resources availability in the country. It is necessary to separate the relative contributions of climate change, LULC change, and impact of anthropogenic effects on runoff generation mechanism. Detailed modeling studies, that consider all such factors, should be carried out for different regions to establish the role and extent of impact of various influencing climate variables on the flow characteristics. These inputs can be useful in finalizing the adaptive strategies for mitigating the climate change impact.

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CHAPTER 8

CLIMATE CHANGE AND GROUNDWATER

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8.0 Introduction

Global climate change threats the supply and management of water resources. The Intergovernmental Panel on Climate Change (IPCC) suggested an increase in the global mean surface temperature by 0.6 ± 0.2°C since 1861, and predicts an increase of 2 to 4°C over the next 100 years. Global sea levels have risen between 10 and 25 cm since late 19th century. Elevation in temperature also affects the hydrologic cycle directly by increasing evaporation of surface water and vegetation transpiration. Consequently, these changes influence amount, timing and intensity of precipitation, which indirectly impact the flux and storage of water in surface and subsurface reservoirs (i.e., lakes, soil moisture, and groundwater). The ripple effect of climate change on water resources may lead to several water quantity and quality problems such as seawater intrusion, water quality deterioration, potable water shortage, etc.

Global climate change directly influences quantity and quality of surface water resources by potential long term changes in climatic variables in terms of air temperature, precipitation, and evapo-transpiration; whereas, understanding the link between the changes in climate variables and groundwater is more complex and enigmatic. The larger anomaly in rainfall pattern manifests frequent and prolonged periods of shallow or depleted groundwater table that also affects baseflows, and, reduced freshwater availability in coastal areas due to seawater intrusion on account of sea level rise. Thus, groundwater resources are indirectly linked to climate change via interaction with surface water resources and recharge process. Therefore, determination of climate change impact on groundwater resources relies on credible forecasting of changes in major climatic variables as well as accurate estimation of groundwater recharge.

This chapter provides an insight into potential impact of climate change on groundwater resources and importance of addressing this scenario as well as its consequences. This narration will contribute to the sustainable management of groundwater resources in the Indian context and will provide the premise for long-term monitoring of climate changes impact on groundwater resources well into future.

8.1 Impact of Climate Change on Groundwater

Although the effect of climate changes on surface water has obvious recognition due to its visible fluctuation in surface water levels and water quality, the potential impact on groundwater resources is of serious concern because groundwater is widely distributed source of drinking water supply and irrigation. However, effect of climate change on surface water resources bodies have been studied extensively but very little research exists on the potential effects of climate change on groundwater.

It is being recognized that groundwater is not a separate entity from the surface above or from the regional hydrological cycle and needs to be managed in a wholesome manner along with surface water resources. Thus, to comprehend the likely consequences of climate change on the hydrological cycle and groundwater resource, it is essential to gain an understanding of the influence of changes in climatic variables on the surface runoff and groundwater.

Changes in precipitation and evapo-transpiration plays significant role on groundwater recharge directly and on groundwater withdrawals or discharge indirectly. Groundwater systems in semiarid and arid regions are critically effected, because even minor variability in precipitation can lead to extreme changes in recharge (Green, Bates, Charles, & Fleming, 2007; Woldeamlak, Batelaan, & De Smedt, 2007). According to recent studies, the spatial variability in projected precipitation is highly effected by global warming and is predicted to boost positive and negative changes in regional precipitation, as well as changes in seasonal patterns (Cook, Smerdon, Seager, & Coats, 2014; IPCC, 2007). Little agreement has been noticed between the magnitude and direction of predicted evapo-transpiration patterns (Barnett et al., 2008). However, increased air temperatures may boost evapo-transpiration, which may result in a reduced runoff and soil water content in certain regions (Chiew & McMahon, 2002). Evapo-transpiration has less effect on groundwater recharge and base flow in temperate and humid regions due to seasonal timing of recharge events (Hunt, Walker, Selbig, Westenbroek, & Regan, 2013). The excess precipitation period is associated with increased recharge and reduced water demand such as for irrigated agriculture, due to lower temperature, solar radiation and higher humidity in these periods (Rosenberg et al., 1999). On the contrary, an increased spatial extent and temporal duration of extreme drought under future climate scenarios are predicted(Bates, Kundzewicz, & Wu, 2008; IPCC, 2007).

The heightened variability in climatic variables such as precipitation, temperature, and evapo-transpiration that is predicted under different climate change scenarios will have variable effects not only on different aquifers but also on different locations within an aquifer due to variations in spatial parameters such as hydraulic properties and distance from the recharge areas.

Chen, Grasby, and Osadetz (2002) Observed that water table responds with respect to precipitation variability in a mid-continent carbonate-rock aquifer differently in individual wells because of the spatial variation in permeability of overlying sediments and recharge characteristics; i.e. groundwater levels at some locations of the aquifer responded to high-frequency precipitation events while certain other areas did not exhibit much change in water levels. . It could be due to the interconnection of highly permeable channels or preferential-flow paths from land surface to the water table (Chen et al., 2002), or differences in thickness of the unsaturated zone.

In mountainous regions, spatial variation in groundwater dynamics may significantly affect stream flow responses to warming (Tague & Grant, 2009). While determining impact of climate change in mountainous regions, groundwater dynamics like subsurface drainages are as important as topographic differences in snow regimes (Tague, Grant, Farrell, Choate, & Jefferson, 2008). Singleton and Moran (2010) have noted that recharge mechanism, storage capacity and residence time of high elevation aquifers are understudied and not understood well. The recharge process in mountain aquifers are complex due to lack of knowledge in changes in the timing of snow packs melting in terms of direction and magnitude which makes it difficult to predict response of mountain aquifers to climate change. A negative feedback between early timing of snowmelt and evapo-transpiration exist in snowmelt dominated watersheds. In this case, snowmelt increases soil water content in the season where evapo-transpiration will be lower which accelerates infiltration and recharge. While, when potential evapo-transpiration is greater and shift in snowmelt timing may reduce soil water content which causes reduction in evapo-transpiration and has an unidentified effect on net infiltration and recharge. The aggregate impacts of these are unresolved challenges which concerns subsurface hydrologic responses to climate-change effects on surface-water hydrology. Therefore, there is a need

to understand and evaluate climate change impact on aquifer systems. As part of the hydrologic cycle, it can be anticipated that any changes in climate will affect groundwater systems by altering recharge (which encompasses changes in precipitation and evapo-transpiration), potentially by changes in nature of the interactions between the groundwater and surface water systems, and changes in demands related to irrigation. The following section describes the effect of climate change on soil moisture, groundwater resources and coastal aquifers.

8.1.1 Soil Moisture

The amount of soil water content is a critical parameter for agricultural management. It has profound influence on the rate of change of actual evaporation, groundwater recharge, and generation of runoff. Global climate models have been applied to simulate soil moisture contents on a very coarse spatial resolution and the results from these models indicate possible direction of changes.

At a regional level, the impact of global climate change on soil moisture depends on the degree of climate change as well as the soil characteristics. The soil water-holding capacity will affect possible changes in soil moisture deficits. As the soil water holding capacity lowers, the sensitivity to climate change will be more. Climate change may also affect soil characteristics through changes in water logging or cracking which alters the storage properties of soil. In cold climate regions, infiltration and water holding capacity of soils also depends on frequency and intensity of freezing. Further, changes in temperature, precipitation and evaporation results in corresponding changes in organic matter content which leads to enhanced losses of green house gases in mineral and organic soils. The emission of green house gases will also affect other soil functions like poorer soil structure, stability, topsoil, water holding capacity, nutrient availability and erosion. The emission of green house gas is also accelerated by the increase in temperature. However, these effects could be counteracted by enhanced nutrient release resulting in increased plant productivity vis-a-vis litter inputs. Increased precipitation enhances peat formation and methane release and vice versa(Defra, 2005).Intensified droughts will leads to shrinking of clay in soils and deformation in building foundations and higher soil temperature may also exacerbate chemical attack to engineered structures with clay caps (e.g., in contaminated landfills), with possibility of increased leachate generation and enhanced landfill gas emissions (Chander, 2012).

The impact of pesticide toxicity due to changing climate variables could vary depending upon the interactions between pesticides and the environment, incidence of pests and diseases under a changing climate. Changes in the amount and intensity of rainfall can increase the risk of pesticides; e.g. drier climate increases pesticide persistence, intense rainfall enhances bypass flow and downward movements. High temperature could counteract leaching process by causing rapid degradation. High intensity precipitation can enhance atmospheric nitrogen deposition on soils which leads to soil disturbances. Flooding and subsidence causes changes in hydromorphology and ecosystem status (wetland and waterlogged habitats) and also enhances soil erosion, leading to the pollution of surface waters.

Trends in soil temperature are important but rarely reported indicators of climate change. There is a close correlation between air and soil temperature. The temperature regime of the soil is governed by gains and losses of radiation at the surface, the process of evaporation, heat conduction through the soil profile and convective transfer via the movement of gas and water. The extent of effect will be varied according to multiple factors and its association between soil and atmospheric temperature. Qian, Gregorich, Gameda, Hopkins, and Wang (2011)conducted a study associated with variation of

soil temperature associated with climate change in Canada. It has been found that air temperature and snow cover depth played an important role in controlling the soil temperature variation. Soil temperature along with soil moisture is a prime mover in most soil processes. Warmer soil temperature will accelerate soil processes, rapid decomposition of organic matter, increased microbiological activity, quicker nutrients release, increase nitrification rate and generally accentuate chemical weathering of minerals.

8.1.2 Groundwater Recharge and Resources

Although groundwater is a major source of water across the globe, specifically for water supply in rural areas in arid and semi-arid regions, however there has been paucity on research about the potential effect of climate on groundwater. Aquifers are reliable source of water which can store water for decades to millennia. However, the sustainability of groundwater systems requires that groundwater withdrawals should match groundwater replenishment.

Understanding aquifer replenishment through rainfall and interaction with surface water bodies is essential to quantify the impact of climate change on groundwater resources. Recharge is the fraction of total precipitation which eventually in filtrates the ground surface and percolates to the water table. Infiltrated water may enter the aquifer rapidly, through macro pores and cracks, or move slowly by infiltration process through the soil pores. Variation in effective rainfall will alter recharge and the change in the duration of the recharge period too. Groundwater recharge may likely increase in mid latitudes for projected scenarios of increased winter rainfall. However, higher evaporation indicates persistence of soil deficiency of water for an extended period that may begin earlier, thus offsetting the increased total effective rain in the region.

Recharge mechanism in aquifers varies with difference in properties / factors associated with them. Aquifers may be confined or unconfined in nature. An unconfined aquifer is replenished via rain or surface water infiltration and the recharge rate varies according to permeability of surface geological material. A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, recharged by rain or surface water infiltrating the permeable rock at some considerable distance away from the confined aquifer. Groundwater in these confined aquifers can sometimes be thousands of years old.

Various studies have attempted to estimate recharge rate by application of C-14 isotopes and modeling. These techniques are applicable for aquifers which are recharged from a short distance over a short duration. Whereas deep-seated aquifers having recharge zone located at larger distances with recharge occurring after decades or centuries pose a challenge in terms of resolving the climate change impact. While attempting modeling of groundwater recharge, the properties of recharge medium are less known due to heterogeneity. Crosbie et al. (2012) Investigated the impact of climate change on groundwater recharge in Australia. As per the study, groundwater recharge and changes in precipitation are extensively interconnected.

According to Hiscock et al. (2011), the projections for potential recharge derived from ensemble of four GCMs for Europe exhibit strong latitudinal dependence on the climate change. According to the hydrological models with uncertainty in GCM projection of precipitation, a substantial reduction in groundwater recharge in southern Europe (Spain and Northern Italy) and an increase in the same in northern Europe is projected (Denmark, southern England, Northern France). This study also implies that projected changes in groundwater recharge for a chalked aquifer for 2080s

is between -26 % and +31% (Jackson, Meister, & Prudhomme, 2011). The recharge projections for southern British Columbia for the year 2080s ranged from -10 % to +23 % compared to past recharge records. The extreme propagation of uncertainty arises from selection of GCMs, downscaling, and hydrologic model showed 53, 44 and 24% of historical recharge records for three Australian sites, respectively. It is observed that simulation results are more deviated due to uncertainty from downscaling rather than selection of different emission scenarios. Simulated climate conditions often predict extremes (such as multi-year droughts) that are outside of the historical baseline climatology (Holman et al. 2009).

8.1.3 Coastal Aquifers

Encroachment of seawater in coastal aquifers, due to landward hydraulic gradient of water table is known as saltwater intrusion. The phenomenon fundamentally occurs because of over extraction of aquifer and land use changes(Singh, 2014; Werner et al., 2013) and threatens urban coastal communities worldwide besides deteriorating productive and consumptive value of costal land.(Bobba, 2002). Climate change further exacerbates saltwater intrusion due to sea-level rise combined with global warming, which would increase demand for freshwater, and with reduced precipitation, ultimately diminish surface water availability for aquifer recharge (IPCC, 2014).

Shallow coastal aquifers are more vulnerable to saline water intrusion and groundwater in low-lying islands is very sensitive to climate change. Decrease in rainfall along with sea level rise amplifies the diminution of the available freshwater volume as well as shrinkage of freshwater lens in the island.

The response to sea level rise varies for confined and unconfined aquifers. Drivers of saltwater intrusion generally exhibit similar trends in governing physical, geological and chemical processes of interaction. The rate and magnitude of these interactions are highly context-specific, assuring the necessity of local investigation for development of adaptation strategies and management. It is needed to research the variation in groundwater recharge and sea level rise to assess the climate change impact on fresh groundwater resources in coastal groundwater systems.

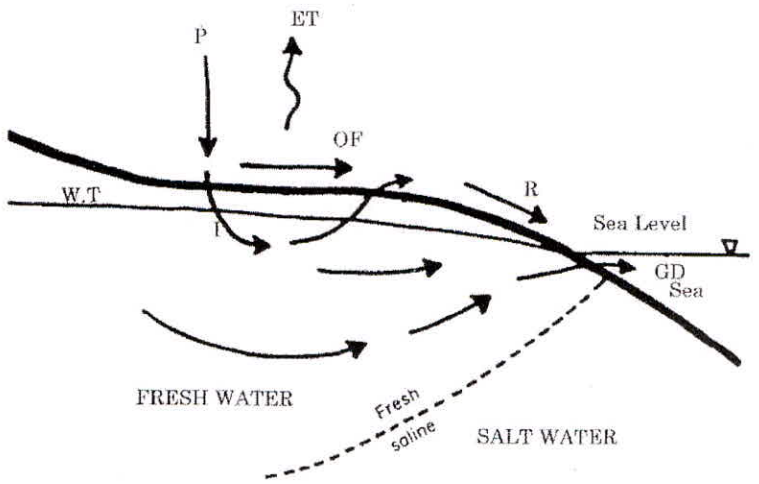


***Figure 8.1**: Schematic illustration of water balance in a coastal groundwater system. (Source: Bobba, 2002).*

8.2 Climate Change Scenario for Groundwater in India

Climate change impact on the groundwater resource is anticipated to be quite severe. About 85% of rural area is depending on groundwater as a major source of drinking water supply. India has a potential of 447 BCM/year of replenishable groundwater (CGWB, 2017). Unfortunately, water table in different regions of India has receded in recent years due to immense withdrawal of subsurface water which has raised serious questions about sustainability of groundwater. The over extracted regions include north western parts of Punjab, Delhi, Haryana and Uttar Pradesh. In western parts of the country, Rajasthan is under groundwater stress due to arid climate and lower groundwater recharge rate. In Peninsular India, groundwater availability is less on account of poor aquifer characteristics.

Another concern associated with groundwater decline is increase in emission of CO_2 due to increased energy requirement for pumping. One of the studies implies that estimated annual carbon dioxide emission has been increased by over 1% for groundwater level decline by 1m in Indian context. A much rational study reveals that according to the area of irrigation, decline in groundwater level for each metre will cause increase in CO_2 release by 4.8%. (Mall, Gupta, Singh, Singh, & Rathore, 2006).

Climate change is expected to affect groundwater due to changes in temperature, precipitation and evapo-transpiration. It is quite clear that different aquifer systems are affected by hydrological processes to varying extent; e.g. Coastal and Island aquifers are impacted by sea level rise and resulting seawater encroachment, where as in land alluvial aquifers are impacted by varying frequency and severity of floods. It has been observed that thickness of fresh water lens was estimated to shrink from 25m to 10m and from 36 m to 28 m for two small flat coral islands for a sea level rise of 0.1 m only (Mall et al., 2006). This observation points towards the importance of aquifer geometry and the impact of climate change.

Agricultural demand, specifically for irrigation, is considered very susceptible to climate change. The necessity and timing of irrigation is controlled by changes in climate at field level. It implies increased water demand due to increased dryness which may get repressed as the soil moisture content increases at critical seasons of a year. As per the national estimates of irrigation requirement, demand would increase by 2025 and globally, it would increase by 3.5-5 % by 2025 and 6-8 % by 2075 without considering climate change scenario. India's agricultural sector meets 52% of its irrigation requirement through groundwater. Therefore, decline in groundwater levels and increased irrigation demand due to climate change need to be addressed urgently in the present scenario as well for meeting crop production requirements for future.

The strong relation between soil moisture and air temperature plays significant role in climate change and frequency of climate anomalies. It is expected that the increase in air temperature in the future would continue. High moisture content in warm air regulates the energy balancing mechanism in environment. The elevated moisture content in the atmosphere may result in climate extremes in the form of intense precipitation, snowfall and increased frequency of floods / droughts. Consequently, soil moisture content, groundwater recharge and frequency of flood / drought events are directly linked to climate change. Several studies have been conducted to study these aspects and it is have found that rise in temperature and decrease in rainfall will lead to soil moisture deficit, further reduction in recharge, and ultimately lead to recession in groundwater levels. However, the hydrological impacts of possible climate change for Indian region(s) / basin(s) have not been studied extensively.

It has been estimated that climate change will increase the demand of power generation capacity approximately by 1.5%. The increased energy consumption in a number of fields is predicted which includes need for cooling space for building, irrigation needs and groundwater pumping.

Various studies have shown that groundwater recharge and discharge conditions are function of precipitation climatic variables, landscape characteristics and human impacts. Therefore, projecting the recharge and discharge patterns are of great significance for future climate scenarios and address issues pertaining to integrated water resource development and management in the years to come.

Literature implies that most of the research studies have investigated the impact of climate change on water resources by coupling climate change scenario with hydrological models. Response of aquifers towards climate change has been researched by associating models of atmospheric processes with unsaturated soil and groundwater models. In these studies, the groundwater model is calibrated to different stresses of climate change and associated groundwater condition. Few of the recent studies on impact of climate change on groundwater resources in India are discussed below.

Ghosh Bobba (2002) analyzed the effects of human activities and sea-level changes on the spatial and temporal behavior of the coupled mechanism of salt-water and freshwater flow through the Godavari Delta of India. The density driven salt-water intrusion process was simulated with the use of a SUTRA (Saturated-Unsaturated TRAnsport) model. Physical parameters, initial heads, and boundary conditions of the delta were defined on the basis of available field data, and an areal, steady-state groundwater model was constructed to calibrate the observed head values corresponding to the initial development phase of the aquifer. Initial and boundary conditions determined from the areal calibration were used to evaluate steady-state, hydraulic heads. Consequently, the initial position of the hydraulic head distribution was calibrated under steady-state conditions. The changes of initial hydraulic distribution, under discharge and recharge conditions, were calculated, and the present-day position of the interface was predicted. The present-day distribution of hydraulic head was estimated via a 20-year simulation. The results indicate that a considerable advance in seawater intrusion can be expected in the coastal aquifer if current rates of groundwater exploitation continue and an important part of the freshwater from the river is channelled from the reservoir for irrigation, industrial and domestic purposes.

Mall et al. (2006) studied sustainable development of surface water and groundwater resources by taking into account climate change and future research needs in India. It was observed that Indian sub-continent is extremely perceptive to climate changes. It is projected that most irrigated areas in India would require more water around 2025 and global net irrigation requirements would increase relative to the situation without climate change by 3.5–5% by 2025, and 6–8% by 2075. In India, roughly 52% of irrigation consumption across the country is extracted from groundwater; therefore, it can be an alarming situation with decline in groundwater and increase in irrigation requirements due to climate change. This point towards need of a crucial research work on following objectives:

- Study phenomenon associated with climate variability and extreme events, its impact on water resources and subsurface water potential.
- Understand the variation of rainfall trend and its impact on run-off and aquifer recharge.
- Investigate the sea level rise due to deglaciation and enhanced rainfall.
- Sea-water intrusions into coastal aquifers.

- Estimating the extent of vulnerability of water resources to climate change; identify the key risks related to climate change on water resources and prioritize the adaptation measures.

According to the National Environmental Policy, it is pointed out that India's precipitation patterns, ecosystems, agricultural efficiency and natural resources are highly impacted by anthropogenically induced climate change. A comprehensive planning and suitable adaptation measures only can prevent the catastrophe of human induced climate change.

Shah (2009) reviewed the mitigation approaches and adaptation measures with regard to climate change and groundwater in India. From earlier times, India has been using surface storage and natural flow to irrigate the crops. However, there has been a sharp descent in the natural irrigation and a huge rise in irrigation through groundwater development by means of large number of small, private tube wells, in the past 40 years. Due to this reason, groundwater has witnessed significant decline in many areas of the country. Climate change may act as a amplifier for this phenomenon. It will multiply the threat to groundwater resource and also increase groundwater's utility for drought-regulated agriculture. Pumping of groundwater with electricity and fuel accounts for around 16–25 million metric tons of carbon emissions which is roughly 4 to 6% of national carbon emission. With a perspective of climate change, western and peninsular India are predicament regions with respect to groundwater. The western and peninsular regions of India, in particular, need to address climate change mitigation and adaptation strategies. In order to accomplish mitigation and adaptation, the country should concentrate on the aspect of subsurface storage (managed) rather than surface storage of water as the prominent water strategy with proactive management of supply-side and demand-side management, and should wisely learn from the experience of other countries (such as Australia, United States) which have good experience in management of aquifer recharge.

Singh(2012) studied the significance of climate change on dynamic groundwater in a drought-prone area viz., Sonar basin in the Bundelkhand region of Madhya Pradesh. The study addresses the generation of future rainfall and temperature, recharge estimation and groundwater simulation for proper management and augmentation of groundwater in the basin for future scenarios. Future rainfall was generated based on the SRES GCM projections for the South-Asia region for baseline, A1FI and B1 scenarios for the time-slice 2004-2039. The site-specific soil, vegetation and climate database needed for the VHELP model were generated and site-specific groundwater recharge was estimated at twelve locations in the basin. The groundwater simulation was done by the water balance method by dividing the whole basin into twelve zones. Finally, the quantification of the impact of climate change on the groundwater recharge and levels for the time-slice 2004-2039 was done. Historical rainfall and temperature show declining and increasing trend, respectively (1972-2003), as a result, future rainfall has a declining trend for the baseline, A1FI and B1 scenarios. As compared to the baseline scenario, the following changes have been obtained for the time-slice 2004-2039:

- change in temperature under A1FI and B1 scenarios is +1.27 and +1.22 °C, respectively.
- change in rainfall under A1FI and B1 scenarios is +3.0 and +4.4%, respectively.
- change in GW recharge under A1FI and B1 scenarios is +2.1 to +3.8% and +1.8 to +6.1%, respectively.
- change in GW levels under A1FI and B1 scenarios is +8.0 and +14%, respectively.

The additional quantity of water required to recharge groundwater in order to attain the sustainable groundwater levels is estimated to be 4.3%. This is approximately 0.6% of the average annual

precipitation in the area. The research may also serve as a decision support tool for exploring different scenarios of groundwater levels under varying recharge conditions and then assess the quantity of water required for artificial groundwater recharge to maintain the sustainability of groundwater. However, vast scope exists for refinement in the study with regards to various data and uncertainty associated with climate change.

Panda and Jena (2016) examined variation in groundwater recharge due to changes in climate and consequent adaptation strategies. The study region pertains to Eastern part of India, having a sub-tropical humid climate and sandy loam soil. Rainfall in the area is found to have wide temporal and spatial variation. Groundwater is being overexploited in this region due to deficit of surface water for meeting the irrigation and domestic demands. Excess groundwater withdrawal is leading to continuous depletion of groundwater levels in the region. Urgent actions are therefore needed to reverse the depleting groundwater levels. It may be via artificial recharge and will be significant under the climate change scenarios.

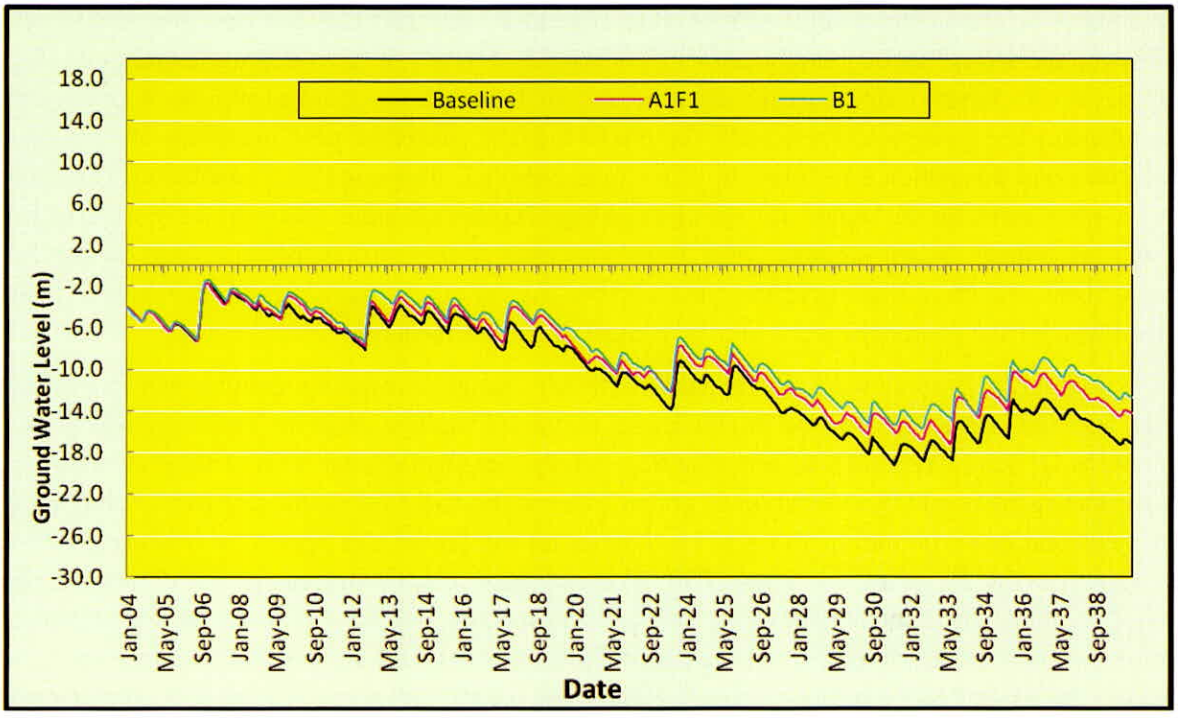


Figure 8.2: *Groundwater Level Variation in Response to Future Rainfall in Zone-1(Source: Singh, 2012)*

Groundwater recharge was modeled using HELP3 software (a quasi-two-dimensional, deterministic, water-routing model) along with global climate models (GCMs) and three global warming scenarios. Changes in groundwater recharge rates were examined for a 2030 climate with a variety of soil and vegetation covers. Sensitivity analysis was done to evaluate the relationship between changing mean annual recharge and mean annual rainfall for various combinations of soil and vegetation. The relationship was found to be statistically significant ($p<0.05$) with a coefficient of determination as 0.81. Vegetation dynamics and water-use affected by the increase in potential evapo-transpiration for large climate variability scenario led to a significant decrease in recharge from 49-658 mm to 18-179 mm respectively. It was suggested that under the climate variability and land use/land

cover change scenarios, appropriate conjunctive use, irrigation scheduling and enhanced recharge practices affecting the groundwater recharge need to be properly understood for sustainability of groundwater resource.

Asoka et al. (2017) used satellite data and local well measurements to characterize the regional patterns of change in groundwater storage and the relative contribution of groundwater pumping and monsoon rainfall in such changes. It was found that groundwater storage has declined in northern India at the rate of 2 cm per year and increased by 1 to 2 cm per year in southern India between 2002 and 2013. It was reported that variability in groundwater storage in north-central and southern India is due to rainfall and recharge variability. On the other hand, variability in groundwater storage in north-western India is mainly due to variability in pumping for irrigated agriculture due to changes in monsoon rainfall. It was suggested that climate-induced pumping is affected by variability in rainfall which is also coupled to warming patterns in the temperatures of sea surface over the Indian Ocean.

Bhanja et al. (2017) studied the measurement of groundwater levels in 3907 wells spread in 22 major river basins of India. It was aimed to assess the spatiotemporal variability of groundwater storage (GWS) anomalies. A dense monitoring network of 3907 observation wells was used to study the dependency of groundwater storage variability on both extent and spacing, the two components of the scale triplet. The results indicate that the mean GWS anomaly sampled at a 0.25-degree grid scale closes to unweighted average over all wells. The absolute error corresponding to each basin grows with increasing scale, i.e., from 0.25 degree to 1 degree. GWS anomalies (relative to the long-term mean) present strong seasonality, with annual maxima observed during the monsoon season and minima during pre-monsoon season. It implies that the spatial variability of GWS anomaly varies with climatic conditions. The study affirms that groundwater storage in most regions varies in strong synchronization due to the impact of monsoons. In India, the spatial variability in groundwater is more strongly affected by climate (such as annual rainfall) in comparison to other factors, such as natural groundwater discharge, etc.

Fishman (2018) concluded that an increase in intra-seasonal rainfall variability (independently of the effect of rising temperatures) will lead to a significant reduction in rice production in India by the year 2050. However, these projections do not take into account the adaptation possibility which includes the expansion of irrigation. Historical data on irrigation, rice yields, and rainfall indicate that irrigated locations experience much lower damages from increasing variability in rainfall. If physical water availability is also accounted, then sustainable use of irrigation water can mitigate less than a tenth of the climate change impact under current irrigation practices. Also, if India continues to deplete its groundwater, then the impacts of increased variability are likely to increase by half.

8.3 Concluding Remarks

- It is necessary to investigate the relationship between climate change and the loss of fresh groundwater resource in different regions. The impact of future climate change may be felt more severely in India because our economy is largely dependent upon agriculture. We are already under water stress condition due to the rise in population and the corresponding increase in demands for energy, fresh water, and food. Though there are uncertainties about the exact magnitude of climate change and its probable impacts, suitable measures need to be taken to prevent or minimize the causes of climate change and mitigate its adverse impacts.

- Problems in groundwater management in India have potentially huge implications due to global warming. The most optimistic assumption suggests that an average drop in groundwater level by one metre would increase India's total carbon emissions by over 1%, because the time of withdrawal of the same amount of water will increase fuel consumption (Mall et al., 2006).
- The studies addressing the impact of climate change on groundwater resources are still in infancy. More field data are required to be generated for getting reliable outcomes. It may help in proper validation of the simulation for the current scenarios. But it is certain that climate change is going to affect the future recharge rates and hence quantum of available groundwater resources. But the climate change impact may not necessarily be negative, as observed by a few investigations. However, quantifying the impact of climate change is difficult and also subject to uncertainties in future climate predictions. There have been mixed and conflicting results based upon general circulation models (GCMs) which raise doubts about their reliability in predicting the future hydrologic conditions. But the global warming threat is real and impacts of climate change phenomena may be many and disturbing.
- Comprehensive water management strategies should be adopted to integrate groundwater and surface water which will considerably reduce the human vulnerability to extremes changes in climate, and also facilitate water and food security.
- Though climate change has been declared unequivocal, the research studies to assess the impacts of climate change on groundwater resources are meager. Reason for this shortfall is that long historical data are required to analyze the characteristics of climate change which may not always be available. Even if the required data are available, there may be uncertainty in model parameters, and driving force of the hydrological cycle. Due to various limitations inherent in the models and unpredictability of various processes driving the hydrological cycle, predicting the long-term effect of a dynamic system is very difficult. Based on available data, the physically-based model of a groundwater system with possible climate change scenarios is essential in order to prevent the deterioration of regional water-resource issues in the future. In spite of the uncertainties in climate change, response strategies derived from the model simulation studies may be quite useful in water resource management.
- There is a need to intensify efforts for monitoring of groundwater abstractions and research on modeling techniques, aquifer characteristics, and recharge rates. It can provide a sound basis for assessing the impacts of climate change and sea-level rise on recharge and groundwater resources.
- From a climate change point of view, India's groundwater hotspots are western and peninsular India. These are critical for climate change mitigation as well as adaptation. To achieve both, India needs to make a transition from surface storage to 'managed aquifer storage' as the center pin of its water strategy with proactive demand- and supply-side management components (Shah, 2009).
- The Indo-Gangetic aquifer system has been getting heavy recharge from the Himalayan snow-melt. As snow-melt-based run-off increases during the coming decades, their contribution to potential recharge may increase; however, a great deal of this may end up as 'rejected recharge' and enhance river flows and intensify the flood proneness of eastern India and

Bangladesh. As the snow-melt-based run-off begins declining, one should expect a decline in run-off as well as groundwater recharge in this vast basin (Shah, 2009).

- In order to assess the probable impacts of future climate changes and socio-economic conditions on groundwater recharge, hydrogeologists must work in coordination with socio-economists, agriculturalists, and soil scientists etc.

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CHAPTER 9

IMPACT OF CLIMATE CHANGE ON WATER QUALITY

Rajesh Singh and Sumant Kumar

9.0 Introduction

The International Panel for Climate Change (IPCC, 2013) reported that the average global surface temperature has increased by 0.85^{0}C over the period of1880-2012 and 0.89^{0}C over the period of 1901-2012 based on independently produced dataset. Therefore, global warming is an indisputable fact. It is projected that by the end of 21st century, mean surface temperature for India will increase by 3.2^{0}C (Bal et al., 2016; Basha et al., 2017) under different representative concentration pathways (RCPs). As a result, various changes in climatic variables will occur on both global and local scales, including surface temperature, precipitation and other extreme hydrological events, such as droughts and floods (Joehnk et al., 2008; Jones et al., 2010). The impacts of climate change on water resources in context of quantity have been reported by many researchers, however, research related to its impact on the water quality is scarce but picking up steadily. The Fourth Assessment Report (AR4) of the IPCC summarized that the trends of climate change in the 20th century would have adverse effects on the water quality, but the report did not provide details on how climate change would exert these impacts on the water quality (Rosenzweig et al., 2007). Climate change can alter the water quality and even the aquatic ecosystems directly or indirectly through various biochemical processes (Dalla et al., 2007; Delpla et al., 2009). Furthermore, the specific effects will vary among different regions and types of water bodies (Whitehead et al., 2009). The knowledge of the different hydrodynamics and biochemical processes that occur in different waters is the key to understand the relationship between climate change and water quality in different water bodies (Mooij et al., 2005; Delpla et al., 2009; Mooij et al., 2009). This chapter provides a review on impacts of climate change on the water quality parameters along with effect on water bodies and illustrated methods for quantification of climate change effects.

9.1 Effect of climate change on water quality parameters

Water quality of surface as well as groundwater is influenced by the surrounding temperature and the precipitation pattern. Change in precipitation pattern affects the runoff which influences the transport of nutrients and other pollutants. Effect of climate change on some of the water quality parameters are briefly described below:

9.1.1 Temperature

The increase in the temperature as a part of climate change will affect the water quality in several ways. Increase in temperature will enhance the chemical weathering. Several researchers have concluded that increase in temperature will result in the increase in the solute concentration by approximately an order of magnitude over a temperature range of 5 -35 °C (White et al., 1999). White and Blum (1995) observed positive correlation between the average flux of solute, precipitation, and temperature based on the following expression-

$$Q_{i,w} = (a_i . P)\exp\left[\frac{E_a}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \qquad (9.1)$$

Where $Q_{i,w}$ = average flux of the solute (mol/ha/yr)

P	=	average annual precipitation (mm/yr)
a_i	=	fitted precipitation dependence
Ea	=	Activation energy (KJ/mol)
R	=	Molar gas constant (KJ/mol/deg K)
T	=	Watershed temperature
T0	=	Reference temperature (Mean annual temperature)

The self-cleansing property of streams is dependent on the aquatic biota and dissolved oxygen concentration. The micro-organisms present in the streams utilize oxygen for oxidation of carbon received by the water body. Although increase in temperature will increase the efficiency of the microbes, however, it will result in lower dissolved oxygen concentration and in turn lower assimilative capacity. Increase in water temperature by 3 0C will results in 10% decrease in the saturated DO concentration (Delpla et al., 2009). Change in the dissolve oxygen concentration will also affect the fish behaviour and survival.

As far as groundwater is concerned, the contaminants are removed through filtration and microbial degradation. The microbial activity is closely related to the sediment temperature and humidity and increase in microbial activity and the process rates can be expected with increase in temperature of the sediment or clay (Van Dijk et al., 2009). Therefore, the increase in temperature will result in the reduced concentration of pollutants in the groundwater. However, reverse is expected w.r.t. the contaminants. The increase in temperature will enhance the chemical as well as microbial induced weathering and dissolution of minerals which, in turn, will lead to higher dissolved solids and geogenic contaminants. The effect of temperature on lakes and reservoirs are described in a subsection.

9.1.2 pH

The pH of any system describe its acidic or basic nature and is directly proportional to the hydrogen ion concentration. The pH of surface water resources is buffered by the CO_2. When CO_2 is dissolved in the water, it is converted into carbonic acid, bicarbonate, and carbonate. Higher the concentration of CO_2, lower will be the pH. The CO_2 concertation in the surface water depends on the difference in the partial pressure of CO_2 (PCO_2) of the surface water and atmosphere, therefore, if the concentration of CO_2 in the atmosphere increases, the pH of the water resources will reduce (Palmer & Pearson, 2003). IPCC (2007) has recorded a decrease in pH, 0.1 unit over 100 years, due to the gradual increase in the levels of CO_2 in the atmosphere. In case of fresh water resources, the pH is also impacted by the microbial mineralization of organics released from the ecosystem as well as anthropogenic activities. Due to increase in the temperature as a result of climate change, the dissolved oxygen concentration in the streams, lakes, and reservoirs will decrease leading to anoxic conditions and release of organic acids as well as hydrogen sulphide. Hydrogen sulphide will get hydrolysed to sulfuric acid and along with organic acids reduce the pH of water bodies which in turn enhance the chemical weathering of bed sediments resulting in high dissolved solids.

It is also expected that high nutrient load and carbon in the anoxic condition will promote algal blooms resulting in increase in CO_2 uptake by the aquatic plants. Uptake of CO_2 by the plants results in decrease in carbonic acid concentration and hence, increase in pH. However, over the period of time

when the concentration of nutrients and organics reduces, the aquatic plants tend to die and sink to the bottom of the water body where microbes start decomposing it due to which the pH decreases (Cao et al., 2011; Liu et al., 2016).

9.1.3 Water Transparency

Transparency of water bodies is affected by the suspended inorganic and organic particulates namely planktons, organics, silt, etc. The climate change will result in intense rainfall, which in turn will lead to increased erosion and transport of nutrients and input of humic substances. Increase in nutrients in the water bodies will result in algal growth reducing the passage of light through the water column. Pilla et al. (2018) observed that the transparency of lakes reduced substantially due to the dissolved organic matter and color because of increased precipitation and recovery from anthropogenic acidification.

9.1.4 Dissolved Oxygen (DO)

The solubility of oxygen in water depends on temperature, pressure, and salinity. Apart from these, it also depends on photosynthesis, respiration, and decomposition. The increase in temperature due to climate change will decrease the solubility of oxygen. It will also lead to enhanced chemical weathering, increasing salinity and will increase the rate of biological activity, both resulting in lower dissolved oxygen. Cox and Whitehead (2009) assessed the impact of climate change on dissolved oxygen of Thames River and concluded that the DO will reduce upto 1.6 mg O_2/l.

9.1.5 Nutrients Concentration

Nutrient loads in the water resources may increase due to increase in runoff and soil erosion along with increase in mineralisation. The increased microbial activities will also add on the releases of nitrogen, phosphorus andcarbon from soil organic matter. In addition, internal nutrient loading may increase with rise in temperature in case of lakes and reservoirs. However, several researchers have modelled the impact of climate change on nutrient load and they found the impacts minimal (Chang et al., 2001; Bouraoui et al., 2002; Jeppesen et al., 2009; Cousino et al., 2015; Robertson et al., 2016).

9.1.6 Pathogenic Microbes

Pathogenic microbes may increase in number due to sewage overflows during heavy rain events combined with higher water temperatures. High intensity rainfall may also wash the pathogens from pastureland, a potential store of pathogens, and discharge in the water bodies (Oliver et al., 2005). Storm events may contribute to higher orders of magnitude increases in pathogen loading in watersheds (Ashboldt et al., 2002). Ley et al. (2016) observed a positive correlation between water borne diseases and temperature, heavy rainfall, flooding, and drought that are expected to increase with the climate change; however, the trend was negative between ambient temperature and viral diarrhoea.

9.1.7 DOC Concentration

The concentrations and fluxes of dissolved organic carbon(DOC) are affected by climatic factors. In recent years, many researchers observed an increasing trend in DOC concentrations but there has been extensive debate on the main drivers including the role of climate for the increased concentration trends (Freeman et al., 2004; Monteith et al., 2007). The enhanced microbial activity due to increase in temperature may results in increased sediment respiration of organic material, which in turn results in the increased concentrations of DOC in soils. The DOC from the soils will be washed away to surface waters by the intense precipitation (Huntington et al., 2016).

9.1.8 Hazardous Substances

The research related to influence of climate change on concentration of hazardous substances in water resources is very limited (Barth et al., 2009). The hazardous substances in water can be inorganic or organic in nature. The inorganic substances are metals, which generally bind strongly to soil/sediment particles, and are thus likely to be affected by change in hydrology. Regarding organic contaminants like pesticides, herbicides, pharmaceutically active hydrocarbons etc., the microbial degradation in the soil or environment will be enhanced resulting in speedy removal from the environment. Climate change is likely to change cropping patterns and thus will affect the use of pesticides to a large extent (Bloomfield et al., 2006).

9.2 Effects of Climate Change on Different Water Bodies

9.2.1 Lakes and Reservoirs

Most of the studies related to the impacts of climate change on lakes and reservoirs have been reported on nutrient release, the growth of aquatic plants, eutrophication and salinization. The increase in the water temperature may enlarge the thermal stratification period and deepen the thermocline and further change the hydrodynamics of the water system of deep lakes and reservoirs (Jackson et al., 2007; Brooks et al., 2011). The thermal stratification refers to variation of temperature with depth of lake (Fig. 9.1) and due to which mixing of surface water with bottom gets affected. It has been observed that the stratified period has been increased by up to 20 days in some lakes of Europe and Northern America (Rosenzweig et al., 2007; Delpla et al., 2009). Recent studies showed that mixing of surface water and bottom water has been delayed due to thermal stratification and this effect has led to a decrease in the dissolved oxygen concentration and excessive carbon dioxide, which results in the easy formation of a reductive environment in the bottom water. In addition, some scientists (Han et al., 2009; Wang et al., 2008; Gantzer et al., 2009) has observed the release of nutrients and other pollutants from the sediments due to bottom water hypoxia. A recent study on the Shimajigawa reservoir located in western Japan indicated that, the anaerobic layer would increase by 6.6 m in 2091 ~ 2100 under the A2 scenario (period of 1991 to 2001 was considered base period) and would release phosphorus from sediments, which will lead to an increase in the PO_4 concentration from 1.7 to 5.6 µg/L in the surface water and chlorophyll a concentration would increase from 7.8 to 16.5 µg/L (Komastu et al., 2007).

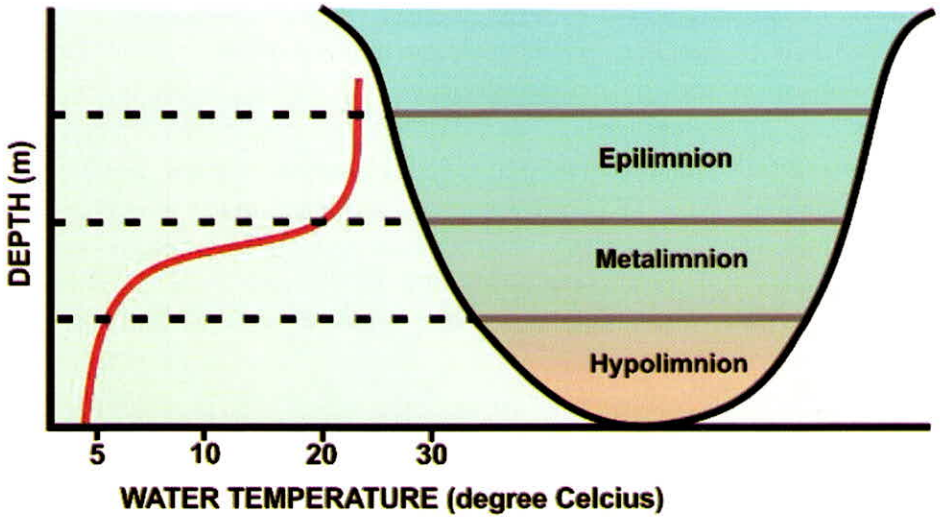


Fig. 9.1: *Typical schematic diagram of thermal stratification of Lake*

Aquatic plants are primary producers and therefore, significant in maintaining ecological system of water bodies (Søndergaard et al., 2011). Some studies have been carried out and it is reported that climate change would enable the growth of phytoplankton in water environments. The increase in the growth of phytoplankton would weaken the light intensity in bottom water and further reduce the species and the amounts of submerged macrophytes. Trolle et al. (2011) studied the effect of climate change by year 2100 on trophic status of lake Rotoehu in New Zealand by applying 1- dimensional lake ecosystem model under the IPCC A2 scenario. The simulation results revealed that cyanophytes would be more abundant in the future climate and their contribution towards chlorophyll-a would be increased by 15%.

Zhang et al. (2012) simulated the impacts of climate change on the non-point source pollutant loads in the Shitoukou reservoir catchment, China. The results indicated that the annual NH_4-N load was significantly decreased at a rate of 40.6 t per decade under the A2 scenario into the reservoir. Nõges et al. (2011) reported that nutrient loadings in the lakes which contribute to eutrophication was increased due to an increase in the winter precipitation of the Ticino river basin of southern Europe.

Mineralization and salinization are considered as other impacts of climate change on lake water quality, and these impacts may affect aquatic ecosystems. Generally, increase in temperature and decrease in rainfall affect the mineralization and salinization of lakes. Liu et al. (2004) reported that increase in the temperature and a decrease in the runoff have been the major reasons for the mineralization of lakes since the early 1960s for the Hei River Basin. Bonte and Zwolsman (2010) simulated the salinization processes in Flevoland Lake and Ijsselmeer Lake in the Netherlands by 2050 using climate and water quality models under two climate change scenarios, i.e., temperature increase of 1 and 2 °C. The results revealed that a temperature increase of 2°C along with a change in the atmosphere circulation pattern would increase the chloride contents in Ijsselmeer Lake by 108 mg/L.

9.2.2 Rivers

The impact of climate change on rivers have been mostly emphasized on nutrient and sediment loads and its transport (Wilby, 2006; Lee et al., 2010; Wilson and Weng, 2011). Martínková et al. (2011) used SWIM (Soil and Water Integrated Model) model to simulate changes in the nitrate load from the Jizera catchment, Czech Republic under the A1B scenario by taking into account point sources and agricultural diffuse sources. The nitrate loads for most of the period were positively correlated with precipitation and water discharge. In another study carried out by Arheimer et al. (2005) for Leonard River system in Southern Sweden to simulate changes in the nutrient loads and algae growth using ecological and water quality models under A2 and B2 scenarios. They concluded that total phosphorus increase by 50%, total nitrogen increase by 20%, and cyanobacteria increase by 80% with increase in the temperature. Prathumratana et al. (2008) studied the correlations between ions content and precipitation and found a negative correlation between them in the Mekong River during the period of 1985 to 2004. Wu et al., (2014) studied the relationship between the river runoff and the major ion concentrations of the Yellow river, China during the period of 1960 to 2000. Three hydrological stations were selected in the Yellow river basin as the study area; namely Lanzhou Station, the Huayuankou Station, and the Lijin Station, which are located in the upper, middle, and lower reaches of the river, respectively. Monthly water quality and quantity data from 1960 to 2000 were retrieved from the Yellow River Conservancy Commission (YRCC). The M-K tests were performed based on monthly quantity and quality data (from 1960 to 2000). The results indicated that concentrations of total ions, Ca^{2+} and Mg^{2+} showed increasing trends from 1960 to 2000. There may be two probable

reasons for the increase in the major ion concentrations in the Yellow River. One reason could be increase in temperature due to climate changes which may enhances rock weathering, which leads to higher major ion concentration in the river water. The other reason may be that the decreasing river runoff abating its dilution effect in the major ions in the river water.

The precipitation changes due to climate change play a key role in influencing the water quality of rivers. The precipitation intensity governs the soil erosion and transport of many pollutants from soil and ground surface which results into non-point source pollution. Furthermore, the precipitation will also affect the river runoff and thus influence the water self-purification capacity. Very few studies are available for investigating the impact of floods on the water quality due to non-availability of water quality data. Hrdinka et al. (2012) reported the impacts of the flood occurred in 2006 and the drought observed in year 2003 on the water quality at the Bechyně, Lužnice River and Varvažov, Skalice River stations in central Bohemia, Czech Republic. Their results revealed that both the extreme events i.e., flood and drought significantly affected the water quality as compared with the reference conditions and it is also reported that the flood event had significantly greater impact on the water quality than the drought. The concentrations of metals, organic compounds, fecal coliform, and nitrates were observed to increase by 1,760, 1,410, 146, and 121%, respectively during the flood. The soil erosion due to floods events introduces a large number of nutrients, pathogens, and toxins into water environment ecosystems directly or indirectly through various biochemical processes (Dalla et al., 2007; Delpla et al., 2009). The relationship between climate change and water quality of different water bodies depends on different hydrodynamics and biochemical processes that occur (Mooij et al., 2009).

Some studies have also been reported the impacts of droughts on the water quality (Evans et al., 2005; Monteith et al., 2007), which mainly include nitrogen mineralization acidification and increased pollutant concentration. It is obvious that flow is less or no flow during drought period, the lower flow affects the dilution factor (Elsdon et al., 2009), and that is why the concentration of pollutants increases during drought periods. Van Vliet et al. (2008) studied the impact of droughts on the water quality of Meuse River in Western Europe and the results showed that the concentrations of chlorophyll-a increased by 72.8% in 1976 and by 167% in 2003 compared with reference years, due to decreases in the dilution effect.

9.2.3 Seas

The sea is the largest water system environment and contains the richest biodiversity and greatest productivity. Studies on the impacts of climate changes on the seawater quality have mainly focused on marine biodiversity, ocean acidification, and salinity changes. Several studies have reported that climate change can influence marine pelagic species by affecting their life period and biodiversity (Cheung et al., 2009; Hicks et al., 2011). Edwards and Richardson (2004) quantitatively analysed long-term data of 66 different types of phytoplankton and investigated the effect of climate warming on the ecological community, and found an increase of 0.9 °C in the summer sea surface temperature from 1958 to 2002. Cheung et al. (2009) simulated the global patterns of a sample of 1,066 exploited marine fish and invertebrates in 2050 under the SRES A1B scenario using a dynamic bioclimate envelope model and demonstrated that climate change may result in the extinction of numerous local species in the sub-polar region and an intense species invasion in the Arctic Ocean. The research results established that marine species might be a sensitive indicator for the analysis of the effect of climate change on oceans. Some researchers (Barry, 2010) have studied the acidification of the oceans due to

increased level of CO_2. Some studies (Ferrari et al., 2011; Galaz et al., 2011) have shown that an increase in the carbon dioxide in the surface water would reduce the pH by 0.14 ~ 0.35 units by 2100 and changes the seawater chemistry process (Carere et al., 2011). Salinity changes due climate change also affect the seawater quality. Helm et al. (2010) studied the effect of a salinity change on the ocean density from 1970 to 2005 using global datasets of in situ observations. They found a global pattern in which the ocean salinity increased near the upper- ocean salinity-maximum layer (average depth of ~100 m) and decreased near the intermediate salinity minimum (average depth of ~700 m).

9.3 Methods for the Quantification of the Impacts of Climate Change on Water Quality

The Global Circulation Model (GCM) or Regional Circulation Models (RCM) are integrated with water quality and ecological models to study of the impacts of climate change on the water quality and the ecosystem. The integrated models can be divided into two types: one type is used for analysis of impact of climate change on the pollutant sources in water bodies and other type is used to study migration and transformation of pollutants into water environment. Marshall and Randhir (2008) used the simulated output of precipitation and temperature from GCM as input to SWAT model for prediction of non-point source pollution in the Connecticut River Watershed of New England. Komatsu et al. (2007) used water quality and ecological models to predict the concentrations of nitrogen, phosphorus, biomass, and iron in the surface water of a reservoir from the output data of the GCM under the A2 scenario.

It has been reported that all the model predictions are uncertain to some degree. Therefore, future research may be on the characterization and reduction of the uncertainty. The long-term field monitoring of bio indicators, such as phytoplankton and zooplankton in water bodies will be required to evidence of the impacts of climate change on water quality. For example, Fischer et al. (2011) used Daphnia as a bio indicator to examine its responses to changing temperature in alpine lakes.

In addition, anthropogenic activities, and/or other factors is a key process to be identified for studying the impacts of climate change on the water quality. In general, human activities include pollution discharge, land use, construction, and water abstraction from the surface water and groundwater. In recent years, regression analyses have been the most common approach used to quantify the impacts of climate change and anthropogenic behaviors on the water quality (Veríssimo et al., 2013). Özkan et al. (2012) studied the impact of different activities such as lake morphology, land use, and climate on the phytoplankton richness in 195 Danish lakes and ponds using the ordinary least squares (OLS) multiple regressions method. The results indicated that the water chemistry and the lake morphology had a strong influence on the phytoplankton richness as compared to the climate and land use.

9.4 Case Studies from India

Rehana and Majumdar (2011) examined the impact of change in climate variable on water quality parameter using hypothetical scenarios to represent both greenhouse warming and streamflow changes for the study region Tunga-Bhadra River in India. Water quality scenarios were generated by using QUAL2K model. The authors concluded that low flows will decrease and water temperature will increase resulting in reduction in DO levels and increase in BOD levels.

Rehana and Majumdar (2012) further quantified the future expected risk with a water quality by integrating climate change projections with a river water quality management model. They carried out Canonical Correlation Analysis (CCA) to develop the future scenarios of hydro-climate variables

starting with simulations provided by a GCM and quantified the risk of Low Water Quality (LWQ) corresponding to a threshold quality level by using a Multiple Logistic Regression (MLR) by considering the streamflow and water temperature as explanatory variables. They applied the MIROC 3.2 GCM with A1B scenario to the case study of the Tunga–BhadraRiver and observed a decreasing trend in future streamflow for tributaries of Tunga, Bhadra, Kumudavathi, and Haridra. In addition, the air temperature was observed to be in increasing trend with minor change in relative humidity and wind speed. They found the maximum daily temperature in Tunga–Bhadra river basin with HADCM3 GCM underA2 scenario is increasing by 1, 2.1 and 3.4 °C in the 2020s, 2050s and 2080srespectively. They simulated Steady state DO levels for the present and for the future time slices of 2010–2040, 2040–2070 and 2070–2100 using QUAL2 K and observed decrease in DO levels and suggested these results due to the reduced dilution capacity and low water velocities derived from the reduced stream flows and also due to the changes in reaction rates derived from the increase in water temperature. Future estimates show the DO levels may go up to 3.56 mg/l for the same current conditions of effluent discharge and river geometry.

Walling et al. (2014) carried out impact of climate change and change in drain flow scenarios on water quality of Yamuna River. The study area covers the river Yamuna stretch between Wazirabad barrage and Okhla barrage (21.9 km segment of River) in Delhi. No perennial drains are joining in this stretch except partly treated and untreated wastewater effluents from Delhi. They developed hypothetical scenarios in terms of air temperature and drain flow to study the impact of this scenario on water quality. Firstly, a relationship between air temperature and water temperature was developed based on time series data and then it was used to obtain water temperature for the projected air temperature. QUAL2K model was applied to simulate water quality parameters DO and BOD concentration for different hypothetical scenarios. The results revealed that the effect of climate change in terms of change in air temperature on water quality was very minimal. However, change in drain flow proves to be more sensitive on water quality. It was observed that BOD was susceptible to drain flow fluctuations whereas DO was more prone to climate change.

Whitehead et al. (2015) investigated the potential impacts of future climate change and socio-economic changes on the flow and nitrogen flux of the Ganga river system. The hydrology and water quality of Ganga river basin was simulated using INCA model considering climate change at 25 km resolution. The available data of flow rates and water quality including data at Hardinge Bridge in Bangladesh have been used for model calibration and validation. All climate apprehensions utilized in the study predicted increases in temperature and rainfall by the 2050s with significant increase by the 2090s. These changes generate associated increases in monsoon flows and hence decreased concentrations of nitrate and ammonia are expected due to increase in dilution. It is reported that different future socio-economic scenarios found to have a substantial impact on water quality at the downstream end of the Ganga. The deterioration of water quality may be due to higher population growth, land use change, increased sewage treatment discharges, and higher atmospheric nitrogen deposition etc.

Pathak et al. (2017) analysed water quality characteristics of Ramganga basin using long-term (1991-2009) monthly data by applying INCA-N & INCA-P. The model results were assessed based on Nash-Sutcliffe efficiency (NSE) and percentage bias (PBIAS) statistics. The model was successfully calibrated with r^2 ranging between 0.6-0.8 and was able to capture the trend of nutrient concentration with $r^2>0.5$ and PBIAS within ±17% for the monthly average. High concentrations were detected in the

low flows period and around 50% of the nutrient load was transported by the monsoonal flows. The authors concluded that the increasing trend in nutrient loading would be a threat to the ecological balance and eutrophication risk in the river. The degraded quality of water will also adversely affect the human health.

Jin et al. (2015) investigated the potential changes on the flow and water quality of the Ganga river system using a multi-branch version of INCA Phosphorus (INCA-P) model to simulate discharge and P concentrations at 70points in the Ganga river network. The daily precipitation and temperature data are obtained from output of the Met Office Hadley Centre Regional Climate Model (RCM) HadRM3P for the period from 1971 to 2099. Hydrologically effective rainfall and soil moisture deficits were generated using PERSiST model, which is a conceptual, daily time-step, semi-distributed model designed primarily for use with the INCA models. They used these models to quantify the impacts from a changing climate, population growth, additional agricultural land, pollution control and water transfers for the time slice 2041–2060 and 2080–2099. From the result, they concluded that flows are controlled by the monsoon and present day P concentrations are related to land use and sewage inputsand thus it provides a valuable information about potential effects of different management strategies on catchment water quality.

Jin et al. (2018) used an integrated catchment model (INCA-N) to evaluate flow dynamics and water quality (Nitrogen and Phosphorus), nutrient transport along the river and discharge into delta system and to analyze the impact of climate change and socio-economic drovers in the Mahanadi river system. Model tell us about the increase in monsoon flow at 2050s (2041-2060) and 2090s (2079-2098) which enhance the flood potential. Nitrogen and Phosphorus decreased in concentrations due to increased flow because of dilution. NO_3-N and NH_4-N concentrations were minimum in the summer (April-June) when temperature is highest and the concentrations were predicted higher for high flow months due to the quick flush of nitrogen stored in the soil zone. Increased temperature and longer residence time in the low flow conditions enhance stronger denitrification and nitrification processes resulting in nitrogen loss and lower NO_3-N and NH_4-N concentration. NO_3-N level varies from 0.2 to 0.3 mg/l and NH_4-N concentration less than 0.1mg/l. Reverse trend was observed for the TP concentration. Overall, the authors concluded that the water quality of Mahanadi River is affected by the climate change as a result of increase in rainfall leading to increased flows and hence enhanced dilution of the pollutants.

Whitehead et al. (2018) evaluated the future changes in both climate and socio-economics in Ganga-Brahmaputra –Meghna river system. The land use data 1 km grid resolution DTM with land cover data generated from MODIS satellite and direct discharge of effluent were included into INCA model. INCA-N software requires a daily time series data of precipitation, HER, temperature and soil moisture deficit to get the information about future hydrological conditions. Three SSP scenario is selected to medium economic growth(SSP2), medium plus with some higher economic growth(SSP5), and medium growth minus with a lower economic growth(~SSP3), all upto 2050s. The output of the model suggests an increase in flow under future climate change during monsoon period. The projected changes will affect nutrients being diluted under high flow scenarios but P concentrations will increase in low flow scenarios. The model suggests more frequent drought durations which will lead to higher nutrient concentrations. The authors also studied the socio-economic scenarios and concluded that the impact will be minimal on flows, however, it will impact the nutrient balance with increasing nutrient concentrations under the medium minus scenario.

9.5 Concluding Remarks

Global climate change has many possible impacts on the biogeochemical processes that occur in different types of water environments. The major impacts may be (i) enhanced eutrophication, salinization, and nutrients release, (ii) reduced pH and dissolved oxygen in the water bodies, (iii) increase in the influx of pollutants into the water bodies due to more frequent extreme storm events, (iv) increase in waterborne diseases due to upsurge of pathogens, and (iv) alteration in the aquatic biodiversity composition. However, there are disagreements among researchers regarding the impacts of climate change on the water quality of different water bodies. The changes in water quality are regulated by various factors and most of the studies focussed on some of the factors to determine the effect of climate change on water quality by assuming other factors remains unchanged. Some of the investigators have reported that the climate change in combination with anthropogenic activities will affect the water quality of different aquatic systems. To quantify the impacts of climate change on water quality, the long-term field monitoring of water quality data is required, in addition to that, it is important to improve the methods used to identify the effects of climate change from other confounding factors, such as pollution and land use changes. The available models for understanding the impact of climate change on water quality issues lacks to project the overall scenario, and hence, the development of holistic ecosystem model is the need of the hour to analyse both the sources and the transformation processes of pollutants in water bodies. Measures for adaptation to climate change should be considered in order to fill the gap of supply and demand of water.

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CHAPTER 10

IMPACT OF CLIMATE CHANGE ON FLOODS

Rakesh Kumar, P.C. Nayak, J.P. Patra and Pankaj Mani

10.0 Introduction

India is one of the most flood vulnerable regions in the South Asia. Floods occur often in the region triggered by heavy monsoon precipitation and can cause enormous damages to lives, property, crops and infrastructure. The frequency of extreme floods is on the rise in India. Past extreme floods fall within the range of climate variability but frequency, magnitude and extent of flooding may increase in future due to climate change. From a hydro-meteorological perspective, India is a very important region and encompasses many large river systems: Ganges, Brahmaputra, Indus, Krishna, Godavari, Mahanadi and Narmada. Increases in future flooding can cause extensive damage to rice crops in the monsoon season. This may have implications for food security and hardships especially of poor women and children. Floods can devastate the people living near the flood plains of the rivers causing loss of lives and property. Flooding in coastal cities as witnessed during the Chennai floods of 2015 and Kerala floods of 2018 can be a nightmare for the water managers and district officials. Floods can also impact public health in the flood plains and in the coastal areas.

Floods are likely to be affected by climate change in many ways with changes in temperature, precipitation, river flows and sea levels. These changes would lead to flooding of cities, transport networks, drainage systems, irrigation systems, water supplies as well as public and private installations. The effects of climate change on floods may influence flood risk reduction priorities and may lead to increased flood hazard at many flood prone locations. As per the National Disaster Management Authority, more than 40 million hectares of area in India is prone to floods out of its total area of 329 million hectares. As per the Central Water Commission, about 1,07,487 people died due to heavy rains and floods across India over the last 64 years from 1953 to 2017. Also, there has been damages to crops, houses and public utilities resulting in losses to the exchequer to the extent of about Rs. 365,860 crores. Some of the recent striking examples of extreme floods are the floods faced in Kerala (2018), Chennai (2015), Jammu and Kashmir (2014), Kedarnath (2013), Leh (2010), and Mumbai (2005) are a very few of the regularly increasing flood events in India.

Total economic losses from flood disaster in the southern state of Kerala in 2018 have been tentatively estimated at upwards of Rupees 300 billion and claimed about 483 lives. The predicted rains from August 9 to 15 were 98.5 mm but the state received a rainfall of 352.2 mm. Rainfall of 944 mm occurred in Mumbai on 26th July, 2005, which resulted in the death of more than 500 people. Between 8th November and 4th December in 2015, a series of five extreme precipitation events occurred in Chennai. Heavy rainfall occurred in the Chennai city on 17th November 2015. The recorded rainfall in Chennai was 1,049 mm in November, the highest recorded since November 1918 when 1,088 mm of rainfall was recorded. During 16 to 17 June 2013 the Kedarnath region in Uttarakhand faced a natural disaster along with very heavy rainfall and the resulting flash floods caused the devastating natural disaster. The rainfall of 120 mm within a span of 24 hours caused the flash flood at Kedarnath. The disaster was due to a combined effect of very intense rainfall, outburst of a Chorabari lake and very steep topographic conditions. The Leh region of Ladakh received very heavy rainfall during the

midnight of 6th August in the year 2010 and it resulted in very heavy loss to property. The State of Jammu and Kashmir, experienced heavy monsoon rains that began on 2nd September 2014 and led to unprecedented widespread flooding across the state.

The factors which result in floods are rainfall of very high intensity in a very short time period, poor drainage system, unmanaged reservoir regulation and failure of hydraulic structures. This may further result due to several other causes which may include increase in population, rapid urbanization, increasing developmental activities in the flood plains as well as global warming. The general causes of occurrence of floods in our country are: intense precipitation; cyclones; urban flooding; low flow carrying capacity within river banks for containing the high flood flows as well as silting of the river beds; landslides resulting in impediment of flow and meandering of the river water way; drainage congestion; heavy rainfall and flash floods; dam break flood; river bank and river bed erosion; sediment transport by rivers; floods in coastal areas; reduced velocity of flow due to tidal well as backwater effects and glacier lake outburst flood (GLOF) etc.

Climate change will exacerbate flooding problems over India as the temperatures are increasing over South Asia region, and are projected to continue to increase for the next several decades under all plausible climate scenarios, based on the World Bank study, 2018 (https://openknowledge.worldbank.org/handle/10986/28723). These changes in climate would lead to more frequent flooding, increase in demand for water and rise in the medical issues. According to government data that lend perspective to a new World Bank study that says climate change will lower the standards of living of nearly half of India's population by 2050. India has increased frequency of downpours as well as the gaps between rainy days during the monsoon (IndiaSpend, January 2018, http://archive.indiaspend.com/cover-story/indian-summers-could-last-8-months-by-2070-if-global-warming-continues-85534). As India's climate warms, extreme weather, such as intense rain and floods, are predicted to worsen (http://archive.indiaspend.com/cover-story/new-data-predicts-fiercer-floods-in-brahmaputra-indus-65170).

Ministry of Water Resources, River Development and Ganga Rejuvenation (MoWR, RD & GR), Government of India has launched National Water Mission (NWM) as part of National Action Plan on Climate Change (NAPCC) with the main objective of "conservation of water, minimizing wastage and ensuring its more equitable distribution both across and within states through integrated water resources development and management".

Climate change may alter the distribution and quality of India's natural resources and adversely affect the livelihood of its people. With an economy closely tied to its natural resource base and climate-sensitive sectors such as agriculture, water and forestry, India may face a major threat because of the projected changes in climate. The global warming may affect the hydrological cycle which could result in further intensification of temporal and spatial variations in precipitation, snow melt and water availability. Some of the impacts of climate change on water resources may be: (i) decrease in the glaciers and the snowfields in the Himalayan region; (ii) increased in droughts due to decrease in the number of rainy days; (iii) increased in floods; (iv) effect on groundwater quality in alluvial aquifers due to increased flood and drought events; (v) effect on groundwater recharge due to variations in rainfall and evapotranspiration; and (vi) rise in saline intrusion of coastal and island aquifers due to rising sea levels etc.

It is evident from above that due to possible impact of climate change on water resources, the most affected areas in India would be (i) drought affected areas, (ii) areas prone to floods, (iii) coastal regions, (iv) areas getting low rainfall, (v) areas with over-exploited, semi-critical, critical conditions of groundwater development, (v) areas having poor water quality and (vi) snow-fed river regions. The impact of climate change of floods and the way forward to develop suitable adaptation strategies are described in the following.

10.1 Literature Review on Floods under Climatic Change

India has experienced several devastating climate extremes during recent decades. About 13.78% of India's geographical area is subjected to flood disasters (Planning Commission 2011), and about 33 million people were affected by flooding from 1953 to 2000 (Kumar et al. 2005). Mumbai, India's financial capital, received a record 944 mm rainfall on July 26, 2005, causing havoc and several casualties (Kumar et al. 2008).

Impact of climate change on floods in India has been reported in many studies. Gosain et al. (2006 and 2011) modelled 12 river basins of India by using the SWAT model for control or present and GHG (greenhouse gases) or future climate scenario of simulated weather data of HadRM2. They reported that Godavari, Brahamani and Mahanadi may not have water shortage but predicted severe flood conditions. A few sub-basins of the Ganga, Brahmaputra, Krishna, Cauvery and Pennar show some decrease in the peak flow magnitudes. World Bank (2008) suggested that the probability of flood frequency and its intensity could increase dramatically in Mahanadi basin. The hydrological model projected daily outflow discharges at a gauge station (located in Naraj northwest of Jagatsinghpur and Pun) and results showed that under different scenarios, the probability of flooding will increase substantially. An increase of stream flow during 1956–2007 in the number of particular flood occurrences in Bahadurabad in the Brahmaputra River has been recorded (Climate Change Cell 2009). Dadhwal et al. (2010) reported an increase by 4.53% in the annual stream flow at the Mundali outlet in the Mahanadi basin attributed to a reduction in forest cover by 5.71% for the period 1972–2003.

Mujumdar (2011) presented the flow duration curves projected for the Mahanadi river in East-Central India, using several GCMs. The flow duration curves specify the flow that may be exceeded at a given level of probability, and are used in hydrologic designs of dams, culverts, bridges, and stormwater drainage networks etc. The mid-level flows (flows that are exceeded 40–70 per cent of the time) govern the performance of the system in terms of the water supply for irrigation and hydropower generation and with many projections indicating a likely decrease in the mid-level flows. In peninsular India, Panda et al., 2013 reported that the streamflow at the Tikerpara gauging site of the Mahanadi River basin declined at a rate of 3,388 million cubic meters per decade for the period of 1972–2007. Some of this reduction is attributed to increased upstream usage. For the Ganges-Brahmaputra-Meghna (GBM) basin, the long-term mean runoff is projected to increase by 33.1, 16.2, and 39.7% in the Ganges, Brahmaputra, and Meghna basins, respectively (Masood et al. 2015), by the end of the 21st century.

Mishra and Lilhare (2016) reported that under the RCP 4.5, out of 18 only 4 river basins (Ganges, Brahmaputra, Narmada, and South Coast) are projected to experience significant increase in streamflow during the monsoon season. In the same climate change scenario, Mahi and Tapi basins are projected to experience a decline in streamflow during the monsoon season, however, with a larger intermodel uncertainty. In the near term climate, in 7 basins (Brahmani, Ganges, Godavari, Mahanadi,

Narmada, Pennar, and Subarnarekha) streamflow is projected to increase significantly under the RCP 8.5 scenario. Sudheer (2016) reported that the 5% dependable flow for Barmanghat gauging site in Narmada basin may increase during 2071-99 (end century), varies between 404.7 cumecs (MPIESM) to 610.3 cumecs (CNRM). This suggests that during the future time horizons, the extreme events causing floods may increase marginally towards the end-term (2071-99). Das and Umamahesh (2018) found that mean annual monsoon flows for the periods 2041–2070 and 2071–2000 are likely to decrease compared to the base-line period in Wainganga River basin. Towards the end of the 21st century (i.e. 2071–2100), the decrease in the mean annual monsoon flow is more significant.

There are few studies reported on global flood modelling under climate change. Das et al, 2013 found that by end of century, discharges from the Northern Sierra Nevada with 50-year return periods larger floods will increase by 30–90% depending on climate model, compared to historical values. Corresponding flood flows from the Southern Sierra increase by 50–100%. Hirabayashi et al, 2013 presented a global flood risk for the end of this century based on the outputs of 11 climate models integrated with global river routing model with an inundation scheme to compute river discharge and inundation area. An ensemble of projections under a new high-concentration scenario demonstrates a large increase in flood frequency in Southeast Asia, Peninsular India, eastern Africa and the northern half of the Andes, with small uncertainty in the direction of change.

Asadieh and Krakauer (2017) found that under RCP8.5 scenario, 37% of global land areas experience an increase in magnitude of extremely high streamflow (with an average increase of 24.5%), potentially increasing the chance of flooding in those regions. . On the other hand, 43% of global land areas show a decrease in the magnitude of extremely low streamflow (average decrease of 51.5%), potentially increasing the chance of drought in those regions.

10.2 Non-Stationarity of Hydrological Data

While climate scientists agree that human-caused climate change is influencing weather, they have often been hesitant to draw direct linkages between this phenomenon and specific extreme weather events. Anthropogenic impact on climate change has proven to be more critical than natural causes, human effects in river basins such as land-cover and land-use changes, urbanization, changes in impervious surfaces and drainage network, deforestation and mining also play an important role, which alters the pattern of extreme hydrological events that draw the attention of society and moves policy makers toward better management practices. In terms of magnitude and ubiquity of the hydroclimatic change, it appears that the stationary assumption is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning (Milly et al. 2008). Leading causes of change (*i.e.* nonstationarity) include human intervention (Konrad and Booth, 2002; Schilling and Libra, 2003; Villarini et al., 2009), natural climate variability (Enfield et al., 2001; Jain and Lall, 2000) and climate change driven by increased greenhouse gases (Milly et al., 2008; Hirsch and Ryberg, 2012). Combinations of these will lead to nonstationary flood frequency, a challenge for which the bulk of existing FFA methods is ill-suited (El Adlouni et al., 2007; Gilroy and McCuen, 2012). The poleward projection of the subtropical dry zone may decrease the runoff in some regions (Lu et al. 2007), whereas intensification of the global cycle will become a reason for increasing flood risk (Milly et al. 2002). Hirabayashi et al. (2013) stated through a study using the 11 atmosphere-ocean general circulation models (AOGCMs) that it is necessary to adapt and mitigate strategies for intensified flood and greenhouse emissions, respectively. A similar kind of research carried out by Milly et al. (2002) found an increase in great-flood frequency in 29 major river basins using a single AOGCM and

attributed the cause to radiatively induced climate change. Das et al. (2013) also projected streamflow under climate change and observed that climate change may result in the build-up of streamflow in the future.

Therefore, the extreme quantile of the streamflow cannot be considered as a stationary event anymore in the climate change scenario. Because these hydrological extremes are rare in nature and providing implications about them is a tough task (Mondal and Mujumdar 2016), the nonstationary modeling of extreme events currently is compulsory. High return levels generally are considered in the design of hydraulic structures on the basis of historical series, so that high floods in the future should not cause damage downstream or to structural capacity. However, because of induced climate change, the designed return level is not going to be stationary and the structure may fail more frequently than expected in future periods. Therefore, the differences between the observed and the future return levels should be modeled using a nonstationary approach for assessing the correct measure of risk (Mondal and Mujumdar 2016).

Nonstationarity of hydro-climatic data is a rising concern among the hydrologists and climatologists (IPCC2007). The changing global climate alters the hydrological cycle, which in response is causing variability in the frequency of the extreme events, availability of water, irrigation water use, and quality of freshwater resources (Simonovic 2017). While the significance of climate change impacts on some aspects of the hydrological cycle, such as streamflows remains debatable and inconclusive (e.g., Cohn and Lins 2005; Hirsch and Ryberg 2012), some hydrologists believe that "stationarity is dead" (Milly et al. 2008), the geophysical, biological, economical, and other natural processes are nonstationary (Klemeš 1974 & 1989) and recommend that nonstationary probabilistic models need to be identified and possibly used in some practical cases. Moreover, warming associated with climate change may be causing sea-level rising globally and recent projections of sea level include varying degrees of acceleration in the sea-level rise rate (Bindoff, et al. 2007; Rahmstorf 2007; Vermeer and Rahmstorf 2009; Obeysekera, et al. 2012; Sallenger, et al. 2012, IPCC, 2014). Such increases in sea levels are expected to increase flooding due to storm surges in coastal regions and reduce the reliability of flood-protection systems in coastal watersheds (Obeysekera et al. 2011). In addition, climate change research proposes that the intensity and rainfall associated with major tropical storms may also enhance (Kunkel, et al. 2010), potentially leading to increased rainfall-induced flooding in areas exposed to such storms, while the tropical storm frequency globally may reduce in the future (Knutson, et al. 2010).

Various approaches have been suggested in the literature such as frequency analysis methods to undertake nonstationarity of hydrologic extremes, where the parameters (or moments such as the mean and variance) of a given distribution (e.g., the Gumbel) may vary in accordance with time. They include the following: (1) probability distribution models imbedded with trend components (Cooley 2013; Katz 2013), (2) stochastic models considering shifting patterns (Sveinsson, et al. 2005), (3) models considering covariates (Villarini, et al. 2009, 2010), and (4) probability distributions with mixed components (Waylen and Caviedes 1986; Rossi et al. 1984). In the paleo-flood frequency-analysis techniques, multi-century climatic fluctuations have been incorporated including analysis of wet and dry periods (Biondi et al. 2008). Apart from, some preconceive concepts to handle with nonstationarity in flood-frequency analysis have been proposed, such as adapting the nonstationary peak discharges and applying hydrologic models [taking into account the spatially and temporally varying land-use (Moglen 2003); adjusting flood records for the combined effects of urbanization and

climatic change (Gilroy and McCuen 2012)]. Similarly, a flood-frequency analysis framework that necessitates a process-based extracted flood frequency and risk estimation considering possible future evolution of climatic states has been proposed (Sivapalan and Samuel 2009).

10.3 Non-Stationarity in Design flood

Flood frequency analysis or risk analysis for flood hazards is an important part of the engineering practice whose aim is to obtain relationships between design variables corresponding to a chosen hydrologic risk. Flood frequency analysis, as traditionally practiced, is based on assumption that annual maximum floods conform to a stationary, independent, identically distributed random process. Furthermore, the assumption that floods are independent and identically distributed in time is at odds with the recognition that climate naturally varies at all scales, and that climate additionally may be responding to human activities, such as changes over the past century in atmospheric composition or in global land use patterns, which have changed the climate forcing and perhaps the hydroclimatic response on regional scales in recent decades. Numerous studies have demonstrated that estimated flood exceedance probability can increase quite rapidly with time even in the presence of rather mild rising trends in the annual maximum flood. Thus, it is important to acknowledge that non-stationarities are likely to be present in the records and to discuss potential sources of such trends or non-stationarities. The much cited commentary by Milly et al. (2008) entitled "Stationarity is Dead: Whither Water Management?" is one example. There is considerable evidence of regime-like or quasi-periodic climate behavior and of systematic trends in key climate variables over the last century and longer (see NRC, 1998a for one overview). The unambiguous attribution of cause for such non-stationarities in a finite record is difficult, given the rather rich, nonlinear dynamics of the climate system. Even with stationary underlying dynamics (i.e., no change in the governing equations or parameters), finite sample statistics of a nonlinear dynamical system can be non-stationary as the system evolves from one regime to another. The nature of the nonlinear oscillations of the system as well as regime probabilities and its mean state may change as the external forcings (e.g., solar radiation or greenhouse gases) are changed.

The stationarity assumption in flood frequency analysis has persisted because of (a) short historical records that limit a formal analysis of non-stationarities, (b) the lack of a formal framework for analyzing non-stationary flood processes and the associated annual risk, and (c) institutional adherence to engineering practice guidelines. As record lengths have increased, trends in floods and other processes have been observed. The ongoing global climate change debate and identification of interannual and decadal ocean-atmosphere oscillations (e.g., El Niño Southern Oscillation), and their teleconnections to continental hydroclimate, have led to increased awareness of this issue. Cyclical or monotonic non-stationarities pose a serious challenge to flood frequency and risk analysis and flood control design and practice. If cyclical or regime-like variations arise due to the natural dynamics of the climate system, a relatively short historical record may not be representative for design period analysis. Further, by the time one recognizes that the project operation period has been different from the period of record used for design, the climate system may be ready to switch regimes again. Thus, it is unclear whether the full record, the first half or the last half of the record, or some other suitably selected portion is most useful for future decisions without a better understanding and prediction of the climate regimes. In addition, if a monotonic trend in floods is indicated in a reasonably long record and the possibility of global climate change effects is considered, projections of future flood potential are still unclear. For one, the effects of global climate changes may be more in the variability of the process

than the mean, and may translate into an increased probability of recurrence of certain regimes of climate more than others.

Non-stationarity may be attributed to climate variability or different human influences (e.g. urbanisation, regulation of rivers, construction of dikes, deforestation, etc. Large number of studies have already performed non-stationary flood frequency analyses. However, the way of incorporating changing climate and anthropogenic influences in hydrologic practice has still not been exactly defined and this is clearly an area which should be considered with much more effort in the future. Most of the non-stationary flood frequency analysis methods proposed in the literature involve parameters of a chosen distribution that are dependent on time. The problem with time varying distribution parameters is that it is difficult to justify why they would continue to change in the future exactly in the same way they did in the past. As an alternative, models have therefore been developed that correlate the distribution parameters to hydrological variables such as land use or climatological variables, for example El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and other circulation indices. However, reliable scenarios of such variables for the future are needed. Some authors allowed the distribution parameters to vary both with hydrological variables and with time. The functional forms of frequency distributions have used several different functional forms, such as linear, quadratic and exponential forms in non-stationary flood frequency analysis. Although different levels of nonlinear modeling of nonstationary models have been utilized in the past, selecting the optimal forms of nonlinear functions for use with different time series and determining the method of selecting a nonlinear function for a non-stationary model are still important issues. Attempts have been made by fitting the series with various linear and nonlinear functions, and best functions are selected based on decision criteria viz. mean absolute percent error (MAPE), root mean square error (RMSE), the Akaike information criterion (AIC), and the Bayesian information criterion (BIC) etc.

10.4 Impact on Flood Under Climate Projections

Wang (2016) et al. showed that the number of extreme events exceeding smaller probability will increase for the next 50 years for the Tangnaihai basin in the Yellow River basin in China. The Tangnaihai basin is a large basin with drainage area of 122,000 km^2. According to the analysis of a number of extreme events exceeding given probability, it is found that the extreme events of long duration rainfall exceeding given probabilities (5%, 10%, and 20%) will become more frequent. It is seen that the values of long duration (15 d, 30 d, and 60 d) flood volume extremes of Tangnaihai basin will rise by slightly increasing rate in the next 50 years. On the hypothesis that rainfall of given frequency could result in to flood of the same frequency, SWAT model was used to deduce design flood with the import of design rainfall for the next 50 years, and the long flood volume extremes were achieved. Flood volume extremes in different duration, 15-day design flood volume of given probabilities (1%, 2%, 5%, and 10%) is increasing by 1%–3% based on BCC-CSM-1.1; similarly, 30-day design flood volume is increasing by 1%–3% and 60-day design flood volume is increasing by 3%–6%, respectively. It obvious that the increasing rate of flood volume extremes in given probability is less than 10%, in other words, the flood volume extremes of the Tangnaihai basin would increase with a slight degree. Generally, the long duration hydrologic extremes of the Tangnaihai basin would increase by a slight degree in the next 50 years. The conclusions were addressed on the basis of BCC-CSM-1.1. The authors state that if several more suitable climate change model products were adopted, the conclusions on impact of climate change in study area will be more reliable.

Wobus et al. (2017) state that a growing body of work suggests that the extreme weather events that drive inland flooding are likely to increase in frequency and magnitude in a warming climate, thus potentially increasing flood damages in the future. The authors used hydrologic projections based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) to estimate changes in the frequency of modeled 1% annual exceedance probability (1% Annual Exceedance Probability (AEP), or 100-year) flood events at 57116 stream reaches across the contiguous United States (CONUS). The flood projections were linked to a database of assets within mapped flood hazard zones to model changes in inland flooding damages throughout the CONUS over the remainder of the 21st century. The model generates early 21st century flood damages that reasonably approximate the range of historical observations and trajectories of future damages that vary substantially depending on the greenhouse gas (GHG) emissions pathway. The difference in modeled flood damages between higher and lower emissions pathways approaches USD4 billion per year by 2100 (in undiscounted 2014 dollars), suggesting that aggressive GHG emissions reductions could generate significant monetary benefits over the long term in terms of reduced flood damages. The authors mention that although future work is needed to test the sensitivity of the results to these methodological choices, the results indicate that monetary damages from inland flooding could be significantly reduced through substantial GHG mitigation.

10.5 Impact of Climate Change On Design Flood

Impact of climate change on design flood has been assessed by carrying out a study considering some hypothetical scenarios of climate change i.e. effect of change in rainfall sequencing; effect of rise in the peak of unit hydrograph; effect of change of design rainfall pattern for a snowed as well as rainfed catchment of about 5000 km^2 in area. For this purpose, 1-hour unit hydrograph is derived employing the Clark IUH model. The Clark IUH model parameters viz. T_c = 9 and R = 12 are estimated. The Clark IUH model is used for estimation of the direct surface runoff (DSRO) hydrograph by converting the excess rainfall hyetograph into DSRO. In this study, the design flood was estimated by convoluting the 2-days design storm value with the unit hydrograph derived using the Clark IUH. The various hypothetical scenarios of possible changes in flood hydrographs due to climate change are described as follows (Pandey et al., 2013).

10.5.1 Effect of Change of Sequencing Pattern of Rainfall

The climate change is likely to affect the pattern of rainfall and its intensity, magnitude of rainfall and the number of rain days etc. As a result, the pattern of occurrence of rainfall would also be affected. The design storm has been considered in four cases as shown in Fig. 10.1: (a) design storm as single bell (Case – 1); (b) design storm as two bells (Case – 2); (c) design storm as four bells (Case - 3); (d) design storm as four bells (Case - 4). Design flood hydrographs for various sequence patterns of the hourly rainfall excess are shown in Figure 10.2. The percentage decrease in peak floods for Cases-2, 3 and 4 are observed to be 8.0%, 28.7% and 13.3% with respect to Case-1. Whereas, the percentage decrease in time to for the peak floods for Cases-2, 3 and 4 are observed to be 28.6%, 61.2% and 28.6% with respect to Case-1.

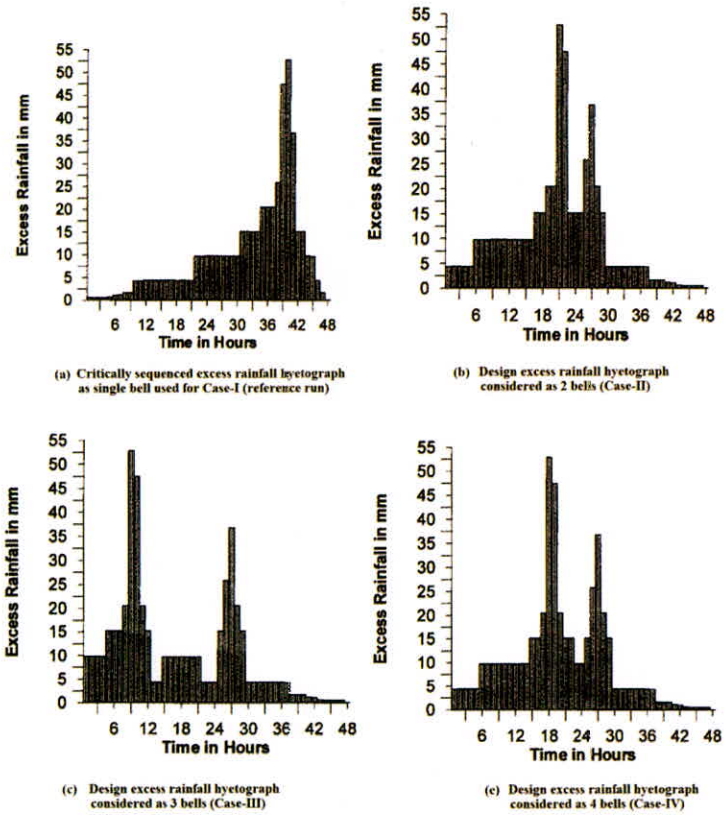


Figure 10.1: *Various sequences of hourly rainfall excess patterns*

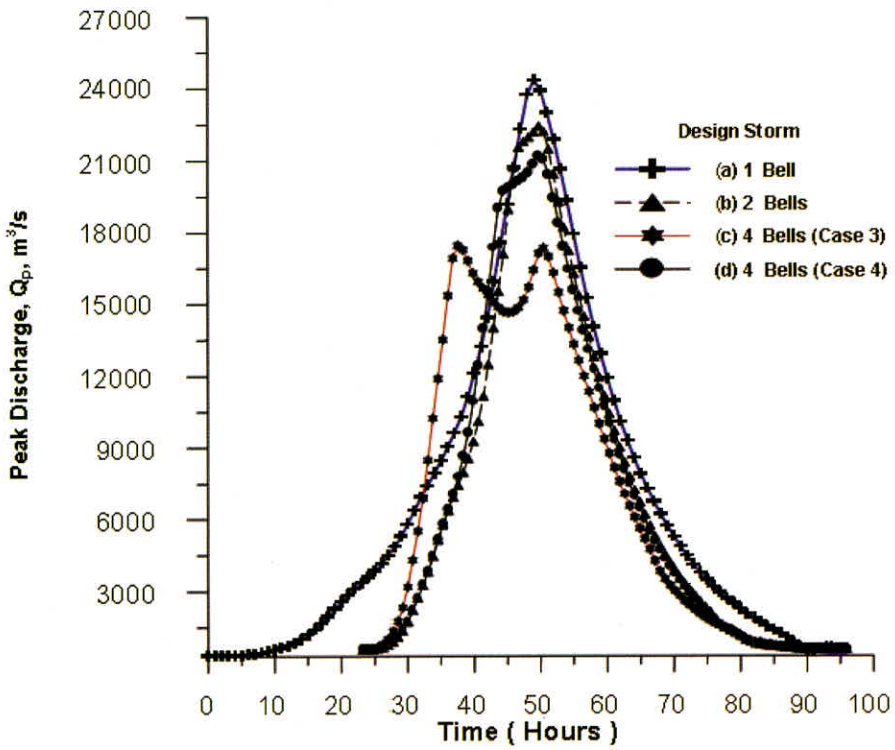


Figure 10.2: *Flood hydrographs for different sequences of hourly rainfall excess*

10.5.2 Estimation of Design Flood for various Percentage Increases in Design Storm Values

The value of design flood (DF) for the study area has been estimated as 6,842 m^3/s. As a result of climate change the hydrological extremes are likely to be effected and the values of rainfall would increase or decrease in different regions; therefore, hypothetical increases are considered in the design storm values for the study area and design flood values have been estimated for such scenarios. When increases of 5%, 10%, 15% and 20% are considered in the value of design flood; it is observed that estimated values of the peak floods are increased by 3%, 8%, 13% and 18% respectively (may vary from case to case) as shown in Figure 10.3.

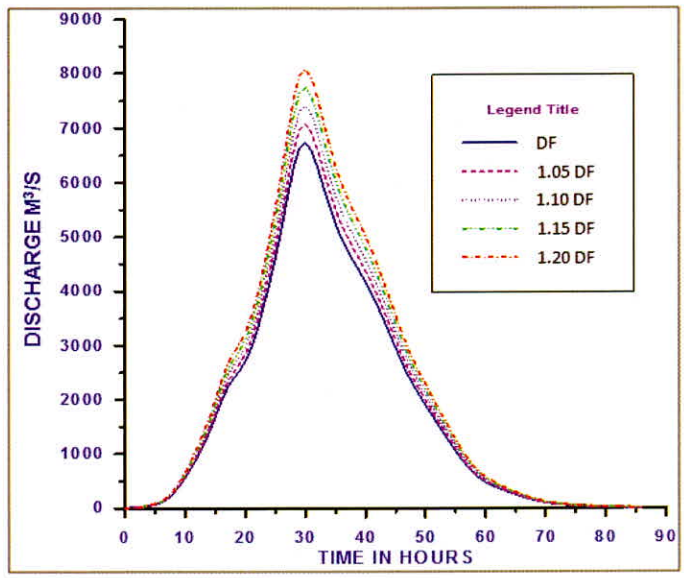


Figure 10.3: *Estimated Values of Peak Floods for the Various Increased Values of Design Strom*

Table 10.1: Estimated Values of Peak Floods and % Deviations in Peaks of Design Floods

Design Flood	**1.05*Design Storm**	**1.10 Design Storm**	**1.15 Design Storm**	**1.20 Design Storm**
	Peaks of Design Floods (m^3/s)			
6842	7064	7401	7737	8073
	% Deviations in Peaks of Design Floods			
	3	8	13	18

10.5.3 Effect of Increase in Peak of the Unit Hydrograph

For analysing the effect of increase in the peak of unit hydrograph on peak design flood, various increases in the unit hydrograph peaks are considered. The different unit hydrographs are used with the

design storm values of one bell (adopted as the reference design storm). Percentage variations in the peak of the unit hydrograph are shown in Figure 10.3. Figure 10.4 shows that design flood peak increases by about 25% for 50% increase of peak of the unit hydrograph.

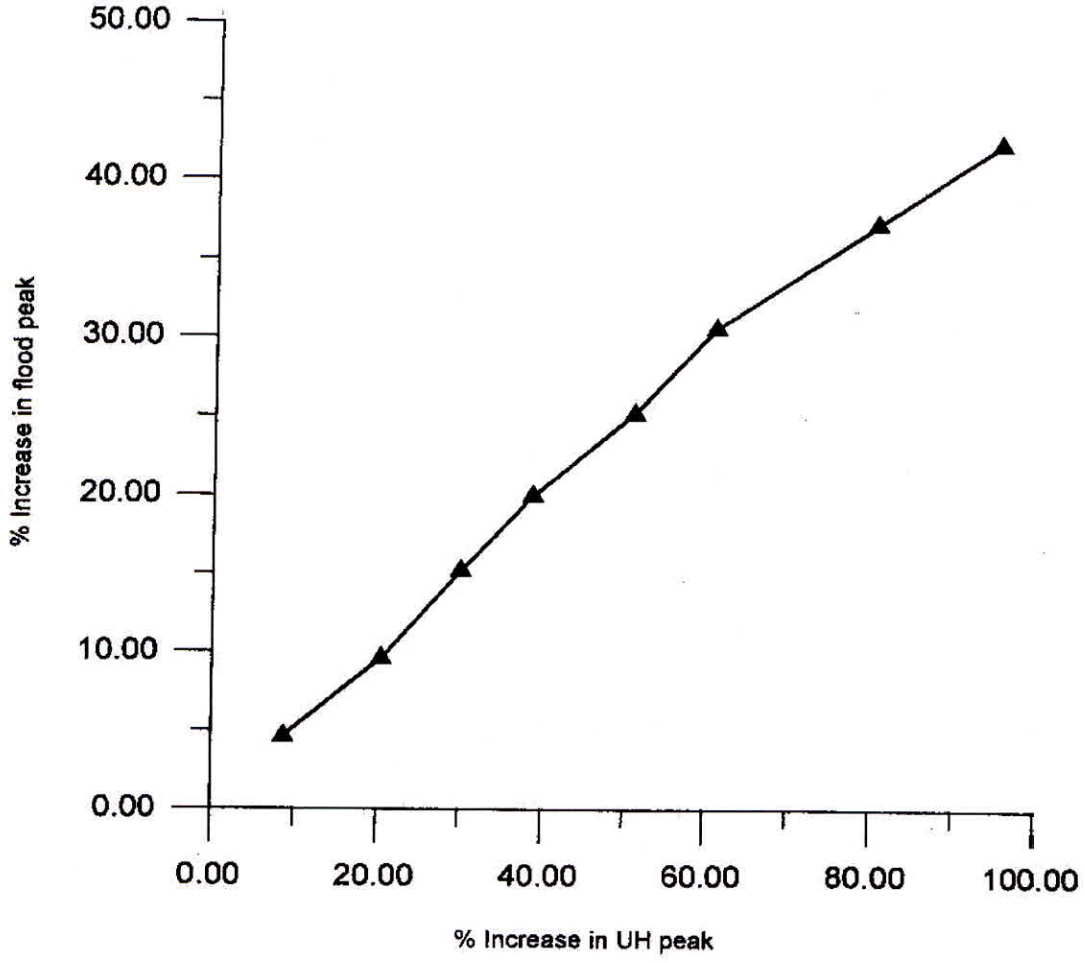


Figure 10.4: *Percentage increase in the peak of flood hydrograph with increase in unit hydrograph peak*

10.5.4 Effect of Change of Temporal Distribution of Design Storm

For studying the sensitivity of rainfall distribution with time two more patterns of time distribution of the rainfall excess values have been considered apart from the distribution pattern obtained from IMD as shown in Figure 10.5. The design flood hydrographs for the three design storm patterns are shown in Figure 10.6. The peak of design flood decreases from 24,359 (reference run/distribution pattern 1) to 20,023 m^3/s that is by 17.8% for the pattern of the design storm. The peak of design flood increases to 27,745 m^3/s that is by 13.9% for the pattern 3 of the design storm. However, it is observed that the time to peak of the design flood is not effected for the design storm patterns considered in the study. It is also observed that the peaks of the design floods are very significantly affected by the pattern of the design flood.

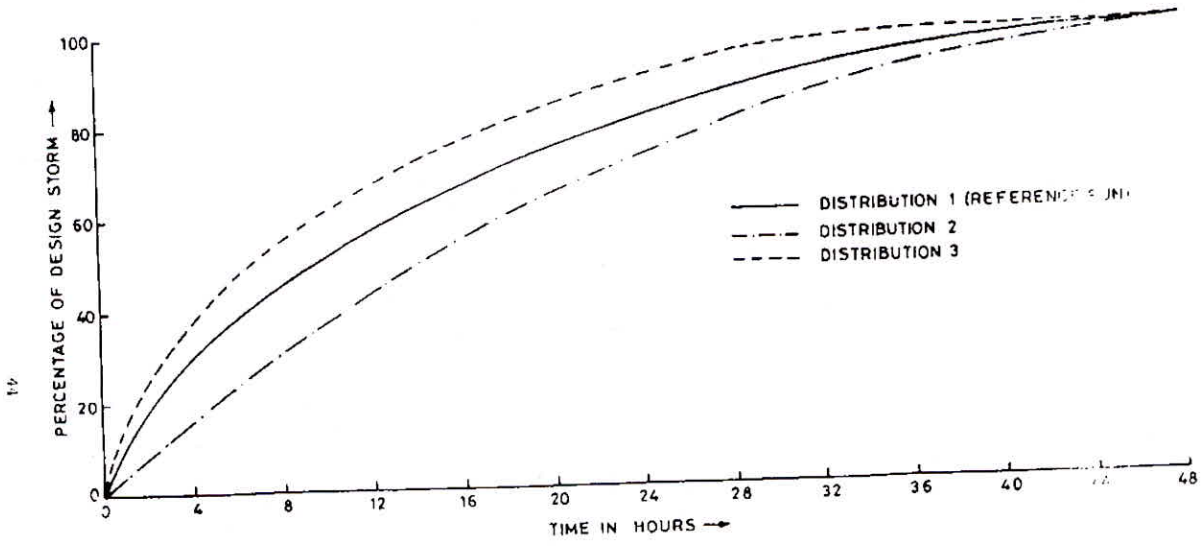


Figure 10.5: Various patterns of the design storm

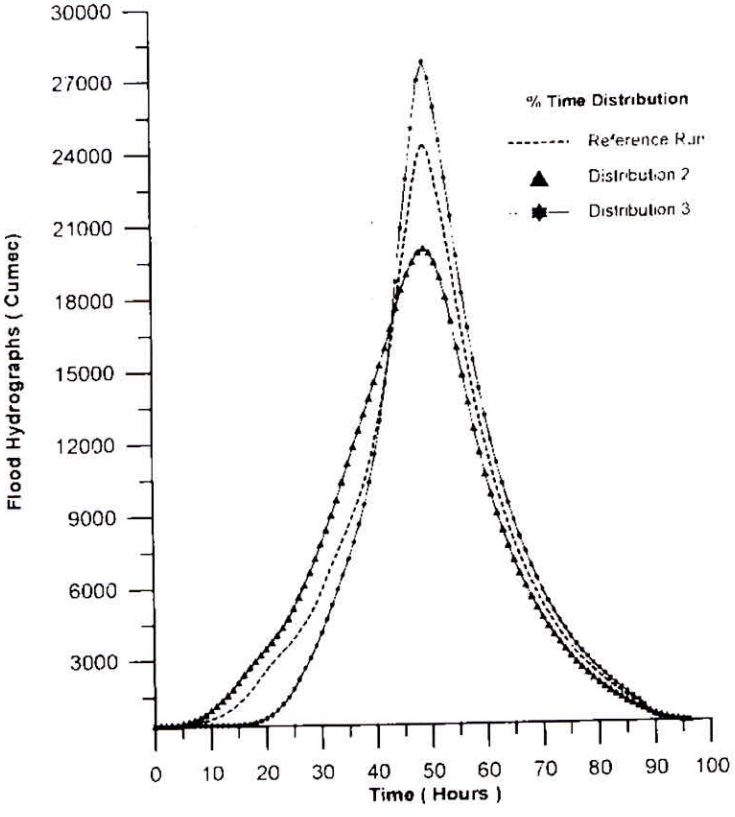


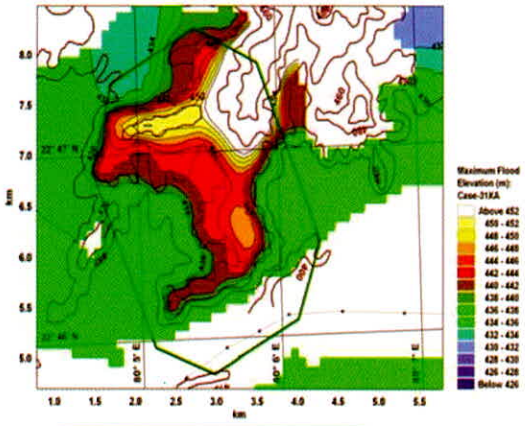
Figure 10.6: Flood hydrographs for different patterns of design storm

10.6 IMPACT OF CLIMATE CHANGE ON FLOOD INUNDATION

For analysing the impact of climate change on flooding, projections of changes in annual mean temperature as well as rainfall have been studied in New Zealand. For this purpose, six greenhouse gas emission scenarios developed for the IPCC have been used. For estimating the impact of temperature on rainfall, weather models have been adopted to replicate the rain for three historical rainfall events. The rainfall increased by 3, 5 and 33 percent on average for the three events. The Topnet model was used for estimation of flow for the rainfall events. The percentage increases of 4, 10 and 37 in river flow were observed in the study. The flood inundation areas for 50 year return period for a mid-high scenario of the year 2080 has been compared with the present scenario for downtown Westport (Preparing for future flooding: A guide for local government in New Zealand, Ministry for the Environment; 2010).

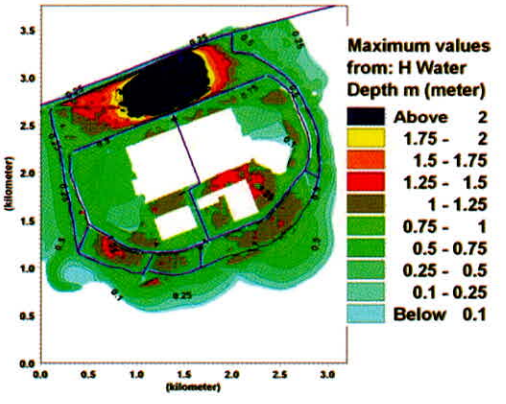
Flood inundation modelling has been carried out using coupled 1-D & 2-D hydrodynamic model MIKE-FLOOD for estimation of safe grade elevation for nuclear power project at Gorakhpur in Haryana considering safety against design flood of the upstream catchment; at site flooding; dam break flooding of the Bhakra dam; canal breaches and design of external and internal drainage systems for the nuclear power plant site. In this study, it is observed that an increase of 15% in the value of 1000 year return period flood leads to 10 cm increase in the safe-grade level of the important installation at the project site.

Also, flood inundation modelling has been carried out using coupled 1-D & 2-D hydrodynamic model MIKE-FLOOD for estimation of safe grade elevation for nuclear power project for site at Chutka in Madhya Pradesh considering safety against design flood of the upstream catchment; at site flooding; dam break flooding of the Bargi and other dams in the upstream and design of external and internal drainage systems for the nuclear power plant site. In this study also the impact of increase of 15% in the value of design flood has been considered for estimation of the safe-grade level of the important installation at the project site.



10.7 IMPACT OF CLIMATE CHANGE ON HYDRAULIC STRUCTURES

The embankments of a river are designed for 50 year return period flood for a reach of about 12 km. Further, the adequacies of embankment level for design flood with climate change have been evaluated. The daily rainfall values are increased by 15% to study impact of climate change on design floods. With 15% increase in rainfall values, the design rainfall values for 50 year return period is estimated to be 35.7 cm. The comparison of flood peak for 50 year is increased by 13%. The simulated water surface profiles for 50 year return period flood



is shown in Figure 10.7.

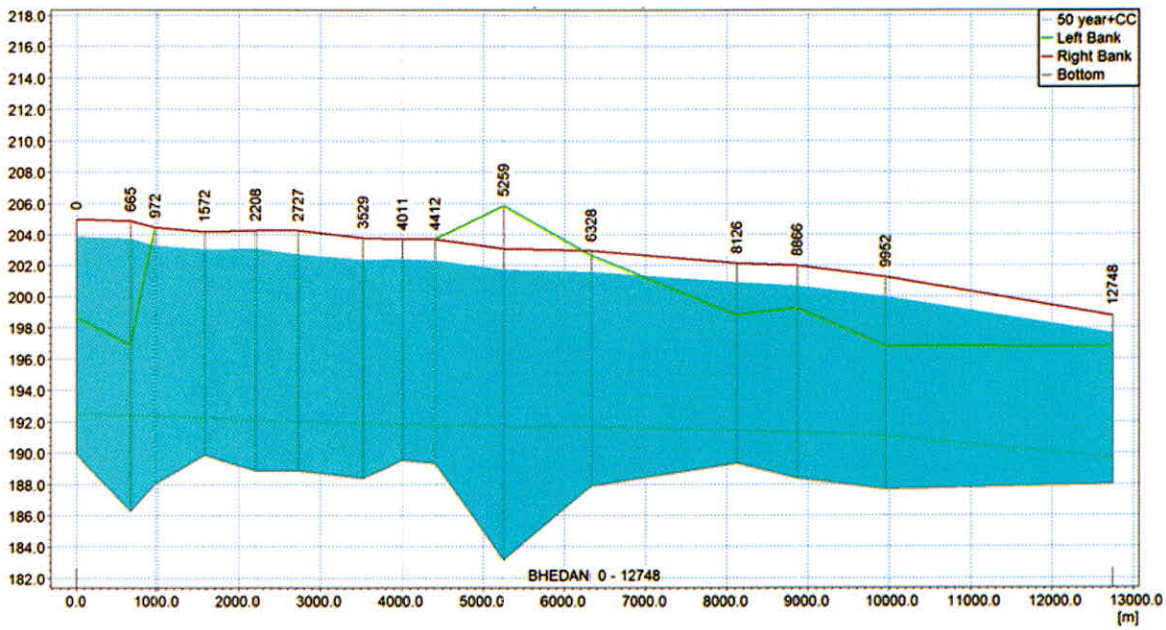


Figure 10.7: Maximum Water surface profile for 50 year+CC return period flood with embankment

The hydrologic and hydraulic analysis for a proposed bridge in lower Himalayas has been carried out for estimation of HFL and flow velocities. The catchment area of the bridge site is 67.06 km^2. The estimated peak floods for 50 and 100 year return periods are 941.62 m^3/s and 1058.75 m^3/s respectively using rainfall data of CWC report (1994). However, the estimated peak floods for 50 and 100 year return periods are 1024.06 m^3/s and 1152.55 m^3/s respectively using rainfall data of CWC report (2015). It is observed that CWC-2015 method provides 8.8 % and 8.9% higher estimates of peak floods for 50 and 100 year return periods as compared to CWC-1994 method. The estimated peak floods for 50 and 100 year return periods are 1157.28 m^3/s, 1386.27 m^3/s respectively using the rainfall data of Narendranagar raingauge station (SUH-LMT).

It is observed that SUH-LMT method provides 22.9 % and 30.9% higher estimates of peak floods for 50 and 100 year return periods as compared to CWC-1994 method. The hydraulic modelling has been carried out using HEC-RAS for various design floods. The bridge geometry is created by adding information of bridge deck, slopping abutments and eleven piers etc. in HEC-RAS. Eleven piers are added based on the centreline of the pier at the upstream and downstream sections. The simulated water level is estimated as 381.66 m, 381.82 m and 382.19 m for discharge of 1157.28 m^3/s (50 year), 1386.27 m^3/s (100 year) and 1982.18 m^3/s respectively (Figure 10.9). The total velocity at upstream and downstream is estimated as 4.02 m/s and 3.96 m/s respectively for the discharge of 1982.18 m^3/s. The increase or decrease in the flood due to climate change may also be considered in the same way for estimating the HFL under the climate change scenarios.

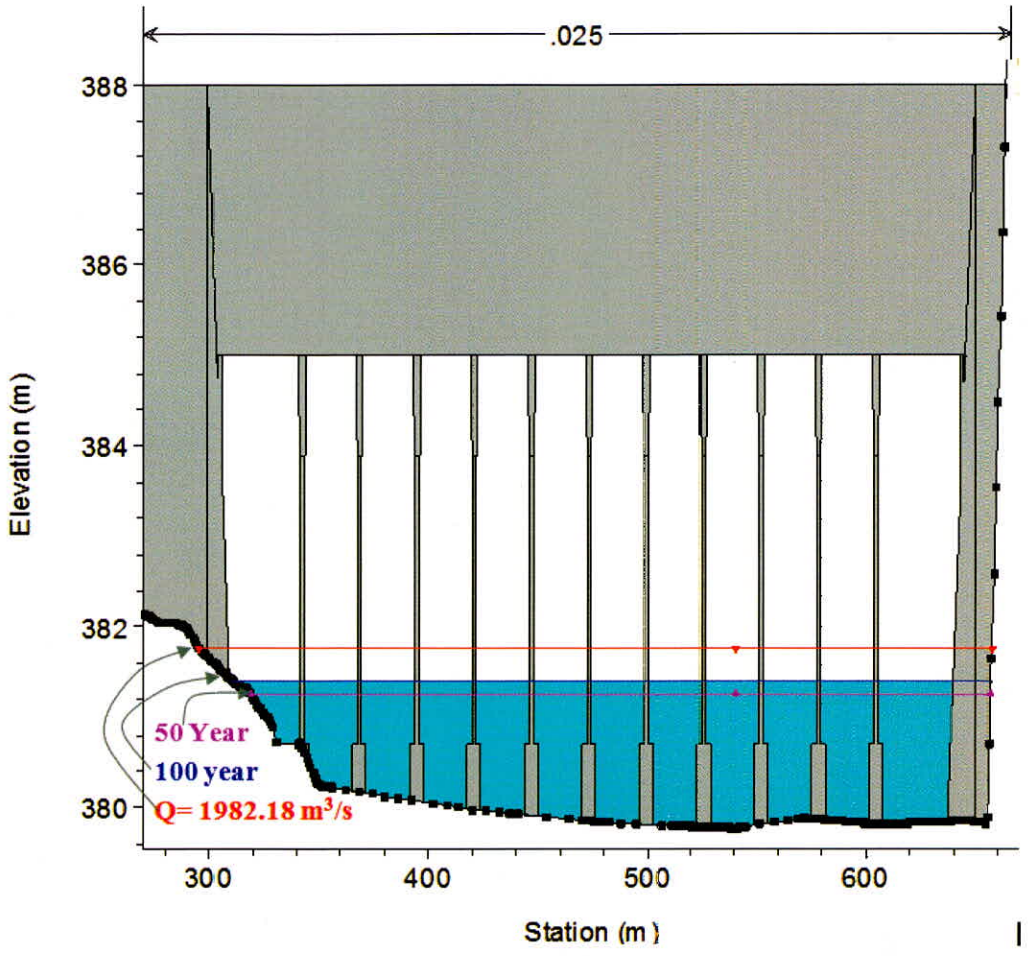


Figure 10.8: Simulated water surface profile for various design floods

10.8 Effect of Increased Return Periods on Flood Frequency Estimates

Now a day, it is generally felt that extreme flood events are likely to be affected due to impact of climate change. In this regard, the large flood events are generally expected to increase because of possibly increase in intensity of severe rainfall and urbanization of the catchments etc. Therefore, the hydrologic design criteria for design of various types of hydraulic structures need to be re-looked. For analyzing this aspect, average values of growth factors of various return periods for the various Subzones may be computed for different increases in the return periods and the resulting percentage increases in the corresponding growth factors with respect to the original growth factors. It is observed that percent deviation in floods of 150 year return period to 100 year return period is minimum 3% for Subzone 3(e) and the maximum 11% for subzone 1(d); whereas the average increase is 7% for 17 Subzones of India (Figure 10.9).

In fact, inclusion of climate change effect in regional flood frequency analysis is a complex procedure and there can be more comprehensive and scientific estimation for this component using procedures based on GCM/ RCM downscaling with various climate change projections employing ensemble modelling approaches by addressing the uncertainty associated with such procedures. The impact of climatic change in regional flood frequency analysis needs to be corroborated by correlation

analysis to be carried out in future.

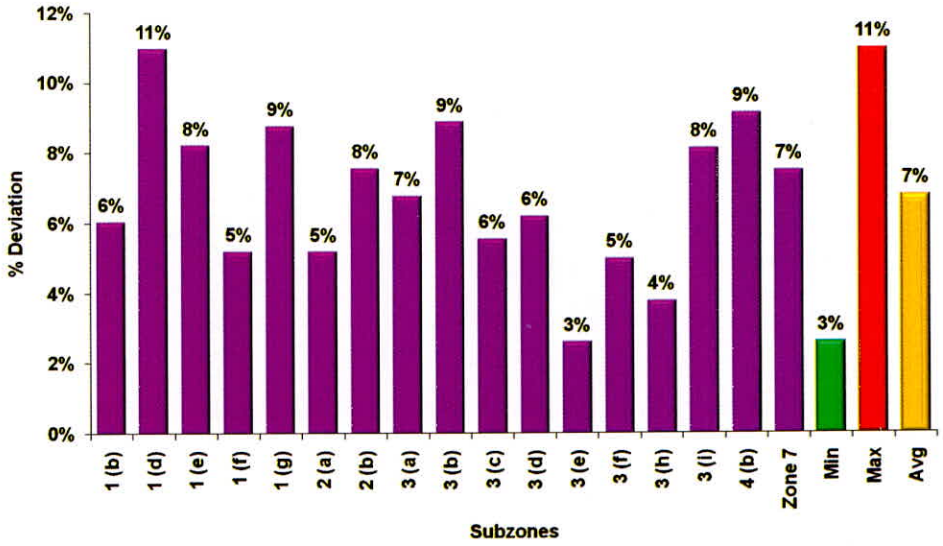


Figure 10.9: Percent deviations in floods of 150 year return period to 100 year return period or 17 sub zones of India

10.9 Adaptation Measures

The major effect of climate change on floods will depend on the magnitude, intensity and distribution of rainfall in time and space. In fact, inclusion of climate change effect on floods is a complex procedure and there should be comprehensive and scientific estimation for this component using procedures based on GCM/ RCM downscaling with various climate change projections employing ensemble modelling approaches by addressing the uncertainty associated with such procedures.

Under design of a hydraulic structure makes it unsafe and susceptible to flood hazard and over design results in its exorbitant cost. For example, it has been observed that for many of the earlier constructed dams in India, design flood estimates are inadequate in the present scenario, mainly because of the new design standards, availability of more data and improvement in the methodologies etc. Under the Dam Rehabilitation and Improvement Project (DRIP), so far review of design flood estimates of about 94 dams have been completed by the project authorities. It has been observed that the revised design flood estimates are higher by 50% for 62% of the dams and about 100% higher for 43% of the dams. These revised design flood estimates necessitate enhancement of spillway capacity to pass design flood and/ or require space in the reservoir for flood cushion. Further, all these aspects require detailed studies in view of considering the impact of climate change on the hydrological extremes. Some of the action points for considering the impact of climate change on floods and their adaptation strategies are mentioned below:

- Setting up of suitable manual and automatic data observation networks for hydro meteorological and related data in the hilly regions for collection of short interval data should be paid attention.
- Data collection, processing, storage, retrieval and dissemination using the state-of-art knowledge in Information Technology sector should be encouraged.

- There should be active collaboration within the institutes and departments engaged in the applications of new methodologies and techniques such as hydrological modelling, soft computing, GIS and remote sensing, down scaling of GCM and RCM data and assessment of impact of climate change etc.
- Estimate design floods for various types of hydraulic structures considering impact of climate change.
  - ✓ Estimate floods of various return periods by using flood frequency analysis for future considering the impact of climate change.
- Estimate flood inundation and flood hazard for the present situation and future considering impact of climate change.
  - ✓ Estimate flood inundation due to floods of various return periods in future considering impact of climate change.
  - ✓ Dam break analysis and generation of flooding scenarios considering failures of single and multiple dams for preparedness, mitigation, response and recovery during emergency to be developed.
  - ✓ Estimate flood hazard and develop flood hazard classification scheme based on extent, depth, elevation and duration of flooding as well as the maximum flow velocity for various return periods using coupled (1-D & 2-D) hydrodynamic flow modelling for the present.
  - ✓ Estimate flood hazard and develop flood hazard classification scheme based on extent, depth, elevation and duration of flooding as well as the maximum flow velocity for various return periods using coupled (1-D & 2-D) hydrodynamic flow modelling for the future considering impact of climate change.
- Early warning and Real-Time Decision Support Systems (RTDSS) for Flood Forecasting
  - ✓ Real time flood forecasting and early warning systems to be developed using the hydrodynamic modelling based on the antecedent rainfall forecasts. Such forecasts may be formulated for 3-day/ 10-day lead time and updated as new QPF data become available;
  - ✓ Real-Time Decision Support Systems (RTDSS) for flood forecasting, flood inundation modelling and early warning to be developed considering the impact of climate change;
  - ✓ Adoption of crowd sourcing and engaging citizen scientists for collection, compilation, processing, analysis and dissemination of data/ information for finding solutions of the flood problems;
- Evaluation of Glacial Lake Outburst Flood (GLOF) hazard
  - ✓ Evaluation of Glacial Lake Outburst Flood (GLOF) hazard and mitigation plans needs to be developed for the potential dangerous glacial lakes;
  - ✓ Develop Mitigation plans for the potential glacial lakes hazards.
- Integrated flood management studies should be carried out for the pilot basins.
- Regulate urban development in flood-prone areas and flood plains
- Preparation of Emergency Evacuation Plans (EAP) for the flood prone areas.

- Design of appropriate drainage systems in urban centres, to quickly drain off the accumulated flood waters in the city.
- Nature-based solutions include widening of natural flood plains, protecting and expanding wetlands, restoring oyster and coral reefs and investing in urban green spaces to reduce flood.
- Checking the insurance policies of infrastructures and buying flood insurances.
- Constructing infrastructures/buildings from flood resilient materials that can withstand direct contact with floodwaters without sustaining significant damages.
- Abandoning affected structures located too close to the shore and relocating houses that are more at risk of flooding to higher ground. Assessment of impact of climate change on floods and revisit of hydrologic design criteria should be taken up. Preparation of standards/ guidelines based on the advanced techniques and tools for integrated flood management should be taken up.
- Appropriate institutional arrangements to achieve these goals would be an effective mechanism to coordinate between different institutions/ departments having expertise in the related interdisciplinary fields.

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CHAPTER 11

CLIMATE CHANGE IMPACTS ON DROUGHTS

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11.0 Introduction

Climate change is arguably one of the most complex global environmental challenges facing the world today and water is the primary medium through which its effects will be translated to other water dependent sectors including agriculture, forests, health, and urban. However, the root causes of the climate change are ingrained across almost all sectors and industries. Global climate change is one of the key factors affecting the hydrological cycle (IPCC 2007). Any change in temperature affects the atmospheric moisture, precipitation and circulation pattern of the atmosphere. The global warming has triggered many changes to the Earth's climate resulting in changes in the characteristics of the extreme weather and climate events. Research is increasingly confirming the intense relationships between the global warming and intense hydrological cycles (Gosling et al. 2016; Ricke et al. 2017; Drijfhout et al. 2015).

The heat waves have increased and all-time high temperature records have been broken in many countries, viz., United Kingdom – 38.1°C, Germany – 40.2°C, India 50°C, France, Italy, Spain etc. resulting in human fatalities. The rising temperature leads to the atmosphere's capacity to hold more water vapour, thereby allowing for both, greater rates of rainfall and runoff when air is saturated and drier (under-saturated) conditions otherwise. A warmer climate increases the risks of both drought – where it is not raining, and floods – where it is raining, but at different times and/or places. Although the impacts of the climate change on the floods and droughts are uncertain (Andersen and Shepherd 2013), the changes in the precipitation intensity and quantum can cause changes in the mean discharges of rivers.

The extreme hydrological events including floods and droughts invariably result in considerable loss to the economy of a region and brings alongwith it massive hardships for the people living in the affected areas. Even though the impacts of the drought are not visible initially as in the case of floods, but they have the potential to cause substantial changes to the ecosystem and society of a region. In recent decades, the extreme drought frequency has increased considerably in many countries (Hoerling et al. 2012; Nandintsetseg and Shinoda 2013; Zhang et al. 2011 and Spinoni et al. 2014). From 1998 to 2002, below-normal precipitation and higher temperatures resulted in droughts covering wide areas of North America, Southern Europe, and Southern and Central Asia. Drought continued in some regions through 2004, including the Western U.S. which endured the most severe drought in 80 years. The worldwide drought has been linked to unusually warm waters in the Indian Ocean and western Pacific, which has been caused by global warming.

Climate change is expected to increase the frequency of droughts and floods in future. The increase in the temperature, changes in the precipitation pattern, its distribution and variability as a consequence of climate change, may lead to changes in the drought characteristics including drought frequency and severity. An increase in the land surface temperature and surface air temperature has been reported by many researchers around the world in the recent decades (WMO 2006). The world's four warmest years on record are 2016, 2015, 2017 and 2018 with temperatures between 0.9°C and

1.2°C above pre-industrial levels (WMO 2019, C3S 2019). However, there may be associated uncertainties due to different interpolation methods and data gaps (Blunden and Arndt 2014). The global average temperature is expected to continue to increase throughout this century as a result of projected increases in greenhouse gas concentrations. IPCC Assessment Report 5 (AR5) climate projections suggests that global temperature relative to 1986-2005 will increase for the mid-century (2046-2065) by 0.4-1.6°C for Representative Concentration Pathway (RCP2.6); by 0.9-2.0°C for RCP4.5; by 0.8-1.8°C for RCP6.0 and by 1.4-2.6°C RCP8.5. The warming projections for the end of the century (2081-2100) are 0.3-1.7°C for RCP2.6, 1.1-2.6°C for RCP4.5, 1.4-3.1°C for RCP6.0 and 2.6-4.8°C for RCP8.5 (IPCC 2013). The higher temperature in future time horizons will lead to changes in the rainfall pattern, higher rainfall variability along with higher evaporation and evapotranspiration. The high variability in the rainfall is expected to result in water scarcity and meteorological droughts whereas an increase in evaporation as a result of higher temperatures may result in higher occurrences of hydrological and agricultural droughts. Climate change has the potential to increase drought disasters, by subjecting various regions across the globe to much higher levels of drought frequency and severity.

The intensification of the hydrological drought, meteorological drought and agricultural drought due to the climate change related impacts will substantially influence the ecosystems, water security, food security and the living conditions of humans living in the affected regions. Managing the water stress in an optimal way may be the key to the sustainable development in future. This chapter presents a comprehensive review of the climate change impacts on droughts along with possible adaptation mechanisms to address it.

11.1 Drought and Climate Change Concepts

Drought is one of the extreme events that can be caused by climate variability as well as external forcing. The ecosystems, agriculture, livelihoods and settlements of a region are much dependent on its climate. This natural disaster invariably affects the agriculture, water resources and society resulting in enormous economic losses. The recurrent droughts seriously threaten the livelihood of billions of people who depend on land for most of their needs. Droughts occur in virtually all climatic zones, and are mostly related to the reduction in the amount of precipitation received over an extended period of time and various factors including high temperatures, high winds, low relative humidity, rainfall distribution, onset and termination of monsoon, dry spells occurrences during crop growing seasons, intensity and duration of rainfall, all play a significant role in the occurrence of droughts (Mishra and Singh 2010). A drought is a temporary aberration whereas aridity is a permanent feature of the climate restricted to low rainfall areas (Wilhite 1992). Similarly, the time scale associated with a heat wave is on the order of a week, whereas a drought may persist for months or years. There are many drought definitions but consistency among various drought definitions is a key to remove any ambiguity in framing drought policies and making decisions (Mukherjee et al. 2018).

The rainfall pattern including its spatiotemporal variability and timing, along with the temperature are the two important variables that govern the drought characteristics. Droughts impact the surface water, groundwater and the soil moisture which is very crucial for agriculture in rainfed areas. From an agricultural point of view, a state of higher than normal temperature will lead to higher evapotranspiration and higher water demands whereas the lower precipitation will result in higher water deficits leading to crop stress, reduction in crop yields or crop failures. Even regions with very high rainfall face drought and understanding of the drought phenomenon is important. Therefore, the

understanding of the drought phenomena and its characteristics are of great importance in the planning and management of water resources (Mishra and Singh 2010).

Since drought is a creeping phenomenon, it is quite difficult to anticipate its occurrence well before it actually occurs. As such, it is difficult to determine the onset of drought even though weather forecasts with longer lead-times are now available from multiple sources with relatively better prediction accuracies. The negative impacts of the drought become evident only after it has crept in, and also there are hardly any structural losses as is seen in the case of the other natural hazards like floods, hurricanes, earthquakes, etc. However, the regular/continuous drought events cause considerable hardships to the local residents by widely affecting their livelihoods leading to malnutrition and deaths. The continuous and regular droughts often result in land degradation and loss of soil cover and fertility in the longer term.

Droughts are initiated by the reduction in precipitation and its variability. These are generally accompanied by high temperatures and heat waves. Even though the moisture deficits that constitute a drought, occur invariably due to precipitation deficits (Dai 2010), but the higher temperatures can increase the evaporative demand considerably, thereby increasing the overall drought impact (Dai 2013; Dai et al. 2004). The impacts of soil moisture deficit and runoff deficit can be very severe, leading to risks of wildfire (Westerling et al. 2006), damage to habitat of endangered species (Palmer et al. 2009) and lower hydropower production (US Energy Information Administration 2014).

Droughts are generally classified into four types, viz., meteorological drought, hydrological drought, agricultural drought and socio-economic drought (Wilhite and Glantz 1985; Smakhtin and Schipper 2008; Mishra and Singh 2010; Hao and Singh 2015). The meteorological drought is defined in terms of the magnitude of shortfall from normal rainfall and duration of the shortfall event. Agricultural drought is linked to the meteorological drought and occurs when the shortage of soil moisture adversely affects the agricultural production due to higher evapotranspiration losses that have not been properly met (Mannochi et al. 2009). Water deficit even for a relatively shorter period during the critical crop growth stages, viz., flowering and fruit set, can cause irreversible damages to crop yields. Agricultural drought is more dominant in rainfed systems; as supplemental irrigation facilities are seldom available in such regions. The hydrological drought is again linked to meteorological droughts which impact the surface water and groundwater availability. The hydrological droughts lag the meteorological and agricultural droughts. The socioeconomic drought is associated with the supply and demand of some economic goods with elements of meteorological, agricultural and hydrological drought. The climate change does have an impact on all the various types of droughts and therefore it is necessary that the future climate change impacts on drought be evaluated for the formulation of appropriate mitigation and adaptation mechanisms.

Climate change and the resulting increase in the maximum and minimum temperature would mean higher consumptive use requirements for vegetation as a result of higher potential evapotranspiration rates. However, the changes in the actual evapotranspiration will depend on the actual water availability which may also get altered due to the changes in the rainfall pattern, its timing and distribution. The irrigated areas may be impacted to a lesser extent under these changes, but a future drier climate will significantly affect the rainfed areas leading to reduction in crop production thereby affecting the food security of the region.

11.2 Sectors Impacted by Climate Change Induced Droughts

The climate change impacts on the extreme events, particularly the droughts is expected to have its effect on multiple sectors including water resources, agriculture, forests, urban, and health. Climate change has the potential to possibly exacerbate the drought characteristics in future. The drought conditions may worsen when higher temperatures coincide with minimal precipitation (Diffenbaugh 2015). It is widely perceived that the water resources sector shall be impacted in many ways. It is expected that the changes in the rainfall pattern and its distribution shall have its impacts on the surface water, groundwater and water quality. The variability in the precipitation pattern and its distribution is expected to have a direct bearing on the stream flows in river systems, storages in lakes and reservoirs which in turn may affect the environment and biodiversity of the region. Similarly, the over dependence on the groundwater systems, particularly during periods of water scarcity and drought due to the climate change impacts is expected to further affect the groundwater systems with problems of depleting groundwater levels and dwindling of the baseflow contribution to the river systems. The water quality, both surface and groundwater is expected to be affected under the influence of greater soil erosion due to high intensity rainfall, reduction in dissolved oxygen due to higher temperature, and higher nutrient contribution to lakes and reservoirs. With higher average temperature and a warmer air, a pattern of lengthy dry spells interspersed with brief heavy precipitation and flooding might emerge. The changing patterns of water availability and precipitation will further increase the water stress and competition among various water users.

Drought is a major natural hazard affecting the agricultural sector in developing countries. The water stress due to the variability in precipitation patterns coupled with increasing maximum, minimum and mean temperature as a consequence of climate change, does not augur well for the agriculture sector, as it may lead to higher evaporative demands, lower soil moisture and variability in water availability. The agricultural productivity may be affected to a great extent with the anticipated increases in the drought frequency, drought severity and drought duration. This may be one of the most challenging aspects of climate change impacts, as to how to ensure the food security for a growing population (Ray et al. 2015; Beddington et al. 2012; Challinor et al. 2014). The changes in the onset of monsoon and increased length of dry spells are expected to considerably affect the agriculture operations, thereby affecting the quality of the agricultural produce and its yield. However, these impacts may differ from region to region and some crops in few regions may also benefit. IPCC 2007 projected with medium confidence, an increase in crop yields by as much as 20% in East and Southeast Asia whereas a decrease in crop yields by 30% is expected in Central and South Asia by the mid-21st century. However, yield of few crops like maize is projected to increase marginally whereas the yields of rice, soybean and wheat are projected to decrease due to warming and water stress. The biodiversity and the soil health shall also be impacted adversely under the impacts of climate change induced droughts.

Climate change and drought directly and indirectly affects the forest sector. The growth and productivity of complex forest ecosystems may be affected due to changes in temperature, rainfall, weather and other related factors. The elevated levels of carbon dioxide also have an impact on the plant growth. The warming temperatures generally may lead to an increase in length of growing season. Many vulnerable species may be also susceptible to extinction. Even though many of the trees are resilient to some degree of drought, the increase in temperature coupled with water scarcity could make future droughts more damaging from the ones experienced in the past. Climate change could alter

the frequency and intensity of forest disturbances such as wildfires and storms as being witnessed in many countries across the globe. Wildfires occur due to heat waves and soil moisture scarcity in forests. In 2011, wildfires consumed more than 8 million acres of forest in the U.S. due to warm temperature and drought conditions during the early summer (USGCRP 2014). Climate change is projected to increase the extent, intensity, and frequency of wildfires. Warmer spring and summer temperature coupled with decreases in water availability, dry out woody materials in forests and increase the risk of wildfire. Fires in-turn release large amounts of carbon dioxide to the atmosphere thereby contributing to climate change (CCSP 2008). These disturbances can reduce forest productivity, change the distribution of tree species and even lead to large scale deforestation. The loss of forest cover which otherwise acts as a carbon sink and also intercepts rainfall and allows it to infiltrate into the soil, will cause erosion of the top soil and cause floods and droughts. Ironically, the lack of trees also exacerbates drought in dry years by making the soil dry more quickly.

The urban temperature is highly influenced by the urban heat island (UHI) effect, which is cause by urbanisation. The urban climate in itself is expected to increase the heat stress experienced by people during periods of high temperature, particularly during night when the UHI is the largest (Pascal et al. 2005). The urbanisation will lead to shift in the water use pattern, with more water required for domestic use for maintaining the higher water use lifestyle of cities. However, the variability in the precipitation with longer dry spells and droughts will lead to severe water scarcity in cities, most of which are already under water stress due to their fast expanding suburbs. Moreover, it is expected that droughts and floods will coexist during the same season as a consequence of climate change. The devastating Kerala floods of 2018 are an example where drought like situation prevailed just after the cessation of the floods in many parts of the State.

11.3 Climate Variables Relevant to Drought

The most important climate variables that are responsible for initiating drought conditions are temperature and precipitation. The temperature variables of interest are maximum temperature, minimum temperature, and mean temperature. The increase in the maximum temperature will have its impacts on the water supply-demand scenario. The water demands for the agriculture sector are expected to increase due to higher consumptive use needs whereas the water requirement for the domestic and industrial sectors are also expected to increase due to higher water demands for cooling systems. The higher temperature shall lead to faster melting of the ice and glaciers leading to variability in the stream flow in the shorter-term and lower water availability in the longer term. Also, the water stored in lakes and reservoirs are expected to deplete faster due to higher evaporation rates as a consequence of higher maximum temperature, thereby affecting the water supply, hydropower generation, ecosystem and biodiversity. The higher temperature will lead to further increase in the use of air conditioning systems releasing more heat into the atmosphere and need for higher energy requirement. Higher energy requirement will translate into higher power generation leading to additional water requirement for cooling systems of the thermal power stations. The higher temperature will also result in lower dissolved oxygen in surface water bodies and rivers including the deterioration of water quality. The impacts of the water scarcity and droughts shall be exacerbated under the regime of higher temperature and heat waves. The higher maximum temperature and its timing are expected to impact the crop growth, particularly during the flowering and seed development stages, which may adversely affect the crop yields.

The impacts of increased minimum temperature exhibit a larger impact on the grain yield than the vegetative growth. It is believed that the daily minimum temperature will increase more rapidly than daily maximum temperature leading to increase in the mean temperature, with detrimental effects on grain yield. The minimum air temperature affects the night-time plant respiration rates and can potentially reduce biomass accumulation and crop yield (Hatfield et al., 2011). The increase in both minimum temperature and maximum temperature coupled with erratic precipitation, aids in developing drought conditions. Precipitation is another important variable, the shortfall of which is responsible for the initiation of meteorological drought and its translation into agricultural and hydrological droughts. The variability in the rainfall is another equally responsible factor for the development of drought conditions and the changes in its onset, affects the agricultural operations and crop yields to a great extent. The erratic rainfall coupled with higher temperatures leads to soil moisture deficits and thereby affects the crop growth and crop yields, particularly in rainfed areas. Similarly, the reduction in the rainfall will lead to reduced stream flows thereby causing hydrological droughts and affecting the irrigation operations. In such a scenario, the surface water storage structures including lakes and reservoirs do not get filled upto their design capacity, thereby affecting the irrigation and hydropower operations.

Another important aspect of climate change is the reduction in the number of rainy days. The reduction in the number of rainy days indicates prolonged intervening periods of dry spell, which may affect the crop growth in rainfed areas. In such a scenario, supplemental irrigation needs to be planned for meeting the crop water requirements during the dry spell periods. High intensity rainfall is projected to increase in future under the impact of climate change. Besides causing floods, this factor is a major contributor of the land degradation process due to the erosion of the top fertile soil under the rain impact. Generally, the land degradation and drought are interlinked and may be the net result of drought and higher temperatures, which is anyhow projected to increase in the future time horizons. In many regions, the annual and seasonal precipitation is not expected to change much under the impacts of climate change, but the variability of rainfall is of much concern. The increased incidences of droughts are expected to have a bearing on the low flows in the river systems, which are very crucial for meeting the various water demands and survival of the biodiversity in the river systems.

11.4 Climate Change and Associated Impacts on Droughts

Goal 13 of the UN Sustainable Development Goals (SDGs) states that "Climate change is now affecting every country on every continent. It is disrupting national economies and affecting lives, costing people, communities and countries dearly today and even more tomorrow". People are experiencing the significant impacts of climate change, which include changing weather patterns, rising sea level, and more extreme weather events. The poorest and most vulnerable people are being affected the most. Climate change increases the odds of worsening drought in many parts of the world in the decades ahead. At the peak of the 2012 US drought, 81 percent of the contiguous United States was under abnormally dry conditions. Globally, drought struck several major breadbasket regions simultaneously in 2012, adding to food price instability.

The frequency and magnitude of droughts are expected to change in the coming decades due to climate change, but the regional evolution of future droughts remains highly uncertain (Collins et al. 2013). The investigation of the evolution of past and future droughts using climate models indicated more severe drought conditions in the future (Dai 2013; Cook et al. 2015; Sheffield and Wood 2008; Taylor et al. 2013; Zhao and Dai 2015; Swann et al. 2016; Orlowsky and Seneviratne 2012). The

hydrological outputs from climate models are not analysed directly, but instead the meteorology from the climate models are used to force offline models to derive estimates of droughts and aridity (Prudhomme et al. 2011; Schewe et al. 2014). However, potential limitations with offline modelling is that it cannot represent important land-atmosphere feedbacks that can modify the drought characteristics, such as the coupling between soil moisture and air temperature (Seneviratne et al. 2010; Koster et al. 2006; Yin et al. 2014).

The selection of an appropriate baseline period is very important for the comparison of future drought under climate change with respect to historical droughts as the reference period (Sheffield et al. 2012). Considering a longer base period, the drought indices can be better calibrated and the future drought events can be compared with appropriate historical droughts. However, the improper choice of baseline period may lead to considerable bias in the drought assessment under climate change. Say, if 1950–2008 is selected as the baseline period, it may include the effects of recent anthropogenic climate change and may mask the climate change signal in the results obtained (Trenberth et al. 2014). The incorporation of soil moisture estimates into the drought indices may improve the drought evaluations and help in avoiding misleading signals into the future. However, the uncertainties associated with meteorological forcing in hydrological models can lead to unreliable soil moisture estimates under climate change scenarios. Most of the studies on dryness and drought based on drought indices do not incorporate the aridity and thereby fail to incorporate humidity and wind speed (Sherwood and Fu, 2014; Fu and Feng, 2014; Feng and Fu, 2013).

The spatiotemporal inhomogeneity of forcing data can trigger large uncertainties in the assessment of drought under climate change. The techniques used for downscaling the coarser resolution GCM/RCM climate data to higher resolution data at the basin scale, is also another source of uncertainty which naturally gets translated into the evaluation of drought characteristics. Therefore, drought indices derived from precipitation require effective downscaling techniques that can resolve discrepancies arising from scale issues, thereby helping the stakeholders to improve decision making (Fundel et al. 2013). Drought assessments using GCM outputs are limited owing to considerable high bias associated with the precipitation estimates (Trenberth et al. 2014; Dai 2011), in addition to substantial intrinsic uncertainties originating from the inter-model variability (Langousis et al. 2014; Langousis et al. 2018; Chen et al. 2011; Deidda et al. 2000).

Even though the impact of reduction in precipitation on drought severity is evident, the possible effects of atmospheric evaporative demand (AED), another major climate component, on the drought severity are unknown. Wang et al. 2012 suggested that the vapor pressure deficit is driving the evaporative demand of the atmosphere in semi-arid regions whereas other studies have argued that the effect of climate change on AED is minimal and solar radiation and wind speed are more important (Roderick and Farquhar 2002; McVicar et al. 2012). These strong uncertainties in current AED trends, and their driving factors and uncertainties, has therefore prevented from arriving at any consensus on the evolution of drought severity in the last decades under a scenario of climate change and global warming. Thus most of the reports on climate change impacts on extreme events indicate only low-to-medium confidence of drought trends at global scale (Seneviratne et al. 2012).

Some of the prominent climate change impacts are expanding deserts and increase in the magnitude of floods and droughts. Climate projections are being used widely for assessing drought conditions for the 21st century on global as well as regional scales (Strzepek et al., 2010; Orlowsky and Seneviratne, 2012; Dai, 2013; Xu et al., 2015; Wang and Chen, 2014; Masud et al., 2017;

Thilakarathne and Sridhar, 2017). Dai (2013) found that droughts are intensifying under the impacts of climate change whereas Sheffield et al. (2012) reported that the changes in drought climatology were insignificant in the recent years. Turner and Annamalai, 2012 suggested that these contrasting results may be attributed to the limitations of the climate models in capturing the regional rainfall patterns. By about 2030, several billion people across the world could face water stress (Arnell, 1999; IPCC, 2013; Duiker and Spielvogel, 2009).

Loukas et al. 2008 evaluated the impacts of climate change on drought severity in Thessaly, Greece using observed precipitation from 50 stations and future precipitation from Global Circulation Model CGCM2 for SRES A2 and B2 scenarios. They reported that the drought severity increased for the complete region with higher drought extremes in SRES A2 scenario. The Annual Weighted Cumulative Drought Severity-Timescale-Frequency curves indicated that large increase in drought severity is expected towards the end of the century. Pereira et al. 2017 assessed the long-term trends in the drought indices including SPI and Standardized Evapotranspiration Index (SPEI) in Brazil at the time scales of 1 to 12 month. They reported that the ET rates have intensified the regional drought conditions and the selection of the time scale had a great influence on the drought trend assessments. They concluded that these trends could have significant reduction in crop yields of sugarcane and citrus crops.

Ukkola et al. 2018 analysed the historical simulations (1950-2004) of 20 models from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) for deriving a variety of drought metrics and thresholds using a standardized drought index for Australia. The variation in the drought characteristics (severity and duration) for the various types of droughts characterized by precipitation, runoff and soil moisture was evaluated. Results indicated that on a global scale, most of the climate models agreed well on most precipitation drought metrics, but systematically underestimated precipitation drought intensity as compared to the observations. However, the runoff and soil moisture droughts varied significantly across models, particularly for intensity. They concluded that the CMIP5 models show large, metric-dependent discrepancies in precipitation, runoff and soil moisture droughts during the historical period and suggested the use of multiple models in drought impact studies to account for large model discrepancies.

Margaret et al. 2008 studied the impacts of climate change and the management options for the world's river basins. They reported that the major rivers worldwide have experienced dramatic changes in flow, reducing their natural ability to adjust to and absorb disturbances. Loss of native biodiversity and risks to ecosystems and humans from increased water shortages and floods is expected in the future. The river discharges were projected under different climate and water withdrawal scenarios alongwith the data on the impact of dams on large river basins, to assess the potential changes in discharge and water stress for dam-impacted and virgin basins. The projections indicate that every populated basin in the world will experience changes in river discharge and many will experience water stress. The magnitude of these impacts is used to identify basins likely and almost certain to require proactive or reactive management intervention. Wurl et al. 2018 quantified the hydrological resilience of a water-limited arid ecosystem under future extraction scenarios and changing climate conditions, through a model that included socially-sustainable management practices. In this study, the hydrogeological and socio-economic components were linked together to address the depletion in the Santo Domingo Valley. The concluded that the depletion of the groundwater resources may lead to

groundwater drought and lead to further water stress during periods of droughts due to limited groundwater availability.

Summarizing all these above discussions, it can be concluded that still there are large uncertainties in the evolution of drought given the complexity of the drought phenomenon in itself, difficulties of drought quantification based on impacts, assessment of future climate variables and difficulties in drought prediction and forecasting and then translating it into policies. However, many of the regional studies carried across the globe and the evidences clearly indicate an increase in the drought impacts and an increase in the drought severity as a consequence of global warming. Reliance on historical climate conditions will no longer be tenable since climate change generates conditions well outside past parameters for current and future planning.

11.5 India Specific Climate Change Related Impacts on Droughts

Climate change is a great challenge to the water resources, food security, and social welfare of 1.2 billion people in the 21st century in India. India is one of the most drought-affected countries in the world (Mishra and Singh, 2011). South Asia and Southeast Asia are among most vulnerable globally to the impacts of climate change based on the risk index released at the annual climate summit at Katowice, Poland. Sri Lanka, Nepal, Bangladesh and India are ranked second, fourth, ninth and fourteenth respectively as the countries most affected by climate change in 2017, whereas Bangladesh and Pakistan are ranked eighth and ninth respectively as the countries most affected by climate change based on the 20-year data from 1998 to 2017 (Eckstein et al. 2019).

India has experienced several devastating climate extremes during recent decades. For instance, the drought of 2016 covered about 10 states and affected about 330 million people, causing an economic loss of $100 billion (ASSOCHAM Report 2016). Numerous studies have predicted an increasing trend in annual surface temperature (Rupa Kumar et al. 1994; Singh and Sontakke 2002; Subash and Sikka 2014) and a significant decreasing/increasing trend in rainfall at different regional and local scales in India (Chaudhary and Abhyankar 1979; Srivastava et al. 1998; Kumar et al. 2005; Kumar et al. 2010; Adarsh and Janga Reddy, 2015). Throughout the 21st century, it is projected that India and Southeast Asian countries will face more warming than the global mean and there will be greater variations in temperature, with higher warming rates in winter than in summer (Christensen et al. 2007). As a result of climate change, droughts have been occurring frequently due to higher rainfall variability which has led to reduced water availability and higher water demands in the last few decades (Mishra and Singh, 2010; Mishra and Singh, 2011). In India, the impact of climate change is expected to be significant in rainfed areas and coastal areas including Gujarat, Andhra Pradesh, Rajasthan, Maharashtra, Odisha, Tamil Nadu, West Bengal, Madhya Pradesh and Bihar. Many parts of the country located in these states were under drought during 2018.

The reduction in the rainfall quantum, reduction in the number of rainy days and the rise in maximum and minimum temperatures will lead to the intensification of droughts in India. Over the last five decades, very severe droughts hit India in the 1960s (1965), 1970s (1972 and 1979), in the late 1980s (1987), and late 2010s (2009), where more than 40% of the area was affected (Kaur 2009). A spatial shift is observed in the droughts in India towards coastal south India, Central Maharashtra and Indo-Gangetic plains (Mallya et al., 2016). A significant decrease in the number of wet days and prolonged dry spells have been observed during monsoon along the east coast (Sen Roy and Balling, 2004) and the Upper and middle Gangetic plains has seen significantly drying trends during summer

(Jha et al., 2013). Gossain et al. (2006) found that under the climate warming scenario, severity of droughts and intensity of floods may increase in many parts of the region.

A World Bank (2008) study for the drought prone arid regions of Andhra Pradesh indicated higher projected temperature (2.3°C–3.4°C) and an erratic increase in rainfall (4% to 8%) which may translate into deteriorating agro-climatic conditions leading to reduction in crop productivity of rice, groundnut and jowar, and substantial decrease in farm incomes. Similar study in the districts of Nashik and Ahmednagar districts of Maharashtra indicated higher projected temperature (2.4°C–3.8°C) and variable increase in rainfall (20% to 30%), which may lead to higher yields of several crops leading to increase in the farmer incomes. However, sugarcane yields are expected to decline substantially across Maharashtra as a result of heat stress caused by warmer climate. In north-western India, an increasing risk is expected because of drought, while an increase in wetness is projected in southern India (World Bank 2013).

The observed impacts of climate change on evapotranspiration (McVicar et al., 2008), soil moisture (Mishra et al., 2014), and stream flow, and climate extremes have increased during the recent decades and are likely to become more prominent under the projected climate change. Most of the studies based on general circulation model (GCMs) suggest that India will face warmer and wetter conditions under the projected future climate (Kumar et al., 2005; Mishra et al., 2014). Bhutiyani et al. 2008 studied the impact of global warming in 20th century on the stream flow pattern in Beas, Chenab, Ravi and Satluj rivers in north-western Himalayas. An episodic variation was noted in discharge in all three seasons on a longer timescale of about 82 years (1922–2004) whereas a statistically significant decrease in the average annual and monsoon discharge and insignificant increase in winter and spring discharge was reported for Satluj river. The decreasing discharge during winter and monsoon seasons in the post-1990 period, despite rising temperatures and average monsoon precipitation strongly indicated decreasing contribution of glaciers to the discharge and their gradual disappearance. On a shorter timescale of last four decades of the 20th century, the Beas River showed a significantly decreasing trend, whereas the other three rivers showed a statistically insignificant change in their average annual discharge (at 95% confidence level).

Based on the IPCC SRES A2 scenario using 17 GCMs, an increased drought frequency is projected in central, north-eastern, west central, and peninsular India in the second half of the 21st century (2050–2099) (Ojha et al. 2012). Monthly rainfall projections based on five GCMs and three emission scenarios (RCP2.6, RCP4.5, and RCP8.5) using kernel regression-based statistical downscaling shows an increase in the occurrences of extreme dry spells over central, southeast coastal, eastern, and some parts of north-eastern India for the 21st century (Salvi and Ghosh 2016).

Kumar et al. 2013 analysed the monsoon droughts over India and reported that the variability is influenced by the El Nino/Southern Oscillation (ENSO). The warming of the equatorial Indian Ocean is responsible for the observed increase in intensity of droughts during the recent decades. Kumar et al. 2017 studied the impact of climate change on water resources of upper Kharun catchment in Chhattisgarh, India. The evaluated the changes in the water balance components using SWAT and bias-corrected PRECIS projections and reported that the simulated annual discharge will decrease by 2.9% for 2020s and percolation decrease by 0.80% for 2020s. These relationships suggested for water stress in the basin in the near future and advocated studies to detect the hotspots.

Mishra and Lilhare (2016) evaluated the hydrological sensitivity of Indian sub-continental river basins to climate change using Soil and Water Assessment Tool (SWAT) and bias corrected downscaled future climate projects for RCP 4.5 and RCP 8.5. Even though they projected precipitation increase of 3-5°C in the post monsoon season, there is large inter-model uncertainty in the precipitation projections. The sensitivity analysis for Ganges and Godavari river basins showed that runoff is more sensitive to changes in precipitation and temperature rather than ET. ET is projected to increase by more than 10% for majority of the river basins. The results indicated that water availability in the sub-continental river basins is more sensitive towards changes in the monsoon season precipitation rather than air temperature and therefore the spatial and temporal (inter-annual) variability in the monsoon precipitation under the projected future climate may play a significant role.

The climate change impacts on the Upper Indus hydrology was studied by Lutz et al. 2016 using an ensemble of statistically downscaled CMIP5 GCM outputs for RCP4.5 and RCP8.5 to force a cryospheric-hydrological model for generation of transient hydrological projections for the 21st century. They concluded that the future of the Upper Indus basin's water availability is highly uncertain in the long run; mainly due to the large spread in the future precipitation projections. Despite large uncertainties in the future climate and long-term water availability, basin-wide patterns and trends of seasonal shifts in water availability are consistent across climate change scenarios. Most prominent is the attenuation of the annual hydrograph and shift from summer peak flow towards the other seasons for most ensemble members.

Reshmidevi et al. 2017 analysed the impact of climate change in Malaprabha river basin in Karnataka using the rainfall and hydro-meteorological variables simulated using Modified Markov Model-Kernel Density Estimation (MMMKDE) and k-nearest neighbour downscaling models. Climate projections from an ensemble of 5 GCMs (MPI-ECHAM5, BCCR-BCM2.0, CSIRO-mk3.5, IPSL-CM4, and MRI-CGCM2) and the hydrological model SWAT were used. A marginal reduction in runoff ratio, annual streamflow and groundwater recharge was projected towards the end of the century. An increase in the irrigation demand is expected towards the end of the century due to the projected increase in temperature and ET. It was also reported that the short and moderate wet spells are projected to decrease, whereas short and moderate dry spells are projected to increase in future. They concluded that the projected reduction in stream flow and groundwater recharge along with the increase in irrigation demand is likely to aggravate the water stress in the region in future.

Gupta and Jain, 2018 analysed the future climate data from Regional Climate Models (RCMs) for RCPs 4.5 and 8.5 for the drought characterisation using Standardized Precipitation Index (SPI), Standardized Precipitation-Evapotranspiration Index (SPEI) and Standardized effective Precipitation Evapo-Transpiration Index (SP*ETI). They reported that the future drought dynamics in most parts of India will depend on the projected increase in ET due to the increasing temperatures. They also concluded that except for few southern states, almost all regions of the country will face escalation in drought and North India is more vulnerable to increase in drought events in the near future.

Sharma et al. 2018 carried out a district-level assessment of the ecohydrological resilience to hydroclimatic disturbances and its controlling factors in India. Ecosystem water use efficiency (WUEe), defined as the ratio of net primary productivity (NPP) to ET, was used as an indicator of ecosystem functioning or its response to hydroclimatic disturbances. Higher ecosystem water use efficiency was found in lower Himalayan regions. The resilience was measured in terms of the ratio of the WUEe under the dry conditions and the mean WUEe, which indicates the ability to absorb

hydroclimatic disturbance. Out of 634 districts only 241 districts were found to be resilient to dry conditions. The forest dominated districts were found to be more climate resilient. Also out of 30 states and union territories (UTs) studied, only 10 states had more than 50% resilient area. The results of this study highlighted the need for better ecosystem management policies in the country.

Jha et al. 2019 carried out a probabilistic evaluation of the vegetation drought likelihood under changing scenarios of temperature, precipitation and soil moisture content and its implications to resilience across India. They also studied the resilience of vegetation cover to disturbances induced by a dry condition. From the investigation, it is observed that at least half the area of 16 out of 24 major river basins is facing high chances of vegetation droughts due to lowered soil moisture levels. The croplands are most likely to be affected by drought, which is of paramount concern for country's food security. It was also found that at least one-third area of 18 river basins is non-resilient to vegetation droughts. Moreover, more than fifty percent of each vegetation type is non-resilient, which points out the fragility of country's terrestrial ecosystems. This study facilitates the understanding of vegetation drought hotspot regions, factors risking the terrestrial ecosystem and their ability to withstand such conditions. The analysis pertaining to evaluation of drought characteristics and detection of climate change signals have been carried out for various basins in India and the results from few case studies are discussed.

The climate variables viz., daily rainfall and daily temperature have been analysed for the Narmada basin for the identification of climate change signals. The variation in the 1-day maximum temperature over Narmada basin is given in Figure 11.1 whereas the variation in the 1-day minimum temperature is given in Figure 11.2. It has been observed that increasing trends at 5% significance level have been observed for both maximum temperature and minimum temperature. However, the increase in the minimum temperature is at a much higher rate than the increase in the maximum temperature (Thomas et al. 2013). A significant increasing trend at 5% significance level has been observed in the 1-day maximum rainfall during 1951-2008 and is given in Figure 11.3. The Mann-Kendal test results for the changes in the heavy rainfall (rainfall > 100 mm/day), very heavy rainfall (rainfall > 150 mm/day) and extreme rainfall (rainfall > 200 mm/day) is given in Table 11.1. It can be observed that these extreme rainfall events have been significantly increasing in the Narmada basin (Thomas et al. 2015). Similarly, the daily maximum and minimum temperature have been analysed for the Chambal basin and the temporal variation in the 1-day maximum temperature and 1-day minimum temperature is given in Figure 11.4 & 11.5 respectively. An increasing trend at 5% significance level has been observed in the maximum temperature whereas no significant trend has been observed in the minimum temperature.

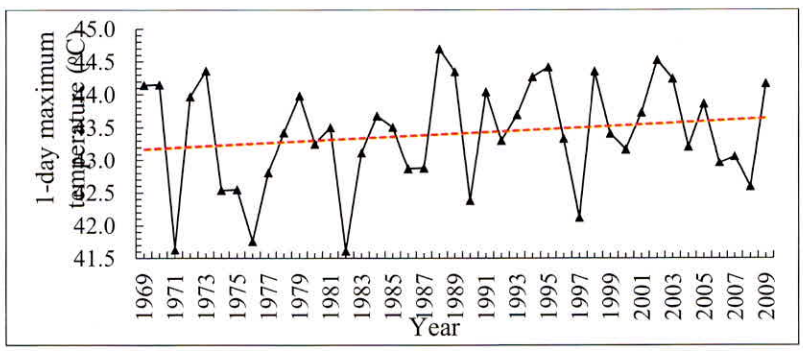


Figure 11.1: *1-day maximum temperature in Narmada basin*

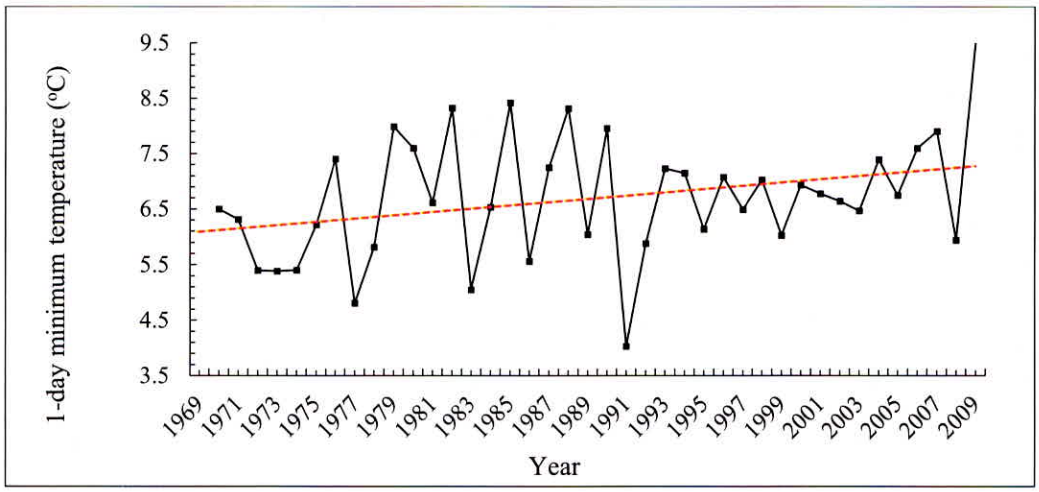


Figure 11.2: *1-day minimum temperature in Narmada basin*

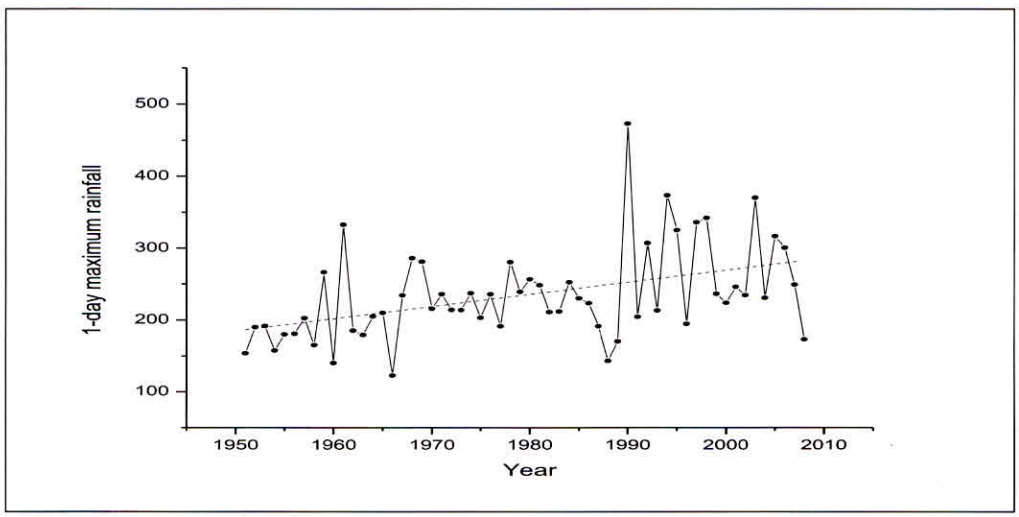


Figure 11.3: *1-day maximum rainfall in Narmada basin*

Table 11.1: Mann-Kendal test statistic for extreme rainfall events in Narmada basin

S. No.	Mann Kendal results	Heavy rainfall	Very heavy rainfall	Extreme rainfall
1.	Test statistic (z)	+2.321	+3.351	+3.704
2.	Inference	Significantly increasing	Significantly increasing	Significantly increasing

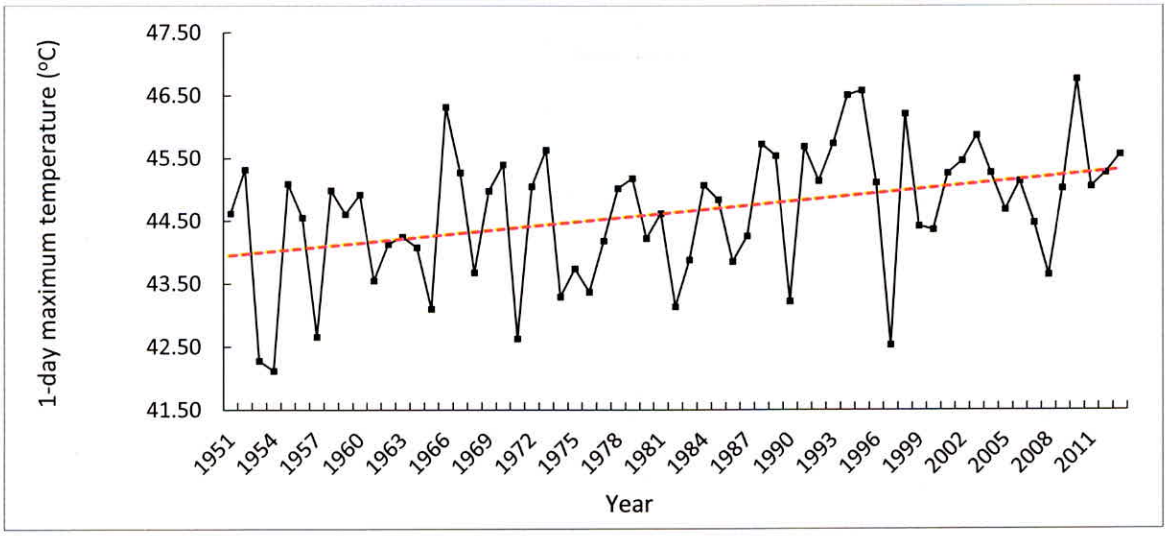


Figure 11.4: *1-day maximum temperature in Chambal basin in M.P.*

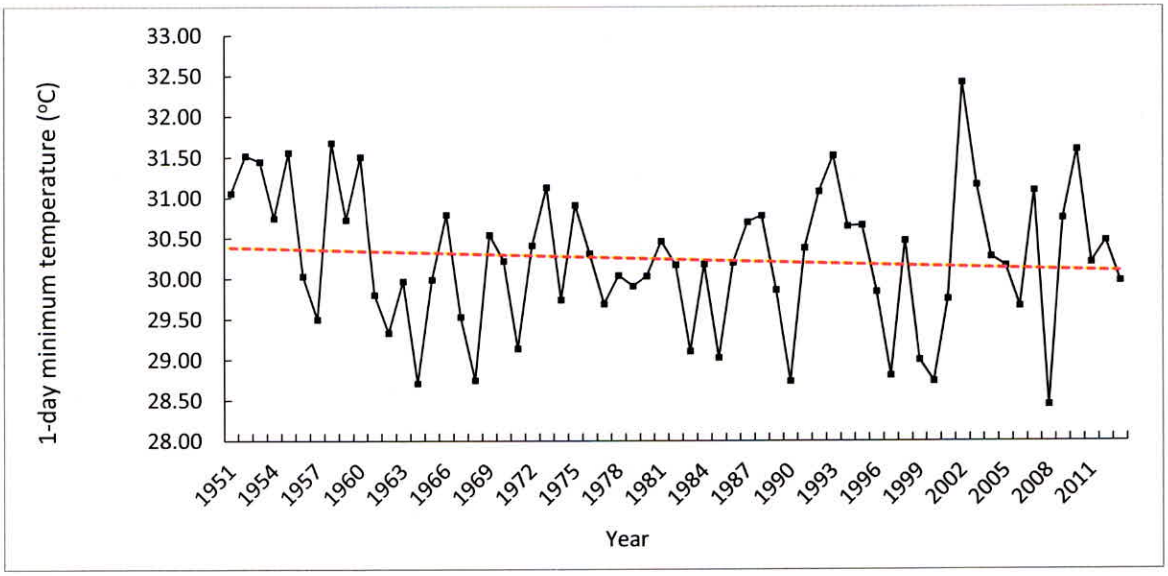


Figure 11.5: *1-day minimum temperature in Chambal basin in M.P.*

In several other major river basins of the country, the number of rainy days has decreased while the number of intense events has increased (Jain et al. 2017). The decrease in the annual number of rainy days for Chambal basin in Madhya Pradesh is given in Figure 11.6. Similarly, a warming trend has been observed across India, with 2016 being the warmest year on record since nationwide records commenced in 1901 (IMD 2016). A warming trend of 0.57°C per hundred years across India has been observed during 1881–1997 (Pant and Kumar 1997) and significant increases in the maximum winter temperature and the minimum post-monsoon temperature were noted during 1901–2000 (Sonali et al. 2017). An increase of 2-4.8°C in average temperature across India is expected based on the projections from 18 CMIP5 models from 1880s to 2080s (Chaturvedi et al. 2012).

The number of clod nights (Minimum Temperature < 10°C) has been evaluated for Chambal basin falling in M. P. and is given in Figure 11.7. It can be observed that the number of cold nights is decreasing in the basin whereas the number of very hot days (Maximum Temperature > 40°C) is increasing steadily in the basin as shown in Figure 11. 8.

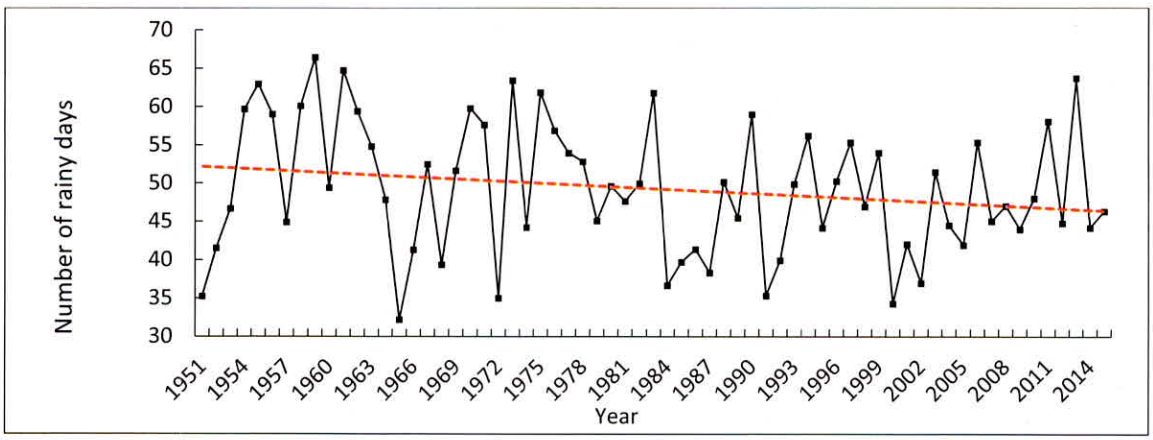


Figure 11.6: *Number of rainy days in Chambal basin in M.P*

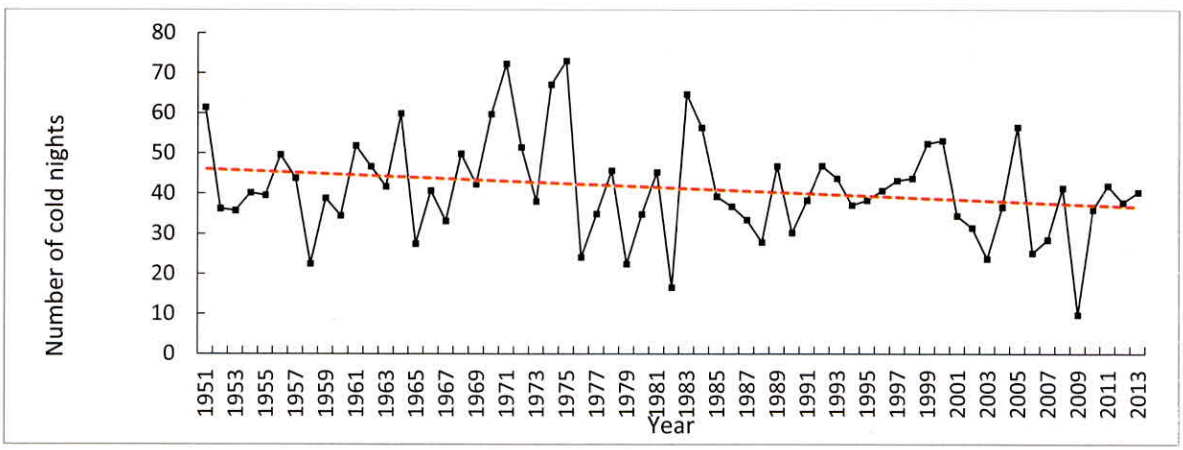


Figure 11.7: *Number of cold nights in Chambal basin in M.P*

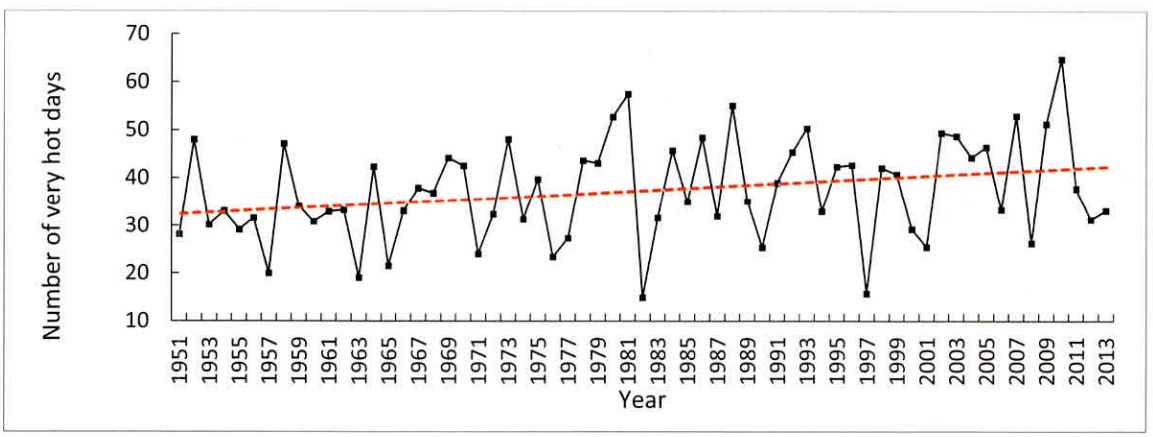


Figure 11.8: *Number of very hot days in Chambal basin in M.P*

The identification of the drought years and the drought severity is generally identified based on the departure of annual/seasonal rainfall from its normal values. The analysis carried out for Bundelkhand region in Central India for the identification of drought years along with the drought severity for the various blocks of Panna district is given in Table 11.2. It can be observed that the drought frequency varies between 1 in 3 years at Ajaygarh, Pawai, Gunera and Shahgarh to 1 in 4 years at Panna.

The identification of drought prone blocks is generally carried out based on the probability analysis of the annual rainfall. A block is considered as drought prone when the probability of the 75% mean annual rainfall is less than 80%. Table 11.3 gives the drought prone blocks identified for Chambal basin in M.P. and are given in. It can be seen that 26 blocks out of the 53 selected blocks are drought prone for Chambal basin in M. P.

Thomas et al. 2015 analysed the meteorological droughts over Bundelkhand region in Central India comprising of six districts in Madhya Pradesh and seven districts in Uttar Pradesh and reported decreasing trends in the annual rainfall and number of rainy days in few blocks in Bundelkhand, even though no clear climate change signals could be detected in the historical climate datasets. They analysed the spatiotemporal variability of drought characteristics using SPI and reported an increase in the drought frequency in Bundelkhand varying between 1 in 3 years to 1 in 5 years.

Table 11.2: Frequency and severity of droughts in Panna district

Data range/ Frequency	Drought years	Departure (%)	Drought severity	Data range/ Frequency	Drought years	Departure (%)	Drought severity
Ajaygarh				Panna			
1964-2010 (1 in 3 yr)	1965-66	-30.30	Moderate	1964-2010 (1 in 4 yr)	1965-66	-41.12	Moderate
	1966-67	-23.12	Mild		1968-69	-34.55	Moderate
	1979-80	-39.29	Moderate		1970-71	-34.17	Moderate
	1981-82	-22.47	Mild		1973-74	-30.78	Moderate
	1983-84	-28.81	Moderate		1979-80	-47.17	Moderate
	1984-85	-48.72	Moderate		1994-95	-26.41	Moderate
	1986-87	-52.13	Severe		1998-99	-23.29	Mild
	1987-88	-28.65	Moderate		2000-01	-32.83	Moderate
	1988-89	-31.69	Moderate		2002-03	-26.36	Moderate
	1989-90	-54.55	Severe		2006-07	-30.95	Moderate
	1991-92	-29.11	Moderate		2007-08	-56.42	Severe

	1992-93	-30.55	Moderate		2009-10	-28.66	Moderate
	1994-95	-48.83	Moderate	Gunera			
	1995-96	-62.90	Severe	1984-2010 (1 in 3 yr)	1986-87	-29.44	Moderate
	1998-99	-21.14	Mild		1989-90	-27.05	Moderate
	2006-07	-53.83	Severe		1995-96	-25.43	Moderate
	2007-08	-81.24	Severe		2002-03	-24.72	Mild
	2008-09	-50.88	Severe		2006-07	-47.68	Moderate
Pawai					2007-08	-31.70	Moderate
1964-2010 (1 in 3 yr)	1965-66	-56.88	Severe		2009-10	-23.65	Mild
	1966-67	-47.61	Moderate	Shahnagar			
	1968-69	-45.75	Moderate	1982-2010 (1 in 3 yr)	1985-86	-21.89	Mild
	1973-74	-33.66	Moderate		1995-96	-21.52	Mild
	1974-75	-29.20	Moderate		1996-97	-34.51	Moderate
	1979-80	-60.32	Severe		1998-99	-32.47	Moderate
	1981-82	-30.50	Moderate		2000-01	-31.39	Moderate
	1986-87	-27.86	Moderate		2006-07	-23.00	Mild
	1987-88	-39.32	Moderate		2007-08	-46.57	Moderate
	1989-90	-26.95	Moderate		2008-09	-23.77	Mild
	1995-96	-34.40	Moderate		2009-10	-23.05	Mild
	1998-99	-51.13	Severe				
	2006-07	-35.85	Moderate				
	2007-08	-30.92	Moderate				

Table 11.3: Drought prone blocks for Chambal basin in M. P.

S. No.	Station name	Normal rainfall	Probability of 75% mean rainfall	Inference
1	Sanwar	930.11	79.20	Drought prone

2	Dewas	979.45	75.28	Drought prone
3	Tonkkalan	979.65	77.86	Drought prone
4	Piploda	894.06	77.30	Drought prone
5	Ujjain	915.23	74.51	Drought prone
6	Sailana	858.54	75.66	Drought prone
7	Khachrod	858.50	75.42	Drought prone
8	Mahidpur	871.39	73.93	Drought prone
9	Ghatia	911.50	78.33	Drought prone
10	Shajapur	963.41	76.42	Drought prone
11	Jaora	809.06	76.38	Drought prone
12	Alot	876.16	74.13	Drought prone
13	Barod	920.14	74.21	Drought prone
14	Agar	921.04	77.32	Drought prone
15	Mandsour	789.21	78.85	Drought prone
16	Sitamau	839.16	74.14	Drought prone
17	Susner	902.21	76.55	Drought prone
18	Garoth	887.63	76.89	Drought prone
19	Bamhori/Chachora	1040.75	77.34	Drought prone
20	Nimach/Jawad	836.35	78.71	Drought prone
21	Bhanpura	870.20	77.07	Drought prone
22	Raghogarh	1037.97	77.04	Drought prone
23	Guna	1032.63	78.01	Drought prone
24	Ratlam	611.18	77.73	Drought prone
25	Sarangpur	720.53	79.12	Drought prone
26	Bagli	737.3	79.69	Drought prone

The temporal variation of the 3m-SPI, an indicator of the meteorological drought is given in Figure 11.9 which indicates continuous droughts in the last decade. Similarly, the 3m-SPI for the Begumganj block in Bina basin is given in Figure 11.10.

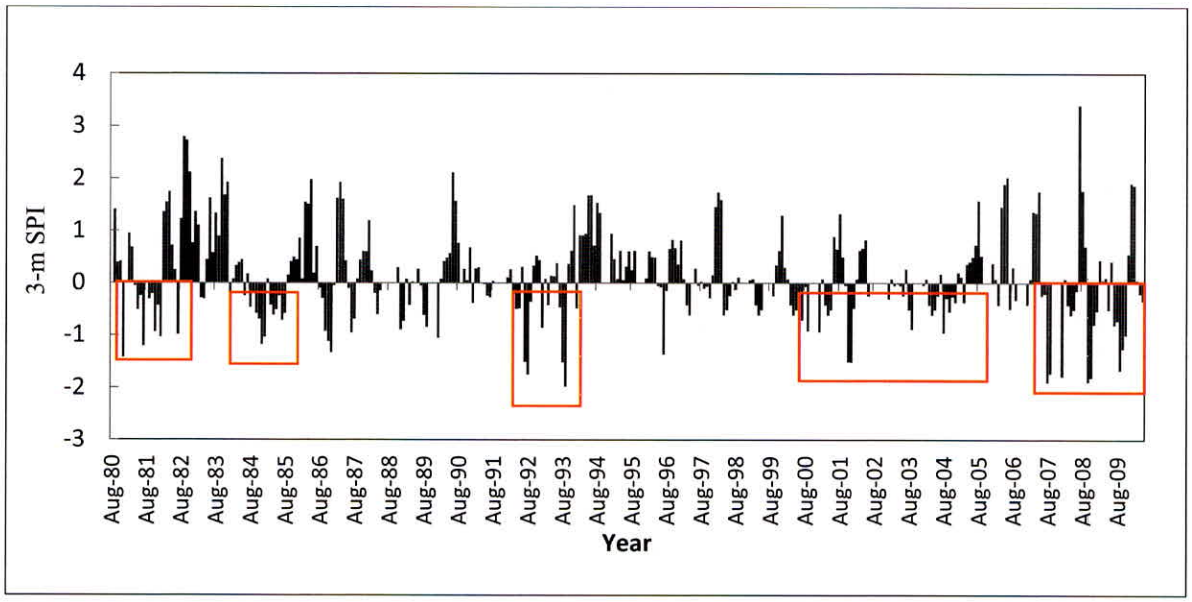


Figure 11.9: *3m-SPI at Lalitpur block in Lalitpur district in Bundelkhand*

The trend in the time series of the 3m-SPI was evaluated using the non-parametric Mann-Kendall test. Only few blocks depicted a falling trend in the 3m-SPI time series indicating the intensification of meteorological droughts in these blocks.

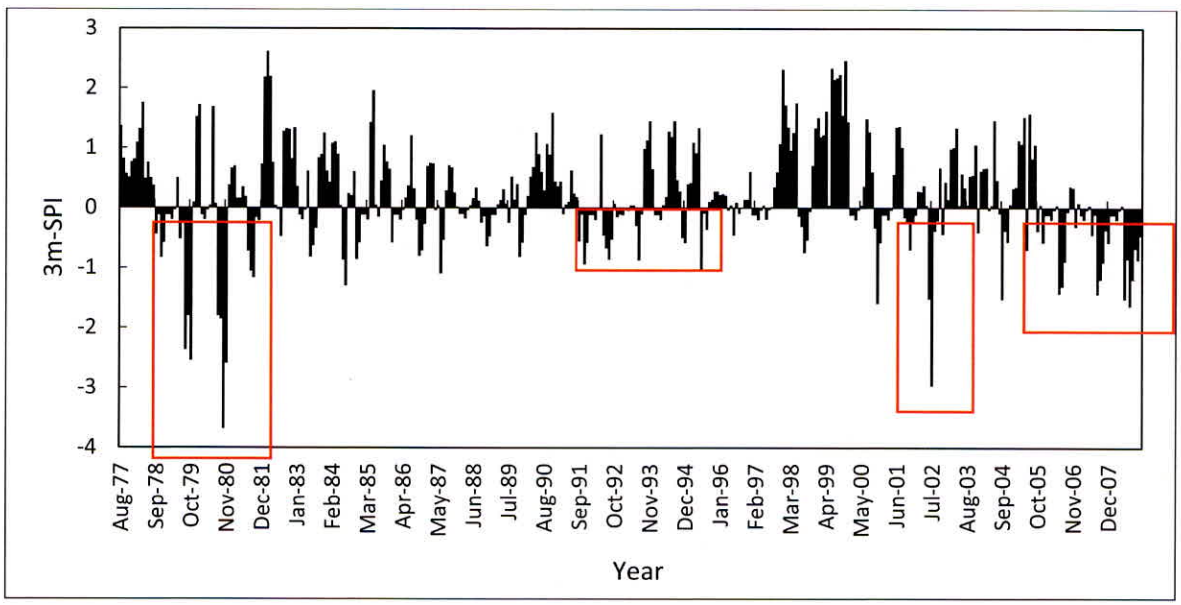


Figure 11.10: *3m-SPI at Begumganj block Bina basin*

Similarly, the surface water drought characteristics have been evaluated using the Surface Water Drought Index (SDI) and the 3m-SDI and 6m-SDI at Rahatgarh gauging site on Bina river and is given in Figure 11.11. It can be observed that there has been a continuous surface water deficit at

Rahatgarh gauging site in Bina river during 2003-04 to 2008-09. This is the period during which the Bundelkhand region faced continuous droughts.

The groundwater droughts have also been evaluated using the Groundwater Drought Index (GDI). The temporal variation of GDI at Rahatgarh in Bina basin is given in Figure 11.12. The spatiotemporal variation of groundwater drought in Bina basin during the monsoon months of 2007-08 is given in Figure 11.13. Five classes have been defined based on the severity of drought as described by GDI, viz., normal, mild drought, moderate drought, severe drought and extreme drought. The progression and withdrawal of the groundwater drought can be understood from Figure 11.13. It can be seen that the northern parts of the basin was under extreme and

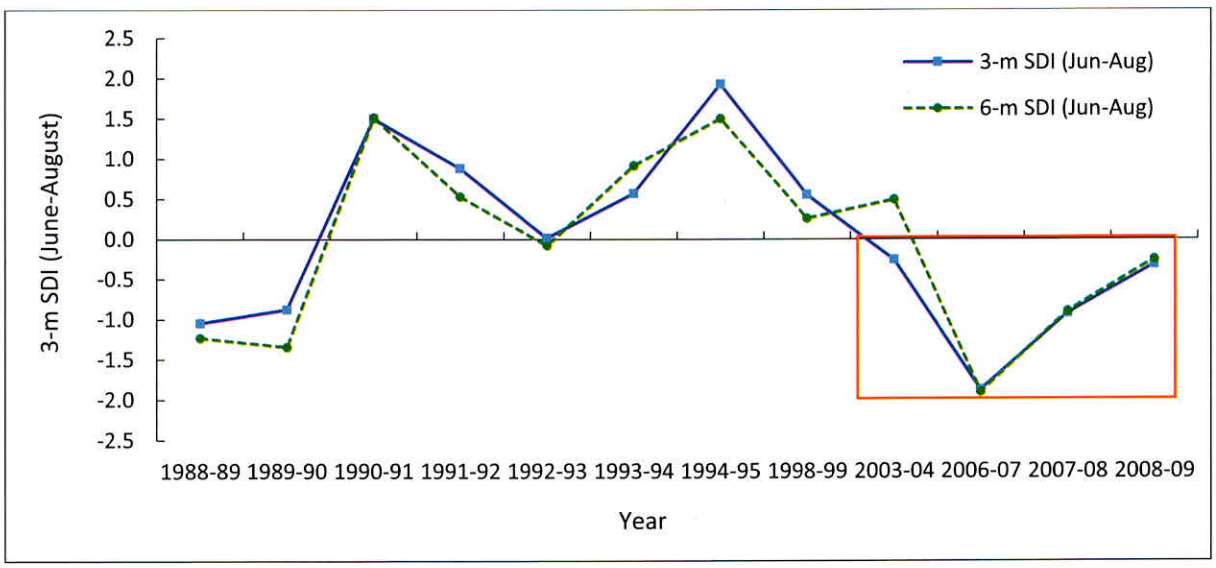


Figure 11.11: *3m-SDIand 6m-SDI at Rahatgarh gauging site on Bina river*

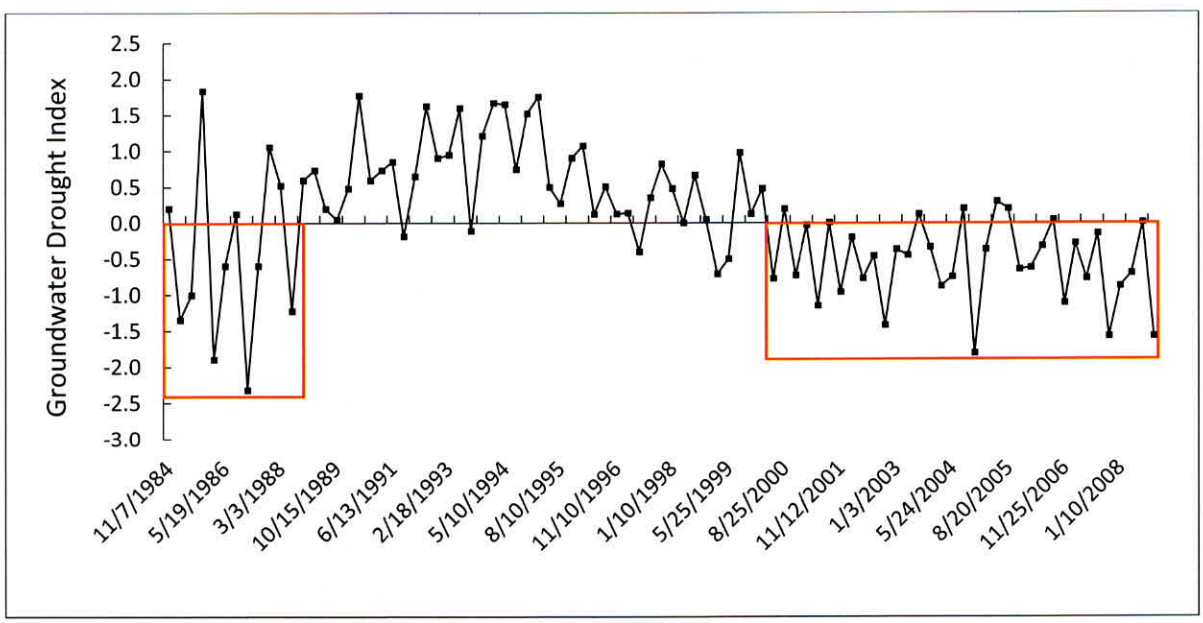


Figure 11.12: *Temporal variation of GDI at Rahatgarh in Bina basin*

severe drought conditions during June 2007. However due to the recharge of groundwater from the monsoon rainfall during the subsequent months, the groundwater conditions improved in the basin and the drought severity in the northern parts of the basin was limited to mild drought only.

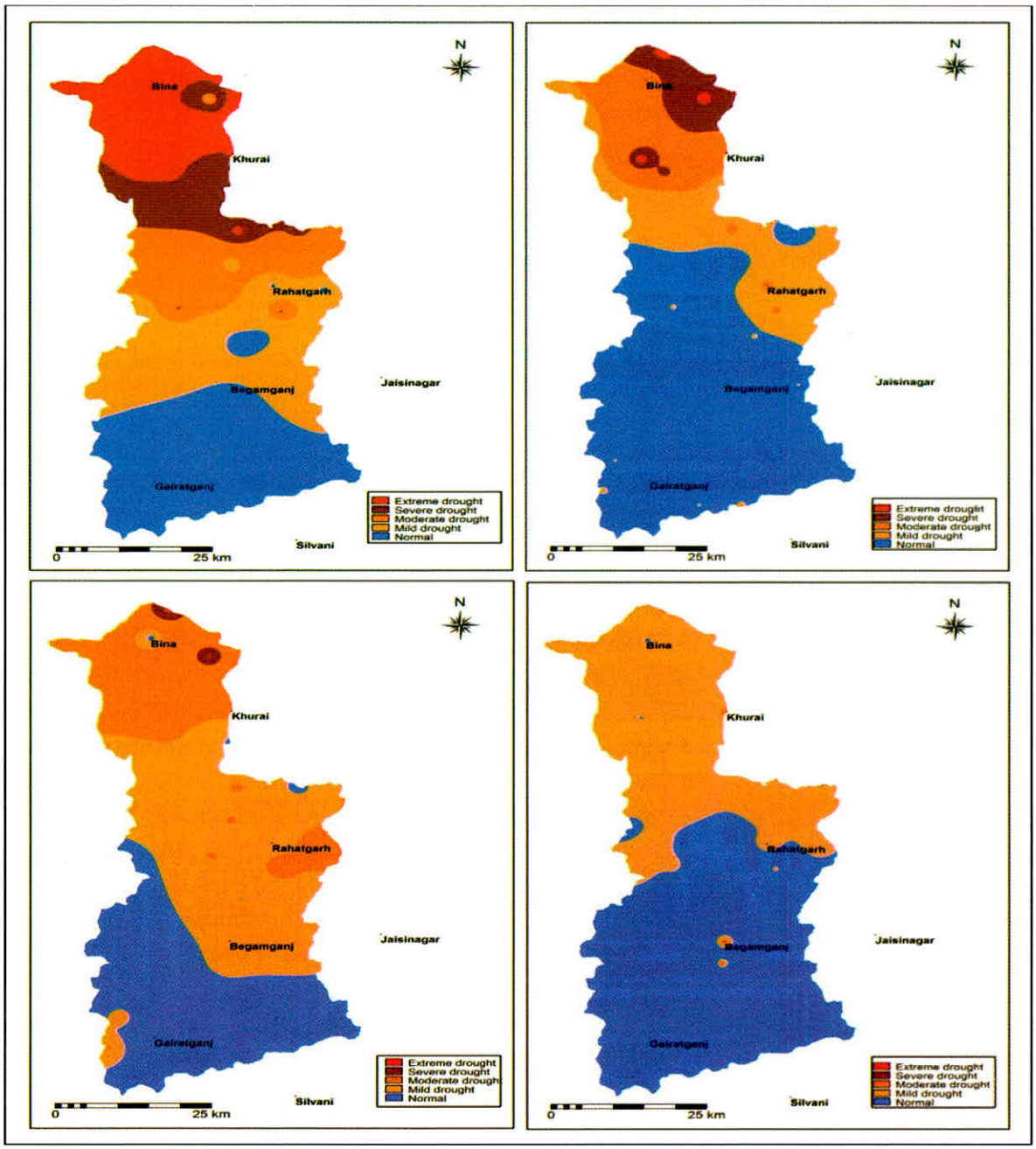


Figure 11.13: *Spatiotemporal variation of groundwater drought in Bina basin*

The changes in the drought characteristics during the future time horizons can be evaluated based on the future climate data available from Global Climate Models (GCMs) or Regional Climate Models (RCMs). An attempt was made to evaluate the meteorological and surface water drought characteristics for future time horizons. The COrdinated Regional climate Downscaling Experiment (CORDEX) datasets for South-Asia have been used for the analysis. The RCM datasets used for the analysis has been based on the Commonwealth Scientific and Industrial Research Organisation

(CSIRO), Conformal Cubic Atmospheric Model (CCAM; McGregor and Dix, 2001) experiments driven by the GCM's viz., ACCESS 1.0, CNRM-CM5, CCSM4, GFDL-CM3, MPI-ESM-LR, and NorESM-M available at 0.5° resolutions for four time horizons, viz., 1970-05 (historical), 2006-70 (near-term), 2041-70 (mid-term) and 2071-99 (end-term) for two scenarios viz., RCP4.5 (low emission scenario) and RCP8.5 (high emission scenario).

The quantile mapping technique has been used for the bias correction of the temperature and precipitation obtained from these RCMs. These climate variables have been bias corrected using the cumulative density function (CDF), which maps the CDF of the RCM variable in the historical period (1970-2005) to the observed CDF based on IMD data during the same period and then applies the same mapping to the CDF of the future RCM variables. The bias correction has been performed separately for each month. This can be considered as an enhanced non-linear technique for removing systematic biases from the RCM future climate data sets based on the CDF's of the observed and RCM climate data during the historical period.

The cumulative drought duration and cumulative drought magnitude based on 3m-SPI (summed over the particular time horizon) has been evaluated during 2006-40, 2041-70 and 2071-99 and is given in Figure 11.14. The drought characteristics have been evaluated using the bias corrected precipitation data from all the six RCMs. Similarly, the hydrological drought characteristics have been evaluated at the various gauging sites located on Narmada river upto Barmanghat gauging site. To obtain the future stream flows, the Soil and Water Assessment Tool (SWAT) was setup, calibrated and validated with the historical precipitation, maximum and minimum temperature and other climate variables. The tested SWAT setup was thereafter forced with the future bias corrected climate variables to obtain the future stream flows for the purpose of evaluating hydrological drought using SDI. The future hydrological drought scenario for Narmada at Barmanghat is given in Figure 11.15.

11.6 Non-Stationary Climate and Drought

The appropriate selection of probability distribution plays an important role in deriving robust drought indices under climate change, especially considering stationary (historical) vs. nonstationary (future scenarios) patterns of climate variables. SPI is based on either Gamma distribution or Pearson type III distribution, whereas SPEI is based on a Log-Log distribution, and these distributions perform considerably well in fitting the time series of the hydroclimatic variables over a wide range of climatic region. However, the selection of a single probability distribution is challenging (Vicente-Serrano et al. 2012). Vicente-Serrano et al. 2012 investigated the best probability distributions for Standardized Streamflow Index (SSI), and reported that log-normal, Pearson type III, log-logistic, general extreme value, generalized Pareto, and Weibull distributions provided good fits to stream flow data for flow frequency analysis. However, none of the six probability distributions were able to adequately fit the stream flow series based on the L-moment diagram. Therefore, the selection of the appropriate distribution in developing a drought index is crucial and, and can generate large uncertainties, if not chosen properly.

Stationarity, which implies physical constancy of mechanisms involved in the hydrologic processes, may not be that much applicable now, due to the substantial anthropogenic changes in the present climate. The assumption of stationarity of a time series implies that it has a probability distribution function (pdf) which is invariant with time.

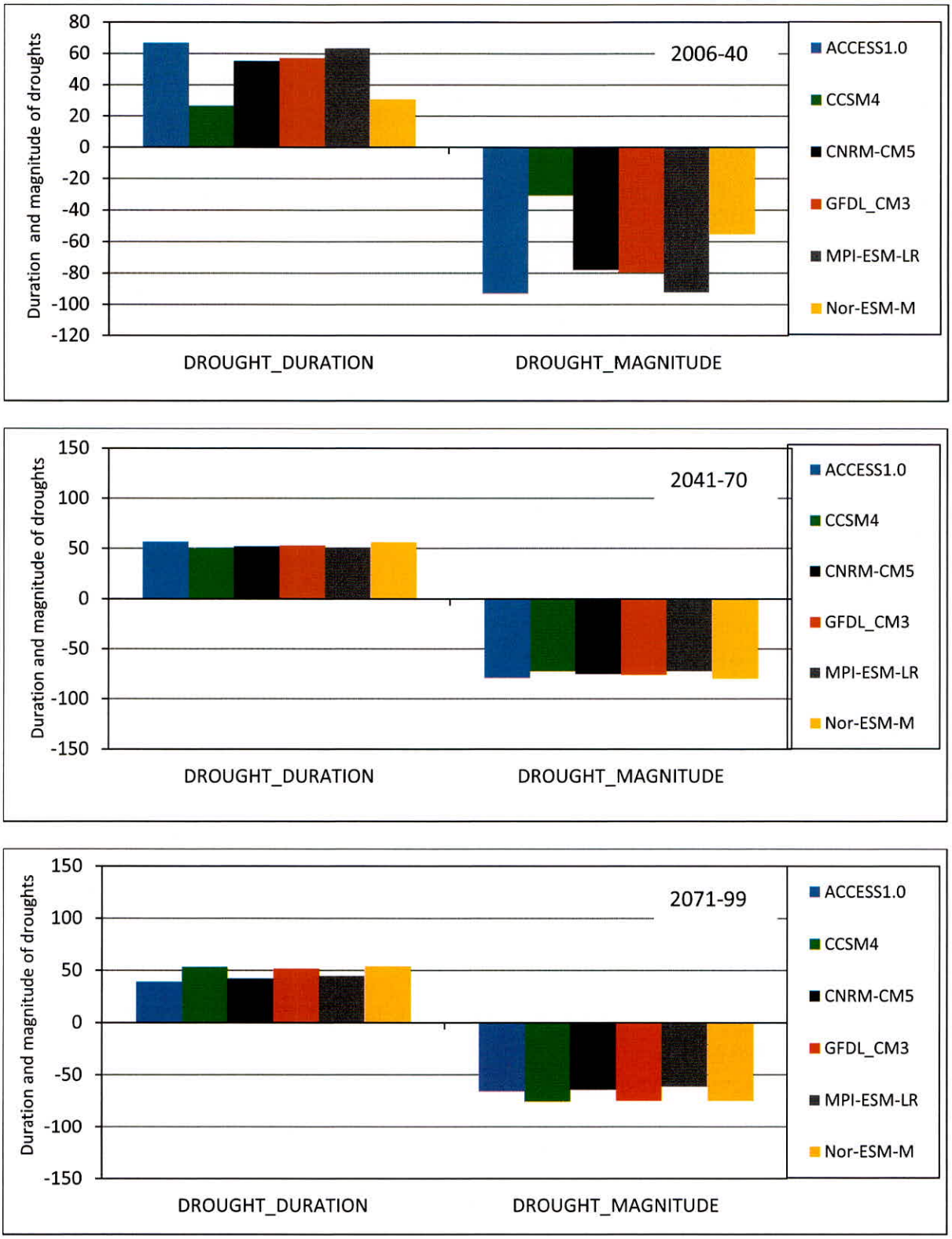


Figure 11.14: *3m-SPI based characteristics of droughts and wet days under RCP8.5 for Narmada basin upto Barmanghat.*

However, this assumption cannot be guaranteed and therefore the nonstationary models capable of producing linear and non-linear variation with time of the parameters of the selected pdfs should be used (Milly et al. 2008; Villarini et al. 2010). Drought characteristics may also be non-stationary and therefore, non-stationary statistics that are deterministic functions of time should be implemented in reliable assessment of drought characteristics in a changing climate (Milly et al. 2008). The probability distribution parameters of precipitation will change over time due to the non-stationary nature of climate variables under future climate scenarios. Therefore, it is important to consider non-stationarity by changing the probability distribution parameters over different timescales to improve drought assessment under climate change. Considering the strong association between precipitation and soil moisture, a similar assumption will also hold for soil moisture.

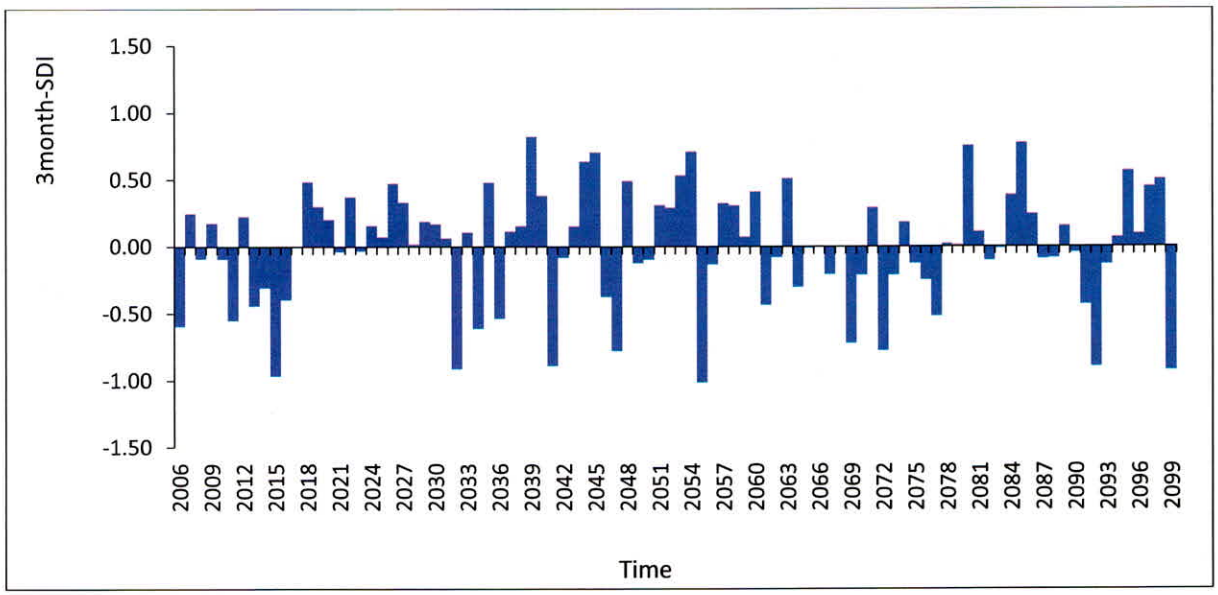


Figure 11.15: *Hydrological drought scenario for Narmada at Barmanghat*

Danielle et al. 2010 quantified the drought risk in a non-stationary climate, wherein the frequency and severity of droughts are analyzed for a range of climate states viz., different phases of the Pacific, Indian, and/or Southern Oceans, to demonstrate the marked variation of drought risk over inter-annual through to multi-decadal time scales. They highlighted the fact that drought risk is not stationary in Australia, rather it varies on a range of time scales viz., seasonal, annual, inter-decadal, multi-decadal, and the palaeo scale and is strongly influenced by the underlying climate state. It was therefore advocated that the drought management strategies based on the 'stationary climate assumption, are likely to fail, even if potential impacts of climate change are factored in. The projections of future drought risk, on either the short (seasonal up to 5 years) or long (more than 10 years into the future) term, currently have limited practical usefulness for water resource managers and government policy makers.

Osorio and Galiano, 2012 carried out the non-stationary analysis of dry spells in monsoon season of Senegal river basin using data from RCMs provided by European ENSEMBLES project for West Africa, together with the observed data. A non-stationary behaviour in the annual series of maximum length of dry spells (AMDSL) was reflected in the temporal changes in the mean and

variance. They used the modelling tool GAMLSS (Generalised Additive Models for Location, Scale and Shape) to develop regional pdfs fitted to AMDSL series for the monsoon season. Since divergent trends were observed in the value ranges for parameters of the probability distribution functions (pdfs), regional pdfs were constructed using bootstrapping distributions based on probabilistic models. The results of the study indicated an increase in the length of dry spells associated with low probability occurrence in monsoon season.

11.7 Adaptation Measures to Address Climate Change Impacts on Drought

Azhoni et al. 2017 suggested some adaptation strategies which can be broadly classified into four aspects namely, i) behavioral, cultural or attitudinal change - which includes community's role in water management, (ii) institutional and structural change which includes an integrated framework for water management (iii) operational and technological change which includes increasing water use efficiency, increasing water storage capacity, promoting artificial recharge, rainwater harvesting, new and low-cost technologies for irrigation, efficient technologies for water conservation and inclusion of climate change aspects in hydrological designs and water resources management and (iv) development and dissemination of knowledge.

Climate change being a risk multiplier for water scarcity and given India's immense geographic diversity, exact policies and interventions will need to be tailored to local conditions. The reduction in the number of rainy days, which implies an increase in dry spells calls for creating new infrastructure for surface water storages. The high intensity rainfall events will lead to faster runoff from the catchment providing less time for the rainwater to percolate and join the groundwater aquifer. Therefore, the necessary infrastructure needs to be created for increasing the groundwater storage. The artificial recharge measures can be promoted towards achieving this goal and the necessary infrastructure could include percolation tanks, injection wells and recharge shafts.

In order to tide over the water stress during droughts as a consequence of climate change, a better option is to diversify the sources of water supply including conjunctive use of surface water and groundwater to reduce the risks. The waste water reuse can be a big step in this direction and the desalination of saline water in coastal regions can provide the alternate sources of water during periods of climate change induced droughts. Another important adaptation tool could be the implementation of the watershed management measures, which focuses on preserving and restoring vegetated land cover, manage runoff and reduce erosion of the fertile top soil. Promoting climate-resilient agricultural practices and cropping patterns is another area to develop resilience against climate change impacts in the agricultural sector. The development of drought-resistant crops, crop diversification, efficient water use, and improved soil management practices can help reduce some of the negative impacts. Diversification into agro-forestry which is more resilient, as well as livestock production can reduce the sole dependence on agriculture and provide the necessary cushion to tide over the adverse situations during crop failures. A paradigm shift to smart subsidies to encourage a shift to dryland cropping that are more suited to local conditions might be a good adaption measure. The efficient use of groundwater resources will need to be incentivized.

The modification of the water demand by supporting practices that reduce water use by thermal/nuclear power plants by promoting the use of reclaimed water instead of fresh water for cooling power plants and use of closed-loop water circulation systems can help in substantial reduction of use of fresh water. Creation of monitoring networks for measurement of discharge, snowmelt,

reservoir levels, river levels, in-stream temperature, and water quality is necessary to have a better understanding of the surface water and groundwater conditions and climate change impacts. The development of real time drought monitoring systems is a much desired step towards adaptation. Drought early warning systems needs to be developed and followed by early actions based on reliability and transparency. The development of Decision Support Systems (DSS) for providing information based on alternate scenarios of climate change and droughts along with the necessary actions to be taken may also help to provide the necessary solutions to address the issues related to climate change and drought. Achieving these suggestions should enable adaptation to be recognized as an opportunity for creative solutions to support continued sustainable development in India.

11.8 Concluding Remarks

Climate change is a real challenge to the world today and it is a well-established fact that the occurrences of extreme events are ought to increase in the future due to the changes in the rainfall pattern and its distribution. It has already been observed that the incidences of droughts have increased manifold in the last two decades in the country. The projected high variability of rainfall both in space and time will aggravate the precarious situation to a much wider extent. Already many regions and cities in the country are bearing the brunt of the drought and its impacts. Therefore, it is necessary to anticipate this natural hazard well in advance so that appropriate policy frameworks can be devised to address this. However, at present there seems to be large uncertainties in the future climate data and these uncertainties are ought to translate in the evaluation of future droughts. The adoption of spatial decision support systems and real time drought forecasting models might be appropriate tools for the policy makers, whose decisions can then be realistically based on multiple scenarios and real time data.

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CHAPTER 12

CLIMATE CHANGE AND SOIL EROSION

Jaivir Tyagi

12.0 Soil Erosion

Soil erosion by water is a serious threat to soil resource. Soil erosion causes reduction in the depth of soil and soil organic matter which consequently leads to low agricultural productivity. Further, it becomes a matter of great concern to water resources engineers when eroded sediments are transported through river channels and cause sedimentation in rivers and reservoirs and reduce their carrying capacity and gives rise to the floods (Greig et al., 2005). The other potential ill-effects of soil erosion include diffuse pollution and degradation of aquatic ecosystem in rivers and water bodies. The soil erosion problem may also lead to the channel instability due to imbalance in sediment supply and sediment transport capacity of the channel (Rakovan and Renwick 2011).

The rate of soil erosion and sediment transport is governed by a complex interaction of climatic, soil, topographic, and land cover characteristics. Therefore, any changes in these characteristics will also lead to changes in soil erosion rates. Since future climate change is expected to alter many of these characteristics, an understanding of the climate change impacts on the future soil erosion rates is crucial for planning a framework of options of protection measures and management practices to meet the future challenges of adverse impacts of climate change.

12.1 Climate Change

There is a broad consensus among the researchers that both temperature and rainfall patterns are changing due to global warming. While it is perceived beyond doubt that temperature would continue to increase in future, there is less agreement as regards the changes in precipitation (Segura et. al., 2014). Concentrations of greenhouse gases in the atmosphere are increasing globally due to anthropogenic activities (Trenberth et al., 2007). Significant progress has been made by the scientific community to understand the climate change phenomena through analysis of numerous long term datasets and improved data analysis techniques. The results of several studies indicate widespread changes in precipitation and weather pattern including occurrence of intense rains, droughts and intensity of tropical cyclones at continental, regional and basin scales. However, such changes at regional or basin scale are expected to be different from global average depending on factors like atmosphere-ocean interactions and orography etc. (Trenberth et al., 2007).

Numerous studies have shown that climate change is occurring in Indian sub-continent too. The results of the studies carried out in India indicate that annual surface temperatures are rising in general (Rupa Kumar et al., 1994; Pant et al., 1999; Singh and Sontakke, 2002; Subash and Sikka, 2014),while a mixed trend of decreasing/increasing rainfall is observed at different regional and local scales (Srivastava et al., 1998; Kumar et al., 2010; Adarsh and Janga Reddy, 2015).In an analysis of monthly rainfall observations carried out for 36 climatological regions in India for the period1901-2003, Guhathakurta and Rajeevan (2008) reported significant decreases in monsoon rainfall for Jharkhand, Chhattisgarh and Kerala, while significant increases in rainfall were reported in 8 regions.

The Indian Institute of Tropical Meteorology (IITM) conducted a daily precipitation analysis using the daily rainfall data of 1901-1995 from nearly 1,000 stations located across the country. Based on the regional climate model HadRM2, the impacts of climate change on water resources were summarised as:

(i) More intense hydrological cycle will result in increased annual average rainfall and increased droughts.

(ii) Increased extreme rainfall amounts with higher rainfall intensity are projected towards the end of the 21st century in all three major river basins (the Krishna, the Ganga and the Godavari). The highest precipitation is predicted in the Godavari basin as compared with other two basins.

(iii) Increased intensity of daily rainfall is also predicted.

(iv) A decrease in the number of rainy days is predicted in the Western Ganga basin, while most parts of the Godavari and Krishna basins are likely to experience increased number of rainy days.

Goswami et al. (2006) carried out rainfall analysis over central India. Significant increasing trend was observed in the frequency and intensity of heavy and very heavy rain events, while low and moderate rainfall events exhibited significant decreasing trend. In an analysis of the summer monsoon rainfall, Singh and Sontakke (2002) found a west ward shift in rainfall activities over the Indo Gangetic Plain Region (IGPR). The rainfall showed a significant increasing trend from 1900 over western IGPR, insignificant decreasing trend from 1939 over central IGPR, insignificant decreasing trend during 1900-1984 but insignificant increasing trend during 1984-1999 over eastern IGPR.

12.2 Physical Basis of Climate Change Impact on Soil Erosion and Sediment Transport

It is perceived that soil erosion rates will change in future with the changes in climate for a variety of reasons, the most direct being a more intense hydrological cycle associated with higher amount of precipitation and high intensity rainfall events of increased frequency (Nearing et al., 2004). The soil erosion that involves the detachment of soil particles and the transport of the eroded particles (Wischmeier & Smith, 1978) is directly proportional to the rainfall erosivity (R factor as used in Universal Soil Loss Equation) which is a function of rainfall amount and maximum 30 minute rainfall intensity. The rainfall events of short duration but of high intensity result in most severe erosion on a catchment. Nearing (2001) and Pruski and Nearing (2002) observed that the change in erosive nature of rainfall would be one of the most direct factors affecting the soil erosion rates due to more intense rains in the coming decades as predicted by IPCC (2007). The climate change may cause a shift from snowfall to rainfall that will translate into increased soil erosion. The intensity, duration, and amount of rainfall and type of precipitation also affect surface runoff leading to changes in erosive power and sediment transport capacity of the surface runoff.

An indirect impact of climate change on soil erosion rates is through changes in vegetation biomass, rising temperature and increased atmospheric carbon dioxide (Zhiying and Haiyan, 2016). More precipitation may result in increased vegetation production. Rosenzweig and Hillel (1998) observed that increased concentration of carbon dioxide in the atmosphere will lead to increased plant production and thereby the increased evapotranspiration rate. The increased plant canopy / vegetation cover provides a protection to soil surface and reduces detachment of soil particles by intercepting the raindrops and dissipating their energy. Temperature changes will also cause decrease or increase in biomass production levels and rates depending on the temperature stress and the altered growing season of the crops. The change in temperature and rainfall pattern may also lead to change in land-use

pattern in order to adapt to a new climatic regime (Williams et al., 1996). The type of land use and vegetation cover influences the overland flow in terms of the roughness. The vegetation and the crop residuals on the ground surface act as dams and reduce the velocity and the sediment transport capacity of the flow.

The resistance of soil against the erosive forces of water depends on the soil texture, structure, permeability, and organic matter content. In general, the soils which have higher permeability, higher organic matter content and improved soil structure are less susceptible to erosion. An increase in moisture level, soil and air temperature due to climate change may cause residue decomposition at a faster rate due to increased microbial activities. Carbon compounds added to soil through soil organic matter affects both the chemical and physical properties of the soil including enhancing the infiltration rate, improving the soil moisture holding capacity, improving and stabilising the soil structure, developing strength of soil aggregates which reduces soil erodibility and provide important benefits in the prevention of erosion and desertification and for the enhancement of bio-diversity. Soil aggregate stability is positively correlated with clay content but negatively correlated with silt and very fine sand content. Higher soil erosion rates under intense hydrological cycle will modify soil properties. The erosion causes loss of organic matter and effects changes in soil texture, porosity, and soil water holding capacity (Heckrath et al., 2005). Erosion specifically detaches finer-sized soil particles (mainly silt) which have higher chances of transport by surface flow than coarser particles. With increasing degree of soil erosion, silt fractions of eroded soil horizons will decrease while sand and clay fractions will usually increase. The eroded fine particles clog soil pores, causing surface crusting, reduction in the soil's infiltration rate, and an increase in runoff. Increased velocity and depth of surface runoff due to intense rainfall events under climate change scenario will further increase its transport capacity and aggravate the sediment transport process in the river catchments. Thus, the rate of soil erosion and sediment transport which are non-linearly related with climatic and catchment characteristics are bound to change in future due to climate change.

12.3 Observed Impacts of Climate Change on Soil Erosion and Sediment Transport

Impacts of climate change on soil erosion are being experienced in various parts of the world (Zhiying and Haiyan, 2016). While there is no dearth of the available studies in the literature on climate change and its impact on water resources, the studies related to its impact on soil erosion and sediment transport are, however, very limited (IPCC, 2007). The available studies have attempted to analyse the impact of various direct and indirect factors related to climate change on future soil erosion rates (Yang et al., 2003; Zhang and Nearing, 2005; Zhang, 2007; Nunes et al., 2009; Maeda et al., 2010; Nunes and Nearing, 2011; Nunes et al., 2013; Mondal et al., 2015; and Khare et al., 2017).

Mathematical modelling has been a common and essential approach in projecting future impacts of climate change (Zhiying and Haiyan, 2016). The approach utilizes General Circulation Models (GCMs) and a suitable hydrological/soil erosion model. The GCMs provide projected climatic characteristics under downscaling for different climate scenarios which serve as input data to the hydrological/soil erosion model to get the soil erosion under changed climate. USE, RUSLE, EPIC, WEPP, SWAT and Erosion 3D are some of the commonly used models for climate change studies. Two downscaling techniques namely, the dynamic downscaling and the statistical downscaling are employed to produce a local scale climate series from global scale series generated by the GCMs.

Based on the above approach, expected impacts of climate change on soil erosion have been estimated by various researchers. The results indicate high variability in future soil erosion rates and sediment yield across the world due to difference in climatic features and the complex interactions that undergo in a catchment under altered climate to produce soil erosion. Although, both increasing and decreasing soil erosion rates have been reported under climate change depending on geographical location, precipitation characteristics, climate scenarios, topographical conditions, and land use/management practices, yet, most studies conclude an increase in the future soil erosion rates under climate change.

Rainfall being a major factor inducing soil erosion, a number of authors have analysed the impact of change in rainfall on the erosion. Pruski and Nearing (2002) reported a change of 1.7% in soil erosion and 2% in runoff for every 1% change in precipitation amount. Zhang (2007) found that an increase of 4-18% in precipitation would increase the runoff and soil loss by 49-112% and 31-167% respectively. In analyzing the change in soil erosion for 11 regions from five US States for the period of 2040-2059, O'Neal et al. (2005) found that a 10-20% increase in annual precipitation resulted in an approximate 300% change in runoff and soil loss. These results indicate that keeping other factors unchanged, the higher amount of precipitation would lead to higher runoff and higher soil erosion.

Since rainfall intensity is known to affect the soil erosion rates greatly, Routschek et al. (2014) studied the impact of rainfall intensities in a catchment in Germany for the period 2031 to 2050 and found that the expected increase of 23% in rainfall intensity during June to August at Chemnitz climate station would result in an increased soil loss (+ 64%) by the year 2050.Despite predicted decline of precipitation, increased soil loss has also been reported due to increased frequency of intense rainfall events in the US(Zhang, 2012),Germany (Michael et al., 2005), Portugal (Nunes et al., 2009), Thailand (Plangoen et al., 2013), Iran (Azari et al., 2016) and Morocco (Simonneaux et al., 2015). The rainfall intensity is reported to have greater impacts on soil erosion than the storm frequency i.e. the number of rainy days (Pruski and Nearing, 2002). Nearing et al.(2005) observed that the combined effect of changes in precipitation amount and precipitation intensity would be more severe than the change in any single factor. Yang et al. (2003) predicted the global average soil erosion to increase by 9% by the year 2090. The increased soil loss is attributed to the increased erosive power of rainfall due to changes both in intensity and amount of rainfall.

The rise in temperature has an influence on the soil erosion as higher temperature may shift the snowmelt timing and would also increase the proportion of precipitation that would be received in the form of rainfall instead of snowfall. Mukundan et al. (2013) reported an increase in soil erosion and sediment yield during winter and early spring as a result of increased precipitation occurring as rainfall; and increased evapotranspiration and decreased runoff in summer due to higher temperature.

Soil erosion, however, may not always increase with increased amount and intensities of rainfall because of increased vegetation cover under increased CO_2 concentration due to climate change. For EI Reno watershed in US, Zhang and Nearing (2005) reported that runoff and soil erosion will decrease due to better crop growth, and higher evapotranspiration and evaporation because of increased temperature. On the other hand, a 13% increase in sediment yield was computed in the Pearl River basin of Southern China despite a 3°C increase in annual temperature (Li et al., 2011). One of the possible reasons for higher sediment yield could be the higher evapotranspiration demand under extreme temperature that induced the decreased vegetation growth. It is reported that the susceptibility of soil erosion to climate change is more in agricultural land use as compared to that in natural land

uses viz., forests which effectively maintained the erosion level at less than 1 tonne/ha/year even under climate change scenario (Nunes et al., 2013; Serpa et al., 2015).

Comparatively, a very few studies on impacts of climate change on soil erosion are available for Indian catchments. The effects of climate change on change in rainfall erosivity for past and future rainfall (1961-2100) were studied by Mondal et al. (2016) in a part of the Narmada river basin in the central India. Nine rainfall locations were selected in the study area and surrounding. A decreasing trend with statistically less than 0.05% significance level was observed in the past rainfall. The future rainfall was predicted using GCMs data from HadCM3 (A2 and B2 scenario) and CGCM3 (A1B and A2 scenario). The projected rainfall for the basin was generated using Statistical Down Scaling Model (SDSM).The predicted rainfall was found to increase gradually in 2020s, 2050s and 2080s. All the stations showed a significant increasing trend (at 0.05% significance level) in the projected rainfall in all the GCMs scenarios with a minimum increase in the A1B scenario of CGCM3 and maximum increase in the A2 scenario of HadCM3.As a result, the increase in rainfall erosivity in 2080s was found to vary from 20.95% in A1B scenario of CGCM3 to 202.40% in A2 scenario HadCM3.The rainfall erosivity during 2020s and 2050s of all nine stations was found to vary from -32.91% to 24.12% and -18.82 to 75.48% respectively. The increase in rainfall erosivity for the projected rainfall is indicative of their higher erosive potential in future.

Mondal et al. (2015) estimated the future soil erosion because of climate change in Narmada River Basin in Madhya Pradesh, India. The future precipitation was generated by downscaling GCM data of HADCM3 for A2 scenario using least-square support vector machine (LS-SVM) and SDSM. The soil erosion in the basin was evaluated using the Universal Soil Loss Equation. The projected precipitation averaged for 30 years during 2011-2040 (denoted by 2020s), 2041-2070 (denoted by 2050s) and 2071-2099 (denoted by 2080s) showed an increase at all the stations. The soil erosion was found to increase by 18.09% in 2050s and 58.9% in 2080s using LS-SVM downscaled data, and 15.52% and 105.80% in respective years using SDSM data. However, a decrease in soil erosion by 5.47% and 8.51% was indicated in 2020s by LS-SVM and SDSM data respectively.

Khare et al. (2017) assessed the impact of climate change on soil erosion in Mandakini river basin, a hilly catchment in Uttarakhand, India using the downscaled GCM data and the USLE. The projected mean rainfall for the study area was computed as 1077, 1350, 1595 and 1978 mm and the rainfall erosivity factor (R) was estimated at 459, 558, 646, and 784 metric tonnes ha^{-1} cm h^{-1} 100^{-1} for 1961–2001, 2020s (2011-2040),2050s 2041-2070), and 2080s (2070-2099) respectively. The sediment yield computed for respective years as 586337, 711328, 824050, and 999746tonnes/year show a remarkable increase in sediment yield from base period of 1961-2001 to 2080s

From the foregoing discussion and available researches, it is clear that the climate change can impact the soil erosion rates directly and indirectly by altering climatic and other catchment characteristics. The expected higher intensity and higher amount of rainfall in future are the key direct factors that will have the greatest impact on soil erosion rates. The catchment condition, specially the change in vegetation and soil characteristics due to climate change can also affect the soil erosion, runoff generation and sediment transport considerably. The soil erosion under climate change is therefore a very complex process but its estimation is highly required to assess the future possible environmental and agricultural problems.

12.4 Concluding Remarks

The climate change has the potential to increase the soil erosion rates and its associated adverse environmental impacts. Therefore, it is crucial to model the future erosion rates using integrated modelling approach in order to assess the potential future agricultural and environmental problems that may arise due to higher soil erosion. The modelling framework that would ideally consist of hydrological, erosion, climate, climate-induced land use/cover change, and crop management practices models is required to achieve more realistic assessments of impacts of climate change on hydrology and associated soil erosion/ sediment transport. The model would help achieve a broad range of results for different crops, crop rotations, shift in cropping season (planting and harvesting dates) for planning the adaptive control measures under future climate change.

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CHAPTER 13

UNCERTAINTY IN HYDROLOGIC IMPACT ASSESSMENT

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13.0. Introduction

Changes in the frequency, magnitude, spatial extent and duration of extreme hydroclimate are one of the most significant consequences of climate change (e.g. Jones, 1999; Seneviratneet al., 2012). Therefore, knowledge of severity, spatial and temporal variability, duration, and frequency of occurrence of extreme hydrological events (i.e. floods or droughts) is important information for an effective planning and design of water resources infrastructure and distribution of water resources to overcome the detrimental impacts of extreme hydroclimate. To project the impacts of changing hydroclimate on the hydrology of Indian sub-continent, it is necessary to analyse the projected future climate at a regional scale. However, this involves three major concerns: (a) general circulation models or global climate models (GCMs) are coarser than the scale of the local phenomenon influencing the regional climate, (b) GCM simulations are primarily the projections of the mean climatic conditions limiting the direct use of these simulations in the study of extreme hydrological events, and (c) the uncertainty introduced into the GCM simulations at several stages of its development and run. Therefore, the issues pertaining to the spatial resolution, extreme climate simulation and model uncertainty needs to be addressed prior to conducting any regional scale impact studies. This chapter discusses various sources of uncertainties in GCM simulations and methods to quantify and/or reduce these uncertainties.

The accuracy of global scale GCMs can be well understood by exploring the physical processes and laws associated with them. A confidence in the projections from GCMs comes from the correct representation of physical laws associated with the climatic processes (e.g. law of conservation of mass, energy and momentum) and better understanding of the current regime of climate, i.e., variability in temperature, precipitation etc. The ability to simulate historical and future climate using a GCM will depend on how relevant the selected models are to the study area of interest (Daniels et al., 2012). Intergovernmental Panel on Climate Change (IPCC) has generated multiple versions of GCMs, from after 1998, with large number of variables associated with certain factors including the changing rate of greenhouse gas (GHG) concentrations, CO_2 concentration levels in the atmosphere, land-use changes, aerosols concentration and ocean warming (Pachauri et al., 2014), most of them have been successfully utilized in various climate change studies (e.g. Ghosh and Mujumdar, 2008; Goyal and Ojha, 2012;Apurv et al., 2015; Singh et al., 2017; Tiwari et al., 2018). However, the projected outcome from each GCM differed considerably and the amount of uncertainty varied with each model run, despite the similar types of application (Pachauri et al., 2014). For example, majority of the GCMs depicted a significant increase in the global averaged near surface temperature over the last few decades, likely associated to the accelerated anthropogenic emissions of GHG, and the future projections indicated further increase however, the magnitude of this change/increase varied from one model to another, for the same period and same region (Chaturvedi et al., 2012; Pachauri et al., 2014; Tiwari et al., 2018), Figure 13.1a.

13.1. Sources of Uncertainty

Although several GCMs, approved by the IPCC exist to simulate climate of the 21st century, intermodal uncertainties are one of the major issues in these simulations. No simulation from one GCM is same as any other simulation from a different GCM, despite using the same emission scenario or representative concentration pathway (RCP), leading to an intermodal uncertainty. Intermodal uncertainty is primarily because of the uncertainties accumulated in each model from various sources at several stages of its development and run. Uncertainty in the climate projections is initially introduced at the stage of model building with the model physics and the numerical structure (method of solving differential equations) used, at the stage of its run with the assumed future emissions of GHGs chosen to force the model, and finally at the downscaling stage with the method or technique adopted (Evans et al., 2012). These three major sources of uncertainty, i.e. uncertainty from GCMs, uncertainty from future emission scenario and uncertainty from downscaling technique, together limit the confidence of the future climate projections from any GCM.

13.1.1. Uncertainty from GCMs

Uncertainty from GCMs is primarily due to the misrepresentation of the climate processes (model physics) or erroneous model structuring (interrelationships) or failure in representing the interannual or decadal variability (Mishra et al., 2014; Tiwari et al., 2014; Xueet al., 2014; Joseph et al., 2018).However, the major source of uncertainty in any climate model is the representation of complex interactions among the subsystems (atmosphere, hydrosphere, lithosphere, etc.) of the global climate system(Berliner, 2003). Although the underlying physical, chemical and biological processes of the earth's system is well understood, numerically representing such processes in a model is cumbersome leading to parametrization of several processes occurring at a spatial scale much smaller than the scale used in the GCM building. In several recent studies, it has been shown that the projected changes in climate from various GCMs differed in magnitude and frequency (IPCC2014). To characterize uncertainty between various GCMs, the Coupled Model Intercomparison Project (CMIP) was initiated by the World Climate Research Programme (WRCP) in 1995 to coordinate experiments by different groups of modellers. Several studies compared the earlier versions (e.g. CMIP2/CMIP3) of GCM projected climate with that of the latest versions (CMIP4/CMIP5) and the results indicated substantial differences (e.g. Onyutha et al., 2016; Sharma et al., 2018). Despite the improvements in model building over the years, the magnitude of uncertainties has not changed significantly (IPCC 2014). Although uncertainty from GCM is inevitable, it can be quantified and addressed to produce a plausible future projection (Mishra et al., 2014; Joseph et al., 2018). For instance, since the ability of any model in perfectly simulating the regional climatic processes is limited, the projections from several GCMs are assembled to produce a mean ensemble or median ensemble representing the most probable future climate (Chaturvedi et al., 2012; Mishra et al., 2014; Trzaska and Schnarr, 2014; Joseph et al., 2018), Figure 13.1.

Uncertainty is also associated with the type of parameterization adopted to represent a specific process in model building (Dickinson, 2012). Furthermore, the method of numerical solution used in solving the non-linear differential equations of the complex earth climate systems is the other source of uncertainty. Several numerical techniques exist to solve these differential equations, and the accuracy of each technique varies depending on the type of problem and the computational costs. Thus, in spite of better understanding and representation of the physical processes controlling the climate, the numerical method induces uncertainty into the solution of the fundamental differential equations

(Harvey, 2012). The other and important source of uncertainty arise from the initial conditions provided to run the model, which can simulate one possible future climate among many others that have the same probability of occurrence. By slightly varying the initial conditions and running the model again, several other possible scenarios can be developed. If averaged over several decades, all these scenarios produce a very similar mean climate statistic, but the individual scenarios help us to better understand and evaluate the possible extreme events (Alexander & Telbadi, 2012). The amount of uncertainty associated with each of these sources is unknown, but the cumulative impact from various GCMs can be quantified by the amount of spread in the projected climate from these GCMs (e.g. Rupa & Mujumdar, 2019).

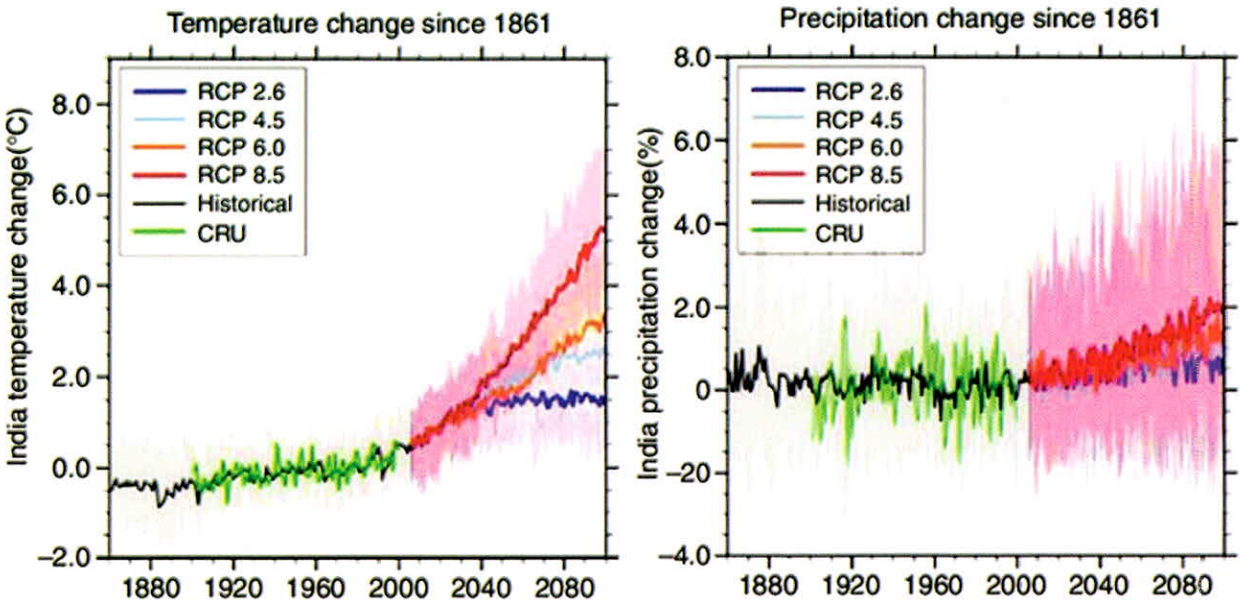


***Figure 13.1**. CMIP5 model-based time series of temperature and precipitation anomalies (historical and projections) from 1861 to 2099 relative to the 1961-90 baseline for the RCP scenarios. Shaded area represents the range of changes projected by the 18 models for each year. The model ensemble averages for each RCP are shown with thick lines. The observed temperature and precipitation trend from CRU is shown by green line and the solid black line refers to model ensemble values for historical simulations. (Source: Chaturvedi et al., 2012)*

13.1.2. Uncertainty from Future Emission Scenario

The second major source of uncertainty in GCM simulations is the knowledge of future environment policies or the magnitude of GHG emissions. Prediction of future GHG emissions is a complicated assignment, and is dependent on several factors including population growth, technological advancements, economic growth, sources of energy and their usage. In general, the GHG emissions are substantially influenced by the future climate policy decisions and human activities. The projections of GHG emissions for use in GCMs are earlier presented as emission scenarios (Nakecenovic et al., 2000), and currently as RCPs (Moss et al., 2008) by the IPCC. "RCPs are referred to as pathways in order to emphasize that their primary purpose is to provide time dependent projections of atmospheric GHG concentrations. They are representative in that they are one of the several different scenarios that have similar radiative forcing and emission characteristics" (Moss et al., 2008). Given all the uncertainties involved, several RCPs have been created to cover a range of plausible emission scenarios

based on the radiative forcing, currently four RCPs, viz. RCP8.5, RCP6.0, RCP4.5, and RCP2.6, are being used (Moss et al., 2008).The optimistic GHG emission scenario aims to likely keep global warming at less than 2°C above pre-industrial temperatures (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and the worst case scenario with very high GHG emissions (RCP8.5).For example, the worst cases scenario or the high GHG emissions pathway (RCP8.5) is based on the assumption that by 2100, the radiative forcing is as large as 8.5 W/m^2 and might increase further. These four emission scenarios produce a range of changes in future precipitation and temperature. For instance, the projections of global surface temperature indicate that the major source of uncertainty arise from the range of GCM simulations based on various GHG concentrations or RCPs, i.e. RCP scenario spread (Hawkins and Sutton, 2009; 2011; Kitmanet al., 2013), Figure 13.2.

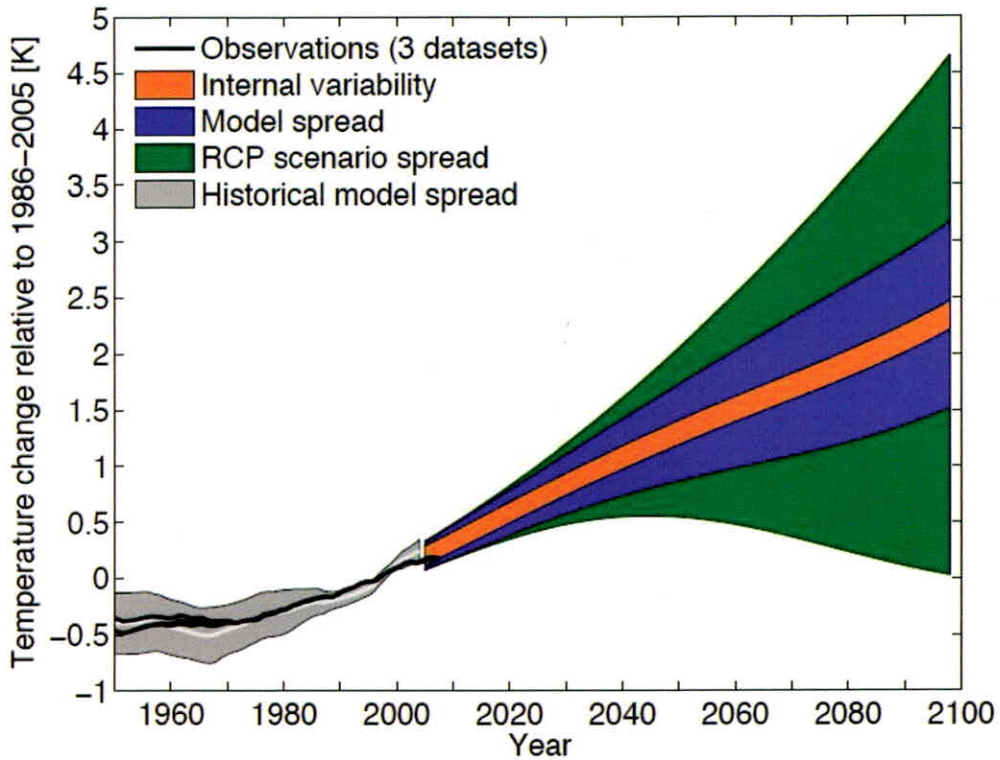


Figure 13.2. *Projections of global mean surface air temperature together with the quantification of uncertainty arising from internal variability, model spread and RCP scenario spread (Source: Kitmanet al., 2013).*

13.1.3. Uncertainty from Downscaling Technique

GCM outputs are currently inadequate for producing reliable and consistent hydrological forecasts, in response to the projected climate change, at spatial scales relevant for decision-making. Therefore, to assess the impacts of climate change at regional scale, downscaling techniques are adopted to spatially scale down GCM simulations. The assumptions made in downscaling technique, dynamical or statistical, further introduces uncertainty in the projections of regional hydroclimate. Dynamical downscaling involves the same set of uncertainties as mentioned for the GCM uncertainty in addition to the uncertainty from the stationarity assumption, i.e. the parameterisations of physical processes represented in GCMs or regional climate models (RCMs) remain valid in the future. The method of downscaling initially inherits the uncertainty associated with the GCM and emissions scenarios, and

the uncertainty is further increased from the assumptions made in downscaling technique (Chen et al., 2011; Teng et al., 2015; Sharma et al., 2018). Therefore, evaluating trade-offs in error associated with GCM and emission scenario and that induced by the assumptions made in downscaling technique is vital. With the same GCM, different downscaling techniques produce different projections. For example, Chen et al., (2011) evaluated six different techniques to downscale the projected climate from the same GCM and found that the simulated streamflow does not agree with each other, despite using the same hydrological model, Figure 13.3.

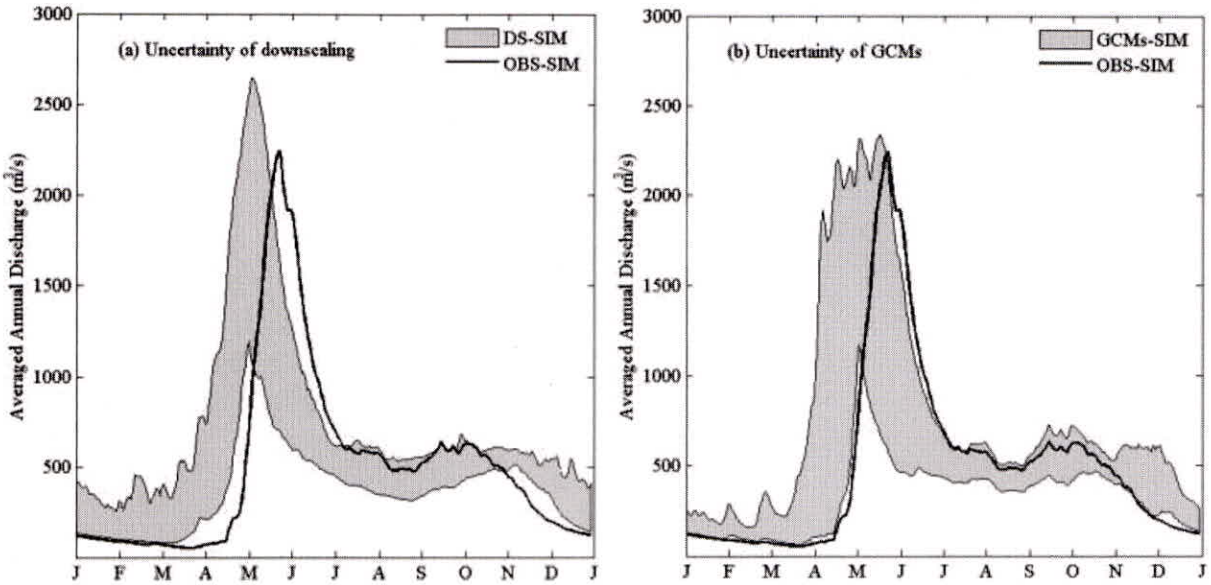


***Figure 13.3**. Uncertainty envelopes of simulated discharge with (a) 6 downscaling techniques and (b) 28 GCMs and emission scenarios using the change factor downscaling method for the future period (2070-2099). The discharge simulated with observed climate data for the reference period (1970 – 1999) is also plotted for comparison. (Source: Chen et al., 2011).*

Many studies have acknowledged the relevance of the dynamically downscaled higher resolution RCMs and they replaced GCMs in majority of the climate change impact assessment studies (e.g. Miao et al., 2016; Sanjay et al., 2017). Regional scale (~ 20 – 50 km resolution) climate phenomenon are comparatively well represented in dynamically downscaled RCMs and are considered more relevant in producing reliable estimates of regional climate. However, a few studies challenge their ability in predicting point-scale climate information, i.e. precipitation or temperature at a meteorological or weather station (e.g. Miao et al., 2016; Tao et al., 2018). In addition, few studies have found that RCMs overestimated the frequency of precipitation, while they underestimated the heavy precipitation (e.g. Singh et al., 2017). Furthermore, several studies have highlighted the spatial and temporal variability in the performance of RCMs (e.g. Leander and Buishand, 2007; Karmalkar et al., 2018). For example, in a recent study, Sanjay et al. (2017) found large uncertainty associated with dynamic downscaling in the projected changes of seasonal temperature and precipitation over the hilly sub-regions within the Hindu Kush Himalayan region by the end of the 21st century.

Several methods of statistical downscaling exist and the uncertainties associated with each method differs. Major sources of uncertainties in statistical downscaling are the stationarity assumption, i.e. historical statistical relationship remains the same in future, and the assumption that a

climate variable will follow a specific distribution which may not be true all the time. For example, the properties of a statistical distribution changes with the size of sample used in the distribution fitting. In addition, the empirical relationships between predictors (e.g. large-scale climatic variables) and predict (e.g. regional precipitation) are influenced by the warming climate. In addition, inconsistencies between the variables representing physical processes, and the inherent uncertainties of each statistical downscaling technique add to the uncertainty in the simulated climate. The statistical downscaling methods do not account for the interactions between the physical processes that define climate, thus producing physically unrealistic climate variables. Quantifying these uncertainties is quite cumbersome, those associated with the assumption of stationary climate in particular (Rupa & Mujumdar, 2019). The future climatic conditions can significantly vary from that of the historically recorded conditions, which were used to calibrate the model.

Despite several studies involving the use of both statistical and dynamical downscaling techniques, no single downscaling technique was found to consistently out-perform other methods (e.g. Haylocket al., 2006; Landman et al., 2009; Gutmannet al., 2012; Roux et al., 2018). Several studies indicate that the method of model output statistics (MOS), bias correction techniques in particular, produced better results when applied to the simulations from the dynamically downscaled models, i.e. reduced uncertainty to some extent (e.g. Landman et al., 2009). Overall, both dynamic and statistical downscaling technique are capable of capturing the spatio-temporal variability in hydroclimatic conditions, but the uncertainties transferred from the GCM simulations, sometimes limit their reliability. Sharma et al. (2018) found that the statistically downscaled hydrological projections captured the observed spatio-temporal variability in hydroclimatic conditions more efficiently than the dynamically downscaled projections. They observed that the uncertainty in the statistically downscaled projections was much smaller than the inter-GCM uncertainty. However, the limitations of the stationarity assumption made in statistical downscaling should be well understood, i.e. the implications of the deviations from basic assumptions should be quantified (Rupa & Mujumdar, 2019).

13.1.4. Uncertainty from Hydrological Models

In addition to the uncertainties associated with the GCM simulations, uncertainty is induced in the projected hydrological responses, such as streamflow projections, associated with the assumptions made in the hydrological model building. The well calibrated hydrological model producing acceptable results for an observed baseline period may not work adequately in projecting hydrological response to a changing climate. Similarly, different hydrological models may respond very differently when forced with the same climate change scenario. Uncertainties in hydrological projections are due to a range of factors, including the reliability and availability of data used to calibrate models, limited understanding of regional hydrologic processes and the omission of other influential dynamics, such as modal and quantitative changes in water and land use (Lacombe et al., 2018). Therefore, a separate quantification of uncertainties is required for GCM downscaling approaches and those associated with the hydrological modeling, respectively. For example, Jana et al. (2018) demonstrated that the method of potential evapotranspiration (PET) estimation used in the hydrological model induced uncertainty in the streamflow projections, i.e. PET estimation methods created a significant spread of projected streamflow for certain months. In addition, the spatial scale of a hydrological model plays a vital role in its efficiency, for example, the global scale hydrological model employs a large grid size and several local hydroclimatic processes are parameterised, leading to less accurate regional hydrologic projections (Thomson et al., 2013). In Indian context, some of the major sources of uncertainties in

hydrological projections arise from representation of various regional hydrological processes with limited understanding, viz., processes involved in extreme weather events, or processes regulating snowmelt and glacial melt, and interactions between groundwater and surface water (Lacombe, 2018). In addition, limited observation networks and data availability present further difficulties in validating models and estimates of water balances (Mathisonet al. 2015). However, a majority of the studies from recent past emphasize that the uncertainties associated with the hydrological models are relatively smaller than those associated with the GCMs, emission scenarios and the method of downscaling (e.g. Sharma et al., 2018; Smitha et al., 2018; Tiwari et al., 2018).

13.2. Climate Uncertainty and Bias Correction

To address adaptive management practices and policies for planned adaptation to changing climate, it is vital to quantify the above-mentioned uncertainties. Producing several estimates of future climate helps in sampling various aspects of future climate (Alexander and Tebaldi, 2012). One method of producing GCM ensemble is to run the model several times by slightly modifying the initial conditions. Thus produced ensemble helps in understanding the uncertainty associated with the internal climate variability, and is the dominant way of producing weather forecasts using numerical weather prediction (NWP) models. Although this ensemble helps in understanding the uncertainty in internal variability over shorter time periods, when averaged over decadal timescale it fails to capture uncertainty when compared to the other methods of ensemble creation. The other method of creating an ensemble, called perturbed-physics ensemble is to run the model several times by slightly modifying the parameters of the physical processes. Meticulous selection of sensitive parameters influencing the climate helps in reducing the required number of simulations. When averaged over longer timescales (e.g. decades), ensembles of perturbed-physics capture larger range of uncertainties compared to those of perturbed-initial condition.

The other method of creating GCM ensemble is either to choose simulations from several GCMs and/or several runs from the same model, regarded as a multimodel ensemble. A multimodel ensemble samples the uncertainties from several GCMs or several simulations from the same GCM. Such ensemble also helps in sampling the uncertainties from different parameterisations of physical processes, and various numerical solution techniques. World climate research programme (WCRP) established coupled model intercomparison projects (CMIP) including CMIP3 (Meehlet al., 2007) and CMIP5 (Taylor et al., 2012)to create and evaluate multimodel ensembles. Similarly, the uncertainties in RCMs can be mapped or evaluated by creating multimodel ensemble of RCMs, platforms such as NARCCAP (Mearns et al., 2009), and CORDEX (Varikodenet al., 2018) aid the creation and assessment of multimodel RCMs. Likewise, an ensemble of statistical downscaling techniques to sample the uncertainty associated with the statistical downscaling is beneficial (e.g. Gutiérrez et al., 2018; Hertiget al., 2018).

In evaluating the GCM simulated climate with the observed climate, the general consensus is that the multi-model ensemble performs better than any individual model (e.g. Pierce et al., 2009). However, the critical steps in creating an ensemble is first the picking of GCMs and second the weightage to be given to individual models. In creating an ensemble, the GCMs are chosen based on the range of projected changes in climate and on the skill of the model in simulating past climate (e.g. Lutz et al., 2016). The skill of the model to simulate historical climate is dependent on various factors including the physics, initial conditions, etc. and not all the models perform the same. Thus the models are given a weight based on their performance, the poorly performing models are given the least or

zero weight. For example, Gillett (2015) demonstrate that the weighted ensemble performed better than the unweighted ensemble. One approach for deciding weightage for each model is the Reliability Ensemble Averaging (REA) method (Giorgi and Mearns, 2002; Sengupta and Rajeevan, 2013). The two criteria used in the REA method are (a) comparison of the models' performance in representing observed climate (bias) and (b) comparison of the models' projected changes to that of the multi-model mean projected change (model convergence criteria). To quantify the uncertainty and the reliability associated with the GCM projections of Indian summer monsoon climate, Sengupta and Rajeevan (2013) created an ensemble of ten CMIP5 GCMs based on the REA approach. They observed that REA method reduced the uncertainty in the ensemble climate and recommend this method for determining forecasts of Indian monsoon. Although multimodel ensembles are created to handle uncertainty, ensemble mean provides a quantitative estimate of one of the most likely future climates. The other approach to account for uncertainty is to project future regional climate as probabilistic predictions based on the weighted frequency distributions. In this method, ensemble probability density function (PDF) is produced based on the weighted performance of each model in depicting probability density functions of observed daily data (Déqué and Somot, 2010).

Bias correction (BC) approach has emerged as a standard procedure to minimise uncertainties in GCM/RCM based outputs, which adjusts (corrects) the modeled output with reference to the observed datasets in the post-processing step (Josef et al., 2018). To improve the reliability of GCM and RCM outputs, bias correction is used in the climate change studies, where bias is defined as the time independent component of the error. Model bias is defined by the systematic climate model error detected during the validation of model simulations with the unbiased climate observations (Teutschbein and Seibert, 2013). It is generally accepted that the GCM/RCM bias arises from misrepresentation of atmospheric physics (i.e. parameterization) in the model (Karmalkar, 2018). The fundamental step of identifying the bias between the model simulated and observed climate forms the foundation for correcting both historic and future simulations of climate from any GCM/RCM (Mehrotra and Sharma, 2015). For successful application of any bias correction method, it is vital that the observed correlations between various hydroclimatological processes are well represented in the bias corrected series. The flow chart of bias correction approach is shown in Figure 13.4. A few more relevant and frequently used and also globally accepted bias correction methods are discussed in the following sections.

13.2.1. Method of Linear Scaling (LS)

The LS bias correction method attempts to perfectly match the corrected values of the GCM/RCM simulated monthly mean climate to that of the historically observed climate (for more details, please refer Fang et al., 2015). In this method, the precipitation and temperature values are corrected at monthly timescale and the corrections are based on the differences between the observed and GCM/RCM simulated data. Precipitation values are corrected using a multiplicative factor and temperature is corrected using an additive term. Chen et al. (2013) adopted this method to correct the downscaled data for hydrologic impact studies over several watersheds of North America. Despite its simplistic approach and wide acceptance in hydrologic impact studies (e.g. Fang et al., 2015), several studies have highlighted the disadvantages of this method (e.g. Chen et al., 2013). For example, this method does not account for the changes in distribution and frequency of the meteorological variable.

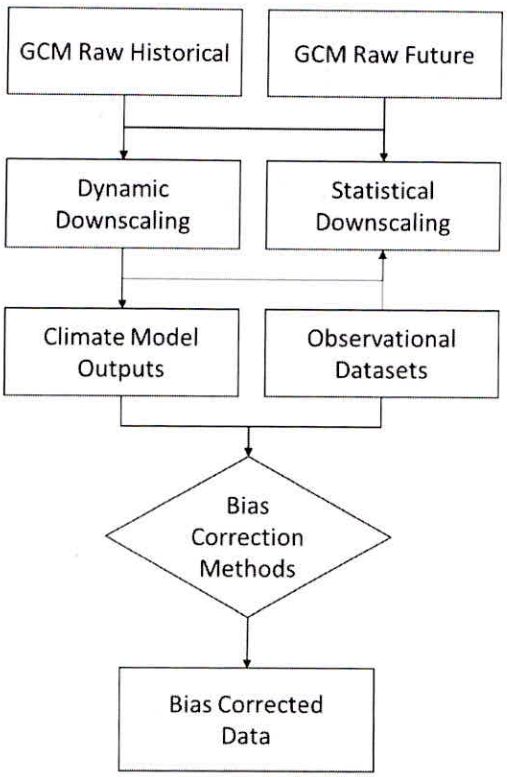


Figure 13.4: *Flow chart showing the general bias correction approach.*

13.2.2. Local Intensity Scaling (LIS) Method

The LIS method corrects intensities and frequencies of wet-day and can successfully improve the biased datasets with too many drizzle (very small amount of precipitation) days (for more details, please refer Schmidli et al., 2006). This method is carried out in two steps: (1) a wet-day threshold for a month is determined from the raw precipitation data to ensure that the threshold exceedance matches the wet-day frequency of the observed data and (2) a scaling factor is applied to ensure that the mean of the corrected precipitation is equal to that of the observed precipitation (Fang et al., 2015). LIS utilizes a spatially variable scaling factor to correct the modelled precipitation at point scale of the observation. Themeßl et al. (2012) performed statistical downscaling and used LIS bias correction method to minimize the gaps between RCMs output and observed precipitation data. They found out that the LIS performed very well in precipitation corrections except in a few instances at higher quantiles, where the precipitation is underestimated. A similar observation was made by Fang et al. (2015), who found that LIS method was able to correctly estimate mean, median and wet-day probability but slightly underestimated the standard deviation and higher quantiles (e.g. 99^{th} percentile). The biggest disadvantage of this method is that it does not make adjustments on the temporal structure of the meteorological variables (Teutschbein and Seibert, 2012).

13.2.3. Power Transformation (PT) Method

The PT method utilizes an exponential form to correct the standard deviation of meteorological series, although it has a limitation in correcting the wet-day probability. To overcome this limitation, the LIS method is employed to correct precipitation prior to applying the PT method (for more details, please refer Fang et al. (2015). This method was often found useful in the correction of mean, median, wet-day probability, wet day intensity, and it also performed well at high order quantiles (e.g. Teutschbein

and Seibert, 2012; Fang et al., 2015). Several studies indicated that this method performed well in capturing coefficient of variation (CV) and mean (e.g. Leander and Buishand, 2007; Terinket al., 2010).

13.2.4. Delta Change (DC) Method

DC method has been used widely to correct the statistically downscaled GCM and RCM outputs with reference to the observed datasets (Rasmussen et al., 2012; Teutschbein and Seibert, 2013; Sarret al., 2015). In this method, precipitation is corrected using a multiplicative factor and the temperature is corrected using an additive term. Comparing the RCM simulated climate with the observed data, Teutschbein and Seibert (2013; 2012) concluded that this is a robust method in correcting mean climate with reference to the observed data. In contrast, Rasmussen et al., 2012 found this method to be less applicable in the correction of standard deviation, wet-day frequencies, and their intensities.

13.2.5. Quantile-based Mapping (QM) Method

The QM based method is a non-parametric bias correction method and can be applied to all meteorological variables without any assumption on their distribution. This approach begins with the empirical transformation and has been successfully applied in the bias correction of GCM/RCM based simulated hydroclimatic variables such as precipitation (e.g. Sun et al., 2011; Wilckeet al., 2013; Fang et al., 2015). This method was found to be efficient in correcting the bias in mean, standard deviation and frequency, including the quantiles (Sun et al., 2011; Fang et al., 2015). This method can be applied in two ways; (1) quantile mapping based on empirical distribution and (2) quantile mapping based on a gamma distribution (Chen et al., 2013). This method is widely used because of its simplistic approach, nonparametric configuration, and its applicability to other hydroclimatic variables (Themeßlet al., 2012). Although several studies conclude that this method gave better results, it is conditional and depends on the spatio-temporal scales of the observed and simulated datasets (e.g. Themeßlet al., 2012; Chen et al., 2013; Fang et al., 2015).

13.3. Concluding Remarks

This chapter includes a significant discussion on the uncertainty associated with the GCM projected climate and the downscaling techniques. Several studies are reviewed and the applicability of high and course resolution data in different parts of the world are addressed. Various complexities associated with the minimisation of uncertainty are explored and several techniques available to adequately address these complexities are discussed. However, the complete removal of uncertainty is nearly impossible by a single deterministic approach and therefore creation of multi-model ensembles should be preferred (Ehret et al., 2012). Future projections from an ensemble of several models (GCM or RCM) are useful in identifying a most likely projection of a future climate and the amount of uncertainty surrounding it. However, building a useful ensemble is the biggest challenge and utmost care should be taken in adequately sampling the uncertainties associated with the projections of future climate and identifying the 'most likely' future climate. Future policy decisions are critical in increasing the uncertainty in GCMs and these decisions could move the future GHG concentrations from higher to lower radiative forcing in the future. Therefore, the decision makers should be aware of the differences in the impacts of high to low representative concentration pathway in the future, which requires a creation of ensemble for each emission scenario separately. Adequate sampling of uncertainty plays a vital role in the creation of such ensembles. The bias correction methods discussed in this chapter would be useful for all regions around the world. Overall, it should be noted that the

uncertainty associated with future climate is largely irreducible both in spatial and temporal scales that are relevant to water resources projects (Lacombe et al., 2018). And GCMs are less capable of predicting variables that are most important for water resources projects, such as local hydrologic extremes (floods and drought). In addition to the uncertainties associated with the GCM and downscaling methods, the assumptions or parameterizations made in hydrological models also induce uncertainty in the hydrological projections. However, the discussions in this chapter are primarily focused on the uncertainty induced from the climate models, because several studies have highlighted that uncertainties associated with hydrological models are relatively smaller when compared to those associated with GCM and emission scenarios (e.g. Sharma et al., 2018; Smithaet al., 2018;Tiwari et al., 2018).

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CHAPTER 14

WAY FORWARD - CLIMATE CHANGE IMPACT ASSESSMENT ON WATER RESOURCES AND ADAPTATION

Sharad K. Jain

Climate change is said to be the most critical problem in the field of water and environment that the mankind has ever faced. Climate change related risks, in conjunction with other risks are increasing at different paces. Some, such as water availability related risks are increasing gradually while some such as floods and droughts risks are increasing rapidly (Lacombe, 2018). Hence, wide ranging initiatives and actions are needed to tackle this global problem.

An essential requirement to handle climate change problem is a detailed scientific understanding of the causes and past trends behind climate change and its impacts. This will help in initiating necessary actions to mitigate the adverse impacts. Various chapters of this report, have discussed impacts of climate change on different components of hydrologic cycle with special emphasis to the impacts in India.

14.1 Knowledge Gaps in Climate Science

Similar to any other emerging area of research, there are many knowledge gaps or "holes" in our understanding about the behaviour of climate system. Among the other things, this also means that uncertainties are associated with future projections and that future climate changes could be significantly different than the projections. Schiermeier (2010) listed four "problem areas" that need to be addressed by climate scientists. These four areas that require more research are: a) regional climate prediction, b) precipitation forecasts, c) aerosols, and d) palaeoclimate data. He, of course, stated that such "holes do not undermine the fundamental conclusion that humans are warming the climate". It was also noted that in the field of climate science, the most crucial information is the least reliable.

14.1.1 Regional Climate Prediction

The projections of future climate at local and regional levels have large uncertainties. These projections form the basis for taking remedial actions such as adaptation projects. As a number of modeling groups across the world are continuously improving their models, it is hoped that the regional projections made by the next generation of models will have reduced uncertainties and will be useful for planners and policy-makers. Availability of better data and more powerful computers will add to these efforts.

14.1.2 Precipitation

For the hydrologists, precipitation is the most important variable to determine the impact of climate change on water resources. It is well known that precipitation is also the variable that is most difficult to model. A number of modeling centers across the world are applying GCMs and making future climate projections. However, in these studies, projections of precipitation are widely different at all scales: global, regional and local. There are several reasons behind this. Besides inadequate understanding of climate system, we have inadequate data to correctly model processes such as cloud formation, orographic effects, thunder-clouds, etc.

14.1.3 Aerosols

Aerosols are airborne particles. A source of uncertainty in climate science is the inability to properly account for the impacts of aerosols on the climate. Scientists don't have clear understanding of the impacts of particles such as sulphates, black carbon, sea salt and dust on temperature and precipitation. Note that different aerosols have different impacts. Overall, aerosols are known to have cooling impact on climate as they block sunlight. However, estimates of the cooling effect have wide variation; some aerosols produce warming effect. Lack of data is another concern. Space and ground-based sensors are used to measure aerosol impact. Schiermeier (2010) noted that the relationship between aerosols and clouds adds another layer of complication.

14.1.4 Palaeoclimatology Data

Temperature data prior to 1850 are scarce but long-term data are needed in climate studies and researchers must find other ways to reveal earlier temperature trends. Palaeo-climatology uses data obtained from sources such as tree rings, coral reefs, lake sediments, glacial movements, etc. Thickness of tree rings have been related with temperature and rainfall. Tree ring growth at some sites have tracked atmospheric temperatures but have diverged from the actual temperatures during the recent decades. It is likely that the trees grow differently when temperatures exceed a certain threshold. In any case, to improve the usefulness of tree ring data, it is necessary to know how different tree species grow under different climates.

Based on the review carried out and presented in this report, a number of issues have emerged which can be broadly classified in the issues dealing with research and investigations to be carried out and actions to be taken for adaptation and management to overcome adverse climate impacts.

14.2 General Observations

a) Due to geographical location as well as topography and economy and population, India is among the countries that are highly vulnerable to climate change. India has to ensure water food and energy security to its growing population, keeping in view the impacts of climate and other changes. We also need to protect our people from water related disasters which are likely to become more frequent, more intense and more widespread with time.

b) The surface mean temperature anomalies for past 100 years or so for India are consistent with global trends in temperature.

c) Due to changes in climate, extreme temperature events can cause severe adverse impacts on society and it is important to understand the likely patterns of long term changes at different locations across the country so that suitable adaptations and mitigation measures can be taken up.

d) Climate models are the best tools to understand impacts of climate changes. So far India doesn't have an indigenously developed model; it would be better to develop an indigenous model for different regions – scientific growth, possibility of developing future scenario that are constant with the emissions and land use land cover changes in India. Of course considerable scientific and infrastructural resources would be needed to develop a model and it will also take considerable time but a beginning needs to be made.

e) Downscaling of climate projections is the process of transferring general circulation model (GCM) output to a finer spatial and temporal scale. Downscaling techniques have been

designed to bridge the gap between the information that the climate modelling community can currently provide and that required by the impacts research community.

f) Downscaling assumes that regional /local climate is conditioned by the climate on larger, for instance, continental or global scales. This is realistic. However, the dependence structures may change in future.

g) Downscaled data are typically bias-corrected to match with the observations but even then they may be unable to reproduce the observed behaviour and the relation between local/regional and continental/global climate may change in the future.

Krishnan and Sanjay (2017) report that CCCR, IITM, Pune have successfully developed IITM-ESMv2, the second version of IITM Earth System Model. IITM-ESMv2 is a radiatively balanced global climate modeling framework that has the capability to address key scientific questions relating to long-term climate change. IITM-ESMv2 would be first climate model from India to contribute to the Coupled Model Intercomparison Project Sixth Phase (CMIP6) for the IPCC sixth assessment report (AR6).

14.3 India Specific Issues and Observations

The various statistical data mentioned in this section have been drawn from published literature including Krishnan and Sanjay (2017), IPCC reports and other sources.

i. The annual average temperatures over the Indian landmass have shown an increasing trend of about 0.6°C/(100 yr) during the period 1901-2010. The highest trend is observed in post monsoon season 0.79°C/(100 yr), and the lowest in the monsoon season 0.43°C /(100 yr).

ii. Annual mean, maximum and minimum temperatures averaged over the country as a whole show significant warming trend of 0.16°C, 0.17°C and 0.14°C per decade, respectively since 1981.

iii. Maximum warming trend is seen during the post-monsoon season. The annual average temperature over the Indian landmass has significantly increased in the region north of 20°N.

iv. The number of warm days and nights has significantly increased over the last 35 years.

v. Overall monsoon rainfall does not show any significant change mainly because the decreasing trend in moderate rain events has been compensated by an increasing trend in heavy rain events.

vi. The annual as well as seasonal (June through September) monsoon rainfall over India shows significant decreasing trend over the core monsoon zone, north-eastern parts and southern parts of west coast.

vii. The total number of consecutive dry days with spell length more than five days has increased significantly, while the total number of consecutive wet days has shown significant decrease.

viii. The Indian region experienced extreme weather events in recent years such as heat waves, cold waves, extremely heavy rain events and many others. These events happen to be more severe and more frequent in recent years, producing devastating impacts on human life, agriculture, water resources, health etc.

ix. The number of warm days averaged over the entire Indian landmass depict significant increasing trend ~ 4.5 days /(35 years) during the period 1981-2015, while the number of warm nights has also increased significantly ~ 3.5 days /(35 years). The number of cold days and cold nights do not show any significant trend. The occurrence of hot days and hot nights,

particularly during the pre-monsoon (Mar-Apr-May) season, were significantly more during the recent 35 years as compared to the previous time epoch.

x. Number of consecutive dry-day index [CDD, the number of dry days (days with daily rainfall < 1 mm)] in the spells where consecutive dry days are at least 5 (i.e., days with PR<1 mm) in a year. CDD is showing increasing trend.

xi. Number of consecutive wet day index (CWD) or the number of wet days [days with daily rainfall > 1 mm] in the spells where consecutive wet days are at least 5 (i.e., days with PR > 1 mm) in a year. CWD is showing falling trend.

xii. There are many critical data gaps in water sector in India. The current assessments of surface water availability are old and need to be updated by following sound hydrological principles. Reliable baseline data are necessary to predict the changes.

xiii. Utilization of water in its various uses is rarely measured. Hence, there is considerable uncertainty in the estimates of water utilization. This is hampering, among the other things, optimal water resources utilization.

xiv. Water quality data in India are scanty; limited variables are measured and at sub-optimal frequency. Good baseline data are needed to understand the impacts of global warming on water quality.

xv. Changes in land use and land cover impact hydrologic response of watersheds as well as emission /sequestration of carbon dioxide. Reliable landuse maps at close times should be prepared and made available to study CC impacts.

xvi. Hydrogeological maps are needed for improved assessment of ground water resources, impact of climate change on them, and groundwater contamination.

14.4. Research and Development Issues

a) It would be helpful to develop a reference climate data network of stations which can provide good quality long term data for improved understanding of the changes in meteorological and hydrological variables across the country (Jain, 2015).

b) As the water quality data are scarce in India, we do not have adequate understanding of the extent of pollution in various water bodies across the country. Hence it would be necessary to strengthen the water quality data networks by deploying required instruments to monitor all the desired parameters. At the same time, detailed modeling should be carried out so that management tasks for restoring good water quality in the natural water sources could be implemented. Additional stresses arising due to global warming and climate change need to be factored in the water quality management programs.

c) In view of lack of data on hydrologic, economic and other sectors, there is considerable uncertainty in the future climate projections for the country. Specifically, the uncertainty may arise due to the use of GCMs for climate projections, use of downscaling techniques, and hydrologic models. Each of these causes of uncertainties need to be addressed so that the uncertainties in projections as well as in decisions based on them could be minimized. This will require wide range of studies.

d) Although the literature has a large number of publications on downscaling from GCM results but very few studies consider impact on climate change on hydrological response of catchments and present qualitative results. Even when studies have an applied element, consideration is seldom given to how results might enable stakeholders and managers to make

more informed, robust decisions on adaptation in the face of uncertainty about the future. In fact, studies on climate change and water adaptation with real-life applications are rare. Paradoxically, the rhetoric has become much more confident about projected changes in temperature and even precipitation at regional scales. Somewhere along the line there has been a disconnection between the suppliers and users of regional climate change scenarios for adaptation and resource planning.

e) We need to develop future projections of max temperature, min. temperature and mean temperature, and precipitation at fine spatial and temporal resolutions for different concentrations of greenhouse gases, such as RCP 4.5, 6.0 and 8.5.

f) It would be necessary to understand how the crop water requirements are going to change across various agro climatic zones in the country in the future and how the warming will impact crop yields at various locations.

g) As food security in the country critically depends on ground water it is necessary to understand the impact of changes in precipitation, temperature and other hydrometeorological variables as well as land use on recharge to ground water. For this purpose, existing mathematical models need to vigorously applied and the parameters use should be based on field assessments.

h) A substantial part of river flow in the lean season comes from ground water contribution. Hence, it is necessary to understand the interaction between river and aquifers in different hydrogeological settings across the country and how this may change with change in climate and other drives.

i) Studies would be required to identify areas where managed aquifer recharge can be practiced to conserve monsoon runoff as well as control decline of ground water tables.

j) A crucial gap in ground water modeling in India is lack of data on sub surface geology and aquifer properties. Some initiatives have been taken recently to address this issue and these need to be replicated to cover larger areas in the country.

k) Understanding the evolution of the Himalayan snowpack and glaciers under future climate change scenarios and their contribution in snow and glacier melt runoff in the Indus, Ganga, and Brahmaputra basins.

l) Himalayas are prone to soil erosion and this process may accelerate if the rainfall intensities increase. A better understanding of soil erosion and land slide mechanism will be needed for taking appropriate remedial measures.

m) Focused attention is needed for reservoir sediment management. Experience from other countries with similar geology and climate, particularly China, will be useful.

14.5 Water Resources Management Issues

a) As the extreme events are going to be more frequent and intense, it will be necessary to develop and strengthen infrastructure to deal with increasing variability.

b) We need to develop ways and means to store water made available during high flow (may be shorter duration) periods so that it does not cause damages in these periods and also can be used beneficially in dry periods.

c) Based on the results of ground water investigations, suitable mitigation measures and regulatory framework needs to be put in place urgently for checking ground water depletion before the situation deteriorates further.

d) A related issue though not arising very much due to climate change is contamination of aquifers due to recharge of polluted municipal and industrial waste in to sub surface zones. In many areas, hand pump water is highly polluted which an evidence that the upper soil layers are already filled with contaminated water which is likely percolate deeper with time. This problem should be addressed immediately before it goes out of control.

e) To manage climate change related risks, both short- and long-term interventions are needed. In short-term, climate adaptation is to be integrated with disaster risk reduction and utilization of natural resources. For the longer-term, plans are to be prepared keeping in view the impact of climate change experienced so far and the future projections.

f) A society which is knowledgeable and aware is more resilient and can better manage the risks. Hence, the society should be made aware and their understanding about climate change risks need to be enhanced.

14.6 India's National Action Plan on Climate Change (NAPCC)

Reports of IPCC and discussions on international forums have been urging the nations to initiate actions tackle challenges arising due to climate change. In response, the Indian government developed a National Action Plan on Climate Change (NAPCC) in 2008 as well as asked all states to prepare State Action Plans on Climate Change (SAPCC). The NAPCC has eight missions that deal with different facets of climate change adaptation and mitigation. Among these, the missions relevant to water sector are: National Water Mission, National Mission for Sustaining the Himalayan Ecosystem, National Mission for Sustainable Agriculture, and National Mission for Strategic Knowledge on Climate Change.

Rattani (2018) reviewed the progress of the missions and reported that "Even though NAPCC has been in existence for close to a decade, … for most missions it has only been three to four years since they came into effect. It is also clear that progress has been almost uncertain for most of the missions". It was found that "institutional, systemic and process barriers — including financial constraints, inter-ministerial coordination, lack of technical expertise and project clearance delays — stand as major challenges in the efficient implementation of the missions. The most obvious source of financing for climate change action is currently the limited government budgetary support". Also, the mission-mode approach for dealing with cross-cutting subjects has not worked (Rattani 2018). Lack of adequate and trained manpower to dedicatedly work on the Missions is another reason that the Missions have not been able to achieve the desired results. A new approach needs to be devised to mainstream the climate agenda in the cross-cutting sectors.

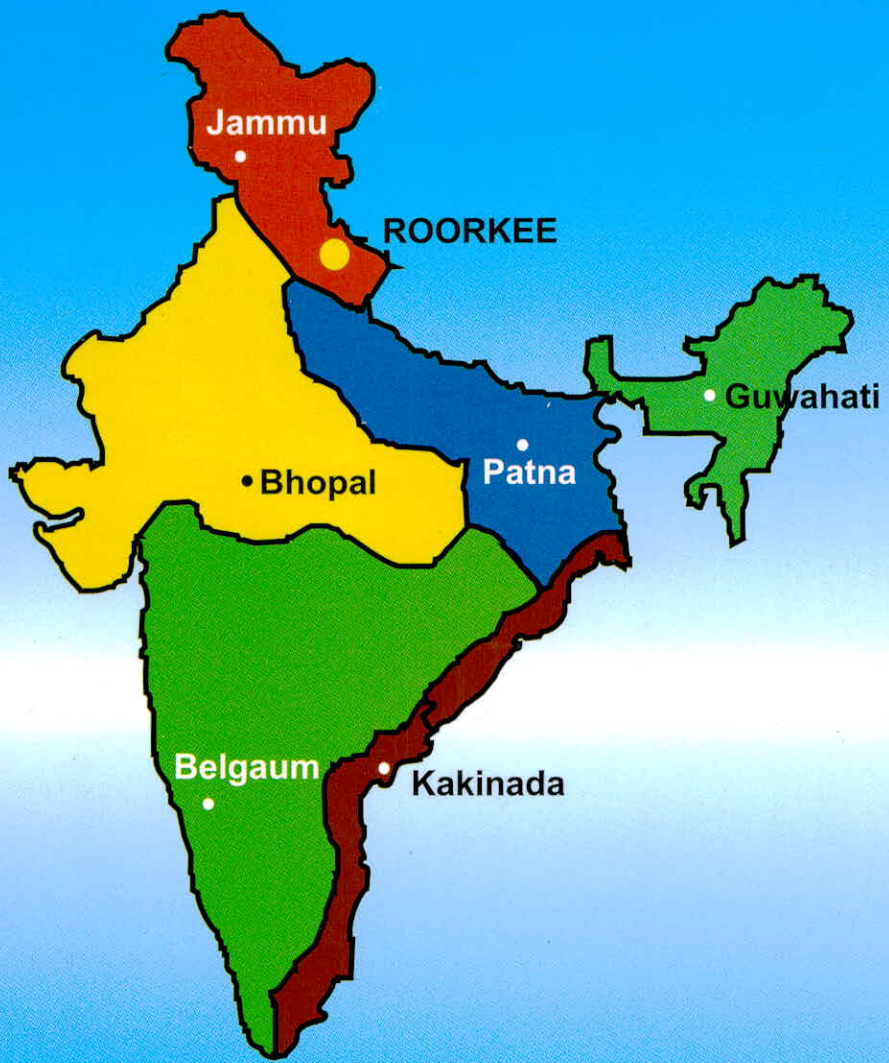
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