CHAPTER 1

CLIMATE CHANGE: AN OVERVIEW

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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.

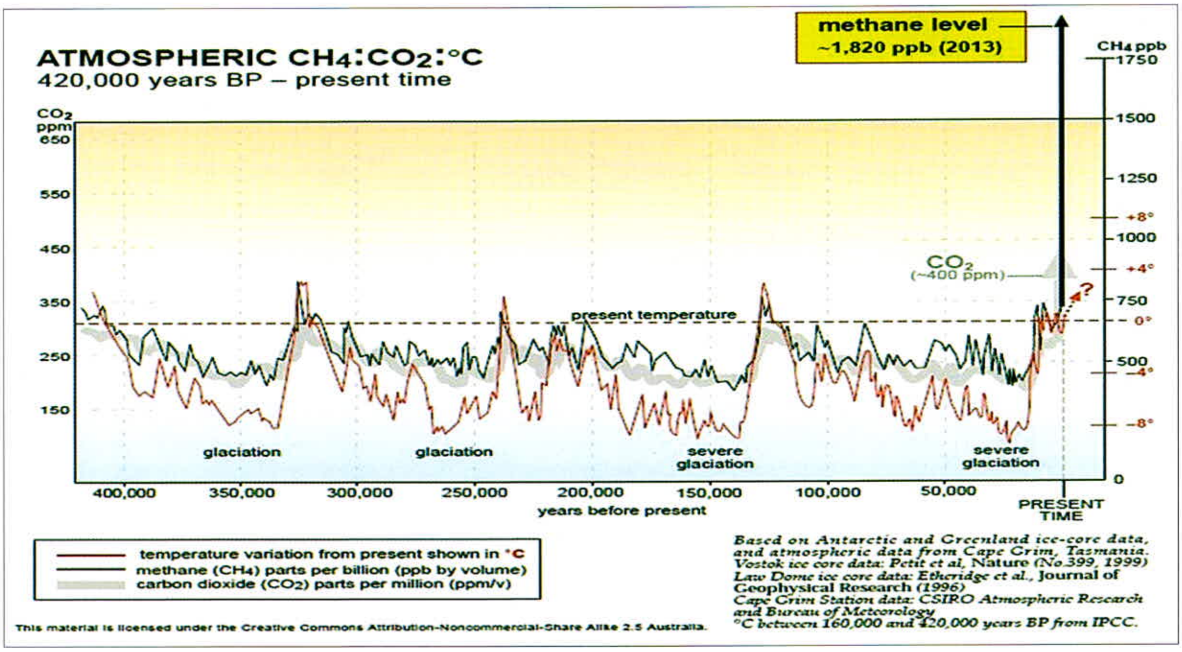

***Figure 1.1**: CO2 concentration since 4,20,000 year BP (Source: IPCC 2014; Etheridge et al., 1999).*

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.

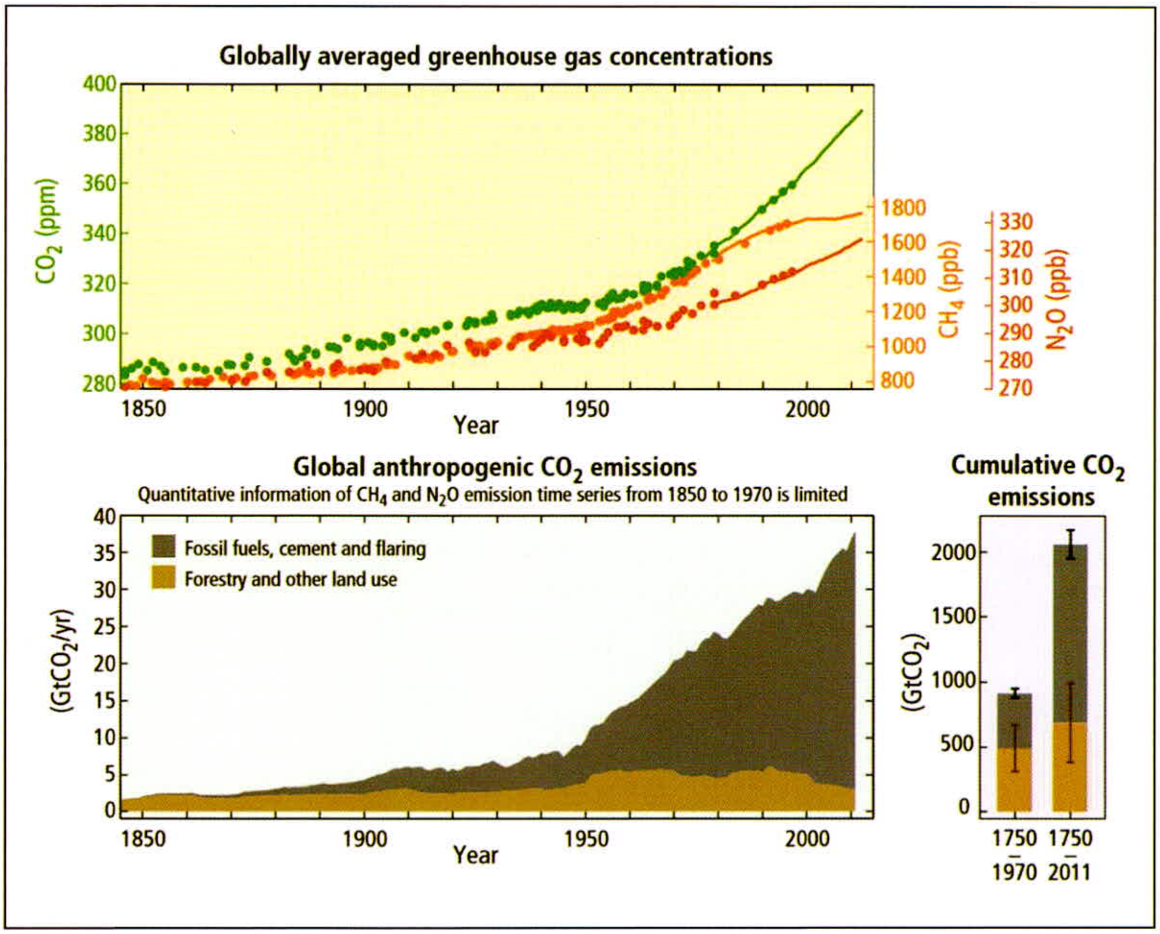

***Figure 1.2**: Total annual anthropogenic GHG emissions scenarios for the period 1850 to 2011 (Source: IPCC, 2014).*

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).

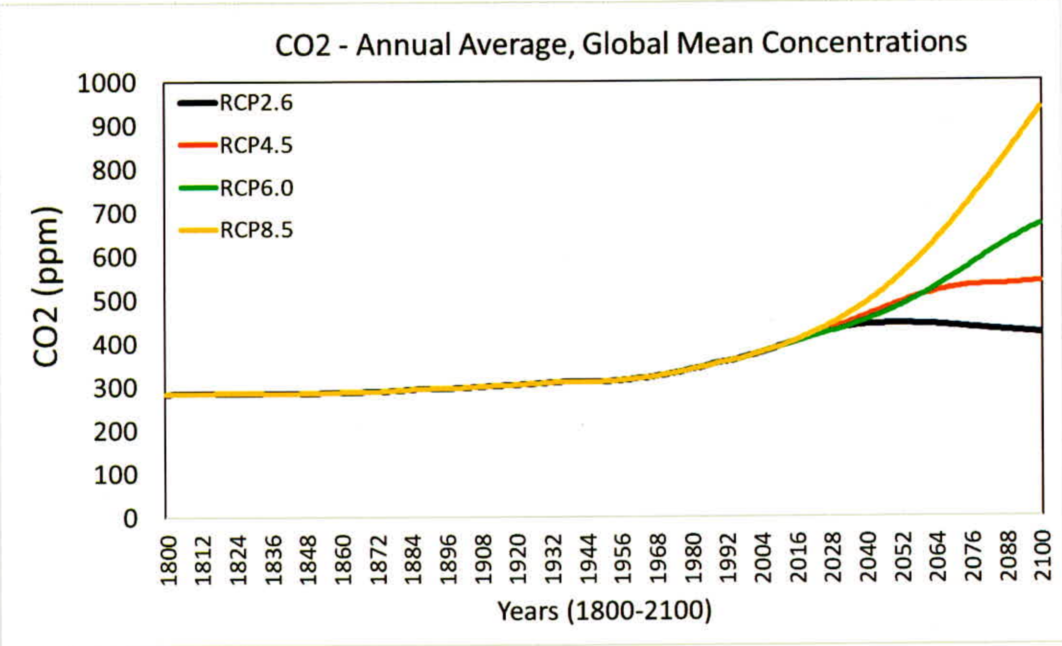

Figure 1.3: *Average annual global mean concentration of CO_2 is increasing from 1800 to 2100.*

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.

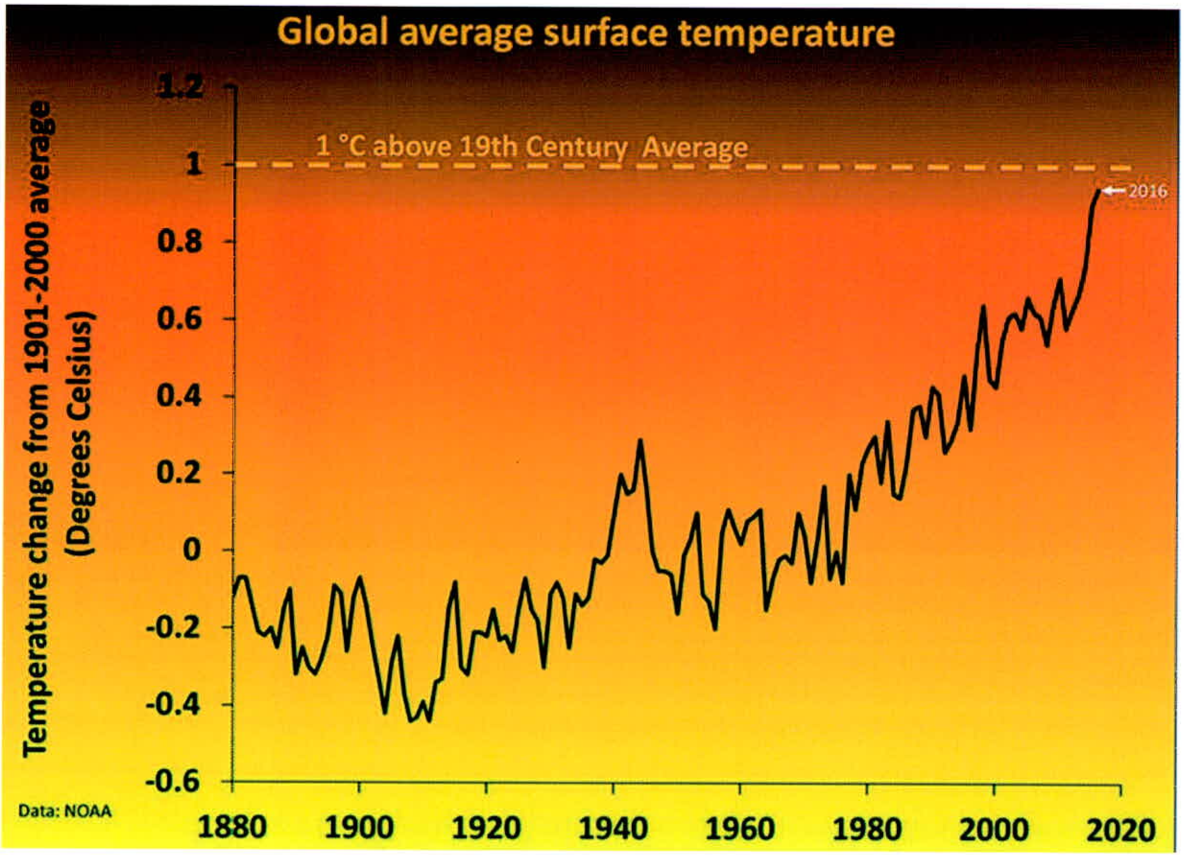

Figure 1.4: *Global average temperature change from 1880-2016 based on NOAA temperature data. (Source: NOAA 2016)*

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.

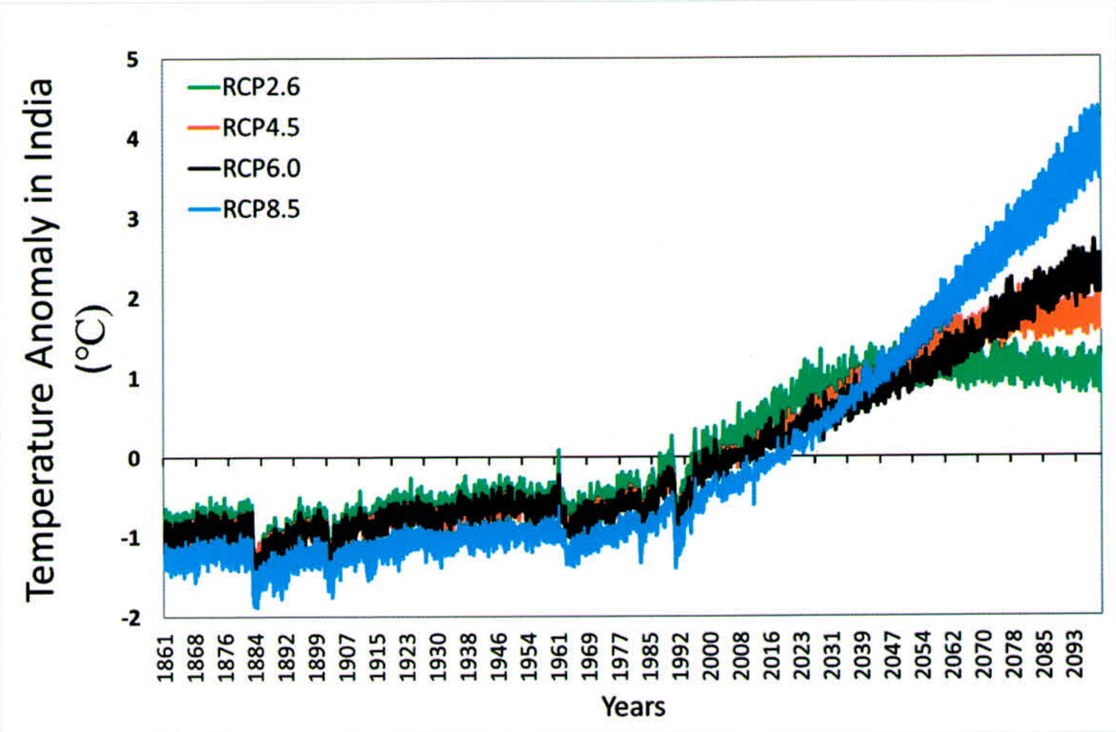

Figure 1.5: Anomalies of mean temperature from CMIP5 multi-model RCP scenarios [low (RCP2.6) to High emission scenarios (RCP8.5)].

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).

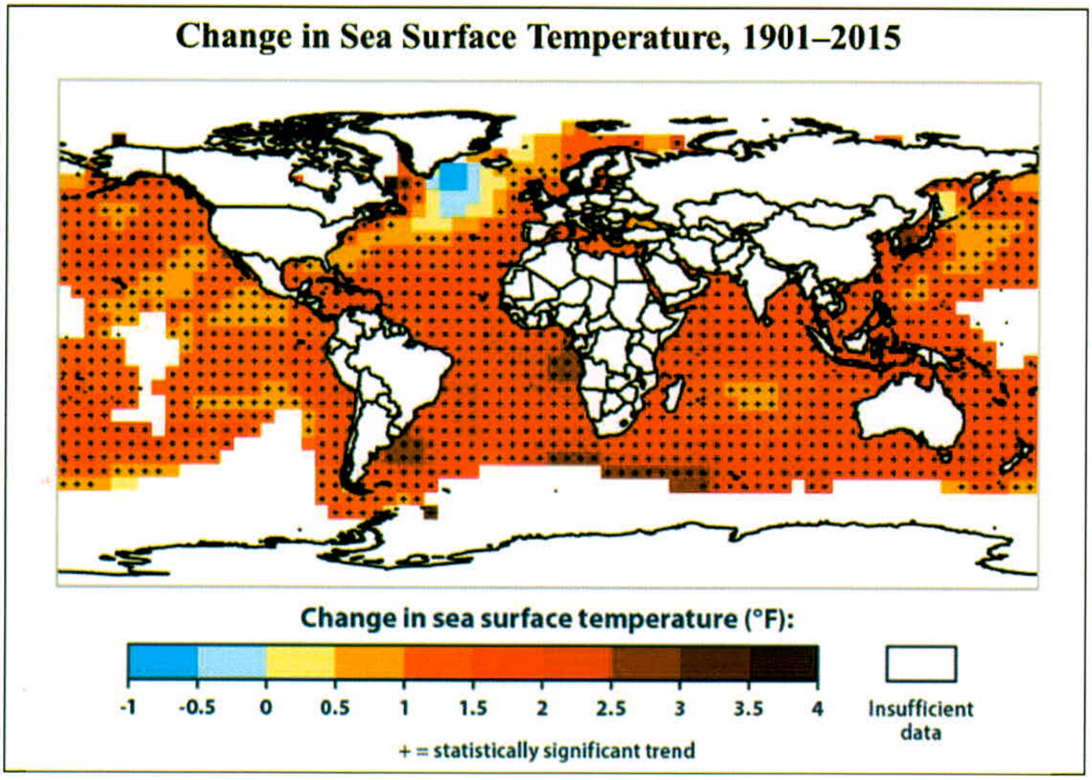

Figure 1.6: *Change in Sea Surface Temperature (SST) during 1901 to 2015 (Source: www.epa.gov).*

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).

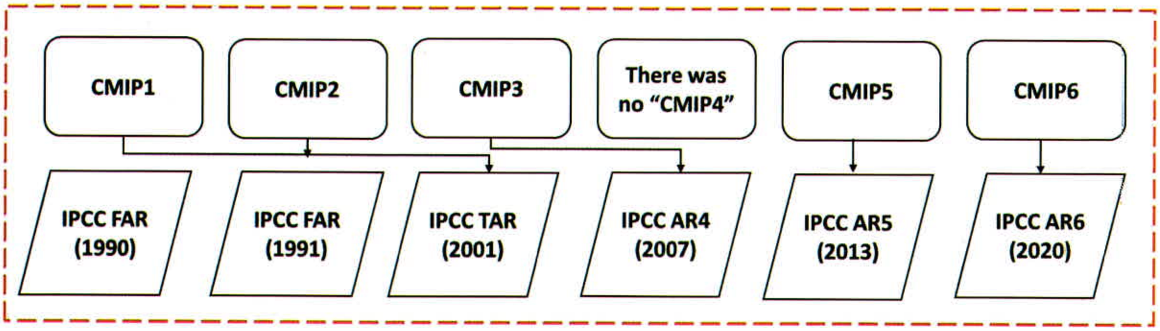

***Figure 1.7**: Progress of the IPCC Scenarios.*

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°), which can be applied for regional/local scale climate evaluations.

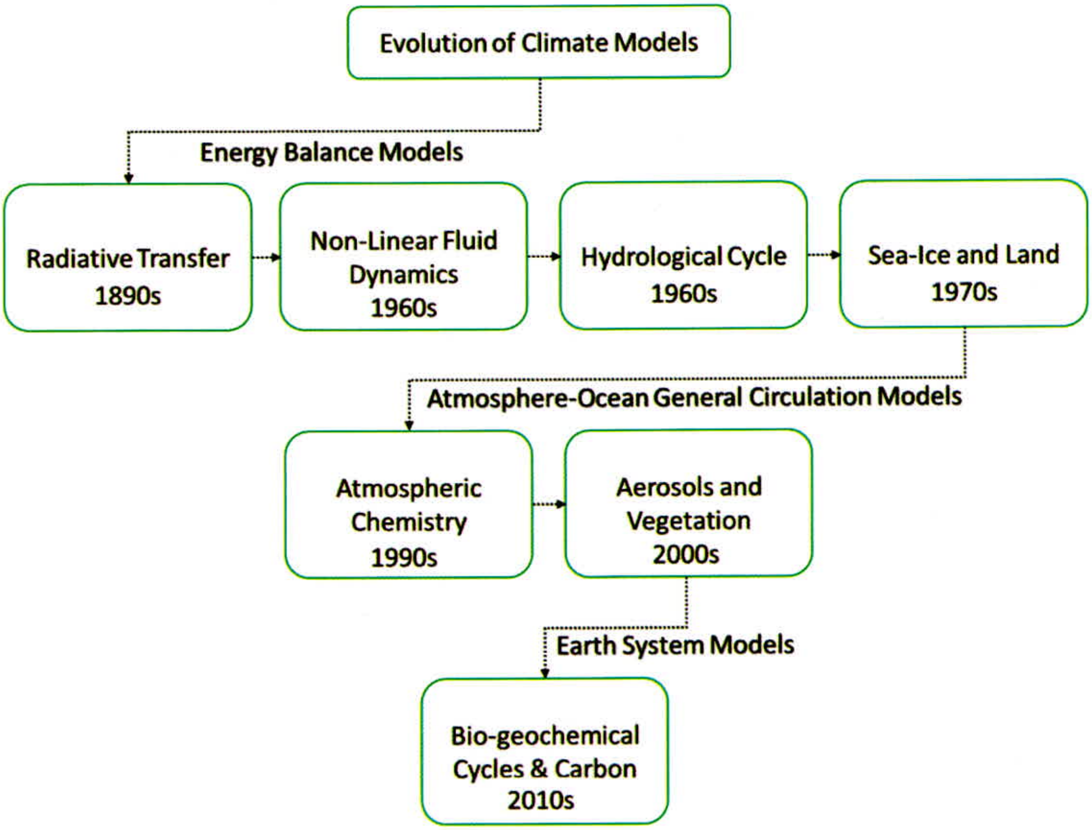

Figure 1.8: *Evolution of GCMs in different decades.*

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 21st century, 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.

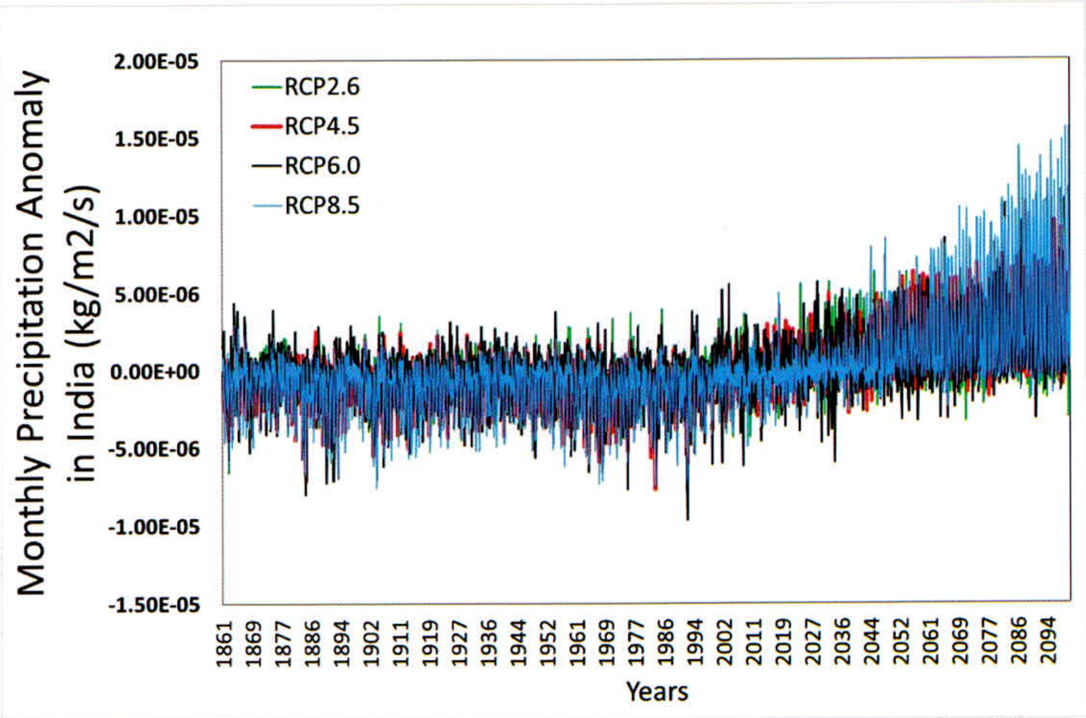

Figure 1.9: *Precipitation anomalies (mean of all CMIP5 GCMs computed under different RCP experiments) showing precipitation changes (1850-2100) in India.*

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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