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Climate Change and Sustainable Water Resource Management

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Abstract
Almost all aspects of climatic patterns are affected by rising level of Greenhouse gases (GHGs) and increasing anthropogenic activities. Change in climate is observed and studied by various researchers. In this article, the present and future effects of climate change on precipitation, temperature, flood events and droughts are discussed in the form of case studies. Significant rising trends in observed temperature are found in some parts Ganga basin. Future trends of temperature and precipitation also shows rising trend in entire Ganga basin. Rajasthan, a semi-arid hot zone, receives lesser rainfall and more prone to droughts. Historical and future trends of Standard precipitation index (SPI), which is a drought index, are also discussed in this study. It is seen that, overall there will be less severe droughts based on annual and monsoon months, but Northern and Western part of Rajasthan will be prone to more sever droughts. Rising level of CO_2 emission is major contributor to the global warming. To keep the global warming lesser than 2°C than pre-industrial time, carbon capture and storage (CCS) is only feasible solution. Maintaining the sustainability of the water resources is of prime importance because (i) due to the rising temperature, the available water resources will decline in the long term and (ii) water requirements will increase due to the growing population and economic advancements. This article also discusses the considerations and components of sustainable water resource management highlighting the approaches employed for managing agricultural water which is a major share-holder in the consumption of water resources.

1. Introduction

Climate change is the significant change in statistical patterns of weather which may sustain for longer duration. Natural climate pattern doesn't remain constant all time, but shows internal variability and fluctuates around a certain value. Climate change is the change in the natural pattern i.e. mean, spread, trend etc. of atmospheric variables. If there is a change in climate due to external forcings, it doesn't correct itself to natural patterns.

Intergovernmental Panel on Climate Change (IPCC) is the leading scientific intergovernmental body, which assess and review the latest information and knowledge of climate and provide guidelines to enable the scientific community to better study the climate change. Working Group on Coupled Modelling (WGCM) established the Coupled Model Intercomparison Project (CMIP) to set the standards to study the general circulation models (GCMs). In the phase 3 of CMIP (CMIP3) different emission scenarios were suggested based on socio-economic, technological and other factors (Solomon et al. 2007). Different CMIP3 emission scenarios are shown in Figure 1. Latest report of IPCC is Assessment Report 5 (AR5) which suggests four probable future emission scenarios (CMIP5) based on different total radiative forcings [1]. These four RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5) (IPCC 2013). Comparison of CMIP3 and CMIP5 for global temperature is also shown in Figure 2 [2].

Climate change is taking place and it's also visible in observed data of temperature, precipitation, sea level etc. Research community is trying to detect the effect of climate change in different areas i.e. Ocean circulation indices (Santer et al. 1995), snow and high elevation sites [3, 4, 5], temperature [6, 7, 8], precipitation [9, 10,

Emissions Scenarios of the Special Report on Emissions Scenarios (SRES). Used in the IPCC 3rd Assessment Report (2001) and Assessment Report 4 (2007).		
A1. Rapid economic growth	**A1FI.** Emphasis on fossil fuels **A1B.** Balanced energy sources **A1T.** Emphasis non-fossil fuels	• Global population peaks in mid-century, then declines • Rapid introduction of new and more efficient technologies • Convergence among regions, capacity building and increased cultural and social interactions • Substantial reduction in regional differences in per capita income
A2. Heterogeneous world		• Self-reliance and preservation of local identities • Continuously increasing population • Per capita economic growth and technological change fragmented and slow
B1. Convergent world		• Same global population growth pattern as in the A1 storyline • Rapid change in economic structures toward a service and information economy • Reductions in material intensity • Introduction of clean and resource-efficient technologies • No additional climate initiatives
B2. Local solutions		• Continuously increasing global population, at a rate lower than A2 • Intermediate levels of economic development • Slower and more diverse technological change than A1 and B1 storylines.

Figure 1: CMIP3 Emission scenarios (Source: https://www.agclimate.net/scenario-planning-series-part-2-bring-on-the-acronyms-a-brief-overview-of-ipcc-scenarios)

11] and streamflow [12, 13, 14] etc. Most of the studies show increasing trends in minimum and maximum temperature as found in most of the Indian regions [7, 8, 15].

This article is divided in five different sections. Brief introduction of climate change, emission scenarios and literature available is given in section 1. Case studies of the effect of climate change are discussed in section 2. Short discussion about CO_2 emissions and control is given in section 3. Sustainable water resources management is elaborated in section 4. The article is concluded in section 5.

2. Effects of climate change: Studies at IIT Roorkee

IIT Roorkee, being a premier educational and research institute, is also encouraging the research work to better understand the climate change and its effect on different atmospheric variables. Some of the researches are discussed in the following paragraphs in the form of case studies

2.1 Case-Study-1: Ganga Basin

2.1.1 Study Area

Ganga basin is stretched in India and Nepal, covering the drainage area of 1,005,800 km^2, out of which 831,400 km^2 lies in India [16] which is nearly 25.2% of the total geographical area of the country. Geographically, it lies between latitudes from 21.25°N to 31.25°N and longitudes from 73.25° E to 89.25°E (Figure 3). Total length of Ganga river is about 2525 km between its origin from Gangotri, Uttarakhand to Bay of Bengal [17].

2.1.2 Data Used

The summary of data used in this study is as follows:

- Observed Precipitation (P) and Temperature (Tas), at $1^\circ \times 1^\circ$ geographical grid

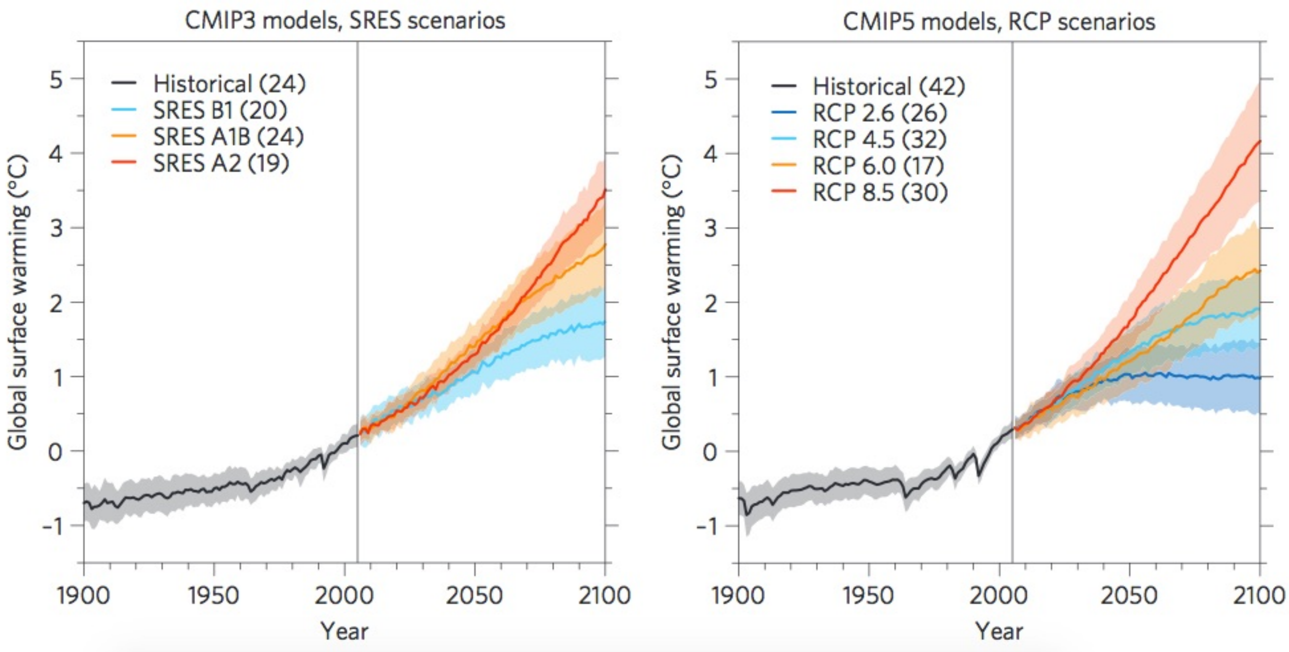


Figure 2: Global temperature change projections for SRES scenarios run by CMIP3 (left) and the RCP scenarios run by CMIP5 (right) relative to 1986–2005. Colored shading shows one standard deviation. The number of models run is given in parentheses. (reprinted from [2])

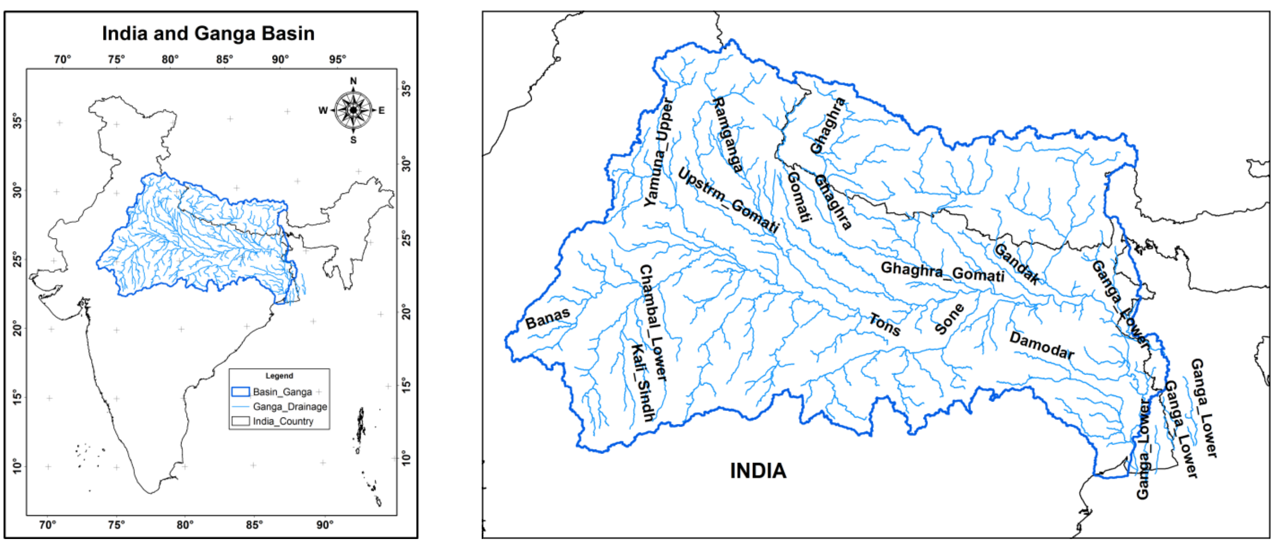


Figure 3: Study area and its location on map

- Downscaled P and Tas using WCRP's CMIP3 data (Maurer et al. 2007), available at $0.5^{\circ} \times 0.5^{\circ}$ geographical grid for 16 GCMs
- Downscaled P and Tas using WCRP's CMIP5 data, available at $0.5^{\circ} \times 0.5^{\circ}$ geographical grid for 18 GCMs

2.1.3 Methodology

Multi-model averaging is done for CMIP3 and CMIP5 data separately, for emission scenarios SRES-A2 and RCP6.0 respectively. The multi-model averaged series of annual total precipitation and annual mean temperature are then used for further analysis. The trends are detected using Mann-Kendall's test and Thiel-Sen's slope estimator.

Mann Kendall Test for trend analysis (ZMK or Z) The Mann-Kendall test [18, 19] is a nonparametric method which is used for detecting trends in a time series. In this paper, it is applied on time series of annual total precipitation (P) and annual average temperature (T). The positive and negative values of ZMK show rising and falling trends in the series, respectively. The ZMK is calculated as shown in equations below and the significance of it is evaluated on significance level 10%, 5% and 1%.

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \begin{cases} 1 & \text{if} \quad (x_j - x_i) > 0 \\ 0 & \text{if} \quad (x_j - x_i) = 0 \\ -1 & \text{if} \quad (x_j - x_i) < 0 \end{cases} \tag{1}$$

$$\text{Var}(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{T} t_i(t_i-1)(2t_i+5)}{18} \tag{2}$$

$$Z_{MK}(s) = \begin{cases} \frac{s-1}{\sqrt{\text{Var}(s)}} & \text{if} \quad s > 0 \\ 0 & \text{if} \quad s = 0 \\ \frac{s+1}{\sqrt{\text{Var}(s)}} & \text{if} \quad s < 0 \end{cases} \tag{3}$$

Where, s=a statistic which is calculated using the data series given as shown in equation (1), x_j & x_i = data points of any time series, ZMK=test statistic for Mann Kendall test, Var(s)=variance of 's', n=length of time series (in years), T=number of ties in time series, ti=number of data point for i^{th} tie.

Thiel-Sen's slope estimator (β) The Thiel-Sen's slope [18, 20] is used to determine the magnitude of trend for a given time series. In this study, it is applied on the time series of annual total precipitation and annual average temperature. The formula for β is shown as below.

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j-i}\right) \text{ for all } i < j \tag{4}$$

The quantitative change (Δx) in time series of a quantity can be calculated as:

$$\Delta x = \beta \times n \tag{5}$$

Where, β = Thiel-Sen's slope, x_i and x_j = data series points, n = length of data series.

2.1.4 Results and Discussions

Spatial distribution of precipitation and temperature for Ganga basin are shown in Figure 4 and 5 respectively. It can be seen that, Eastern part receives and will receive more precipitation than western part for observed and future scenarios, respectively. Temperature is increasing gradually as we move north-east to south-west of the Ganga basin. Observed, CMIP3 and CMIP5 plots are showing nearly the same spatial trend in temperature variation for all time slices.

The ZMK and β values are computed for the observed and projected hydro-meteorological data available over the Ganga basin (Figure 4 and 5 for precipitation and Temperature respectively). The significance of trend values (ZMK and β) is seen at confidence levels: 90% ($|Zcr| = 1.645$), 95% (|Zcr| = 1.96) and 99% (|Zcr| = 2.575). From Figure 6 it can be seen that, for observed precipitation data a decreasing trend is dominating throughout the basin except for a sharp increasing trend at the eastern edge of the basin. Whereas for future scenarios (A2 and RCP6.0), an increasing trend in annual precipitation amount is prevalent throughout the basin. From Figure 7 it can be seen that, there is an insignificant trend in observed temperature data for upper Ganga basin, while an increasing trend is observed in rest of the areas of the basin. For the future scenarios, a significant increase in temperature is prevalent in the entire basin. From ΔT values it can be predicted that by the end of 21st century, the temperatures will rise up to 3 to 6°C as per SRES-A2 emission scenario and 2 to 4°C as per RCP6.0 emission scenario.

2.2 Case Study-2: Rajasthan

The main purpose of this study is to characterize drought in Rajasthan under climate change as it is one of the major vulnerable drought prone areas of India.

2.2.1 Study Area

Rajasthan is a western arid and semi-arid hot zone, which lies between 23°30' N to 30°12' N latitude and 69°30' E to 78°17' E longitude (Figure 8). Rainfall in this region occurs mainly during June–September through the monsoon wind; non-monsoon rainfall is limited and irregular.

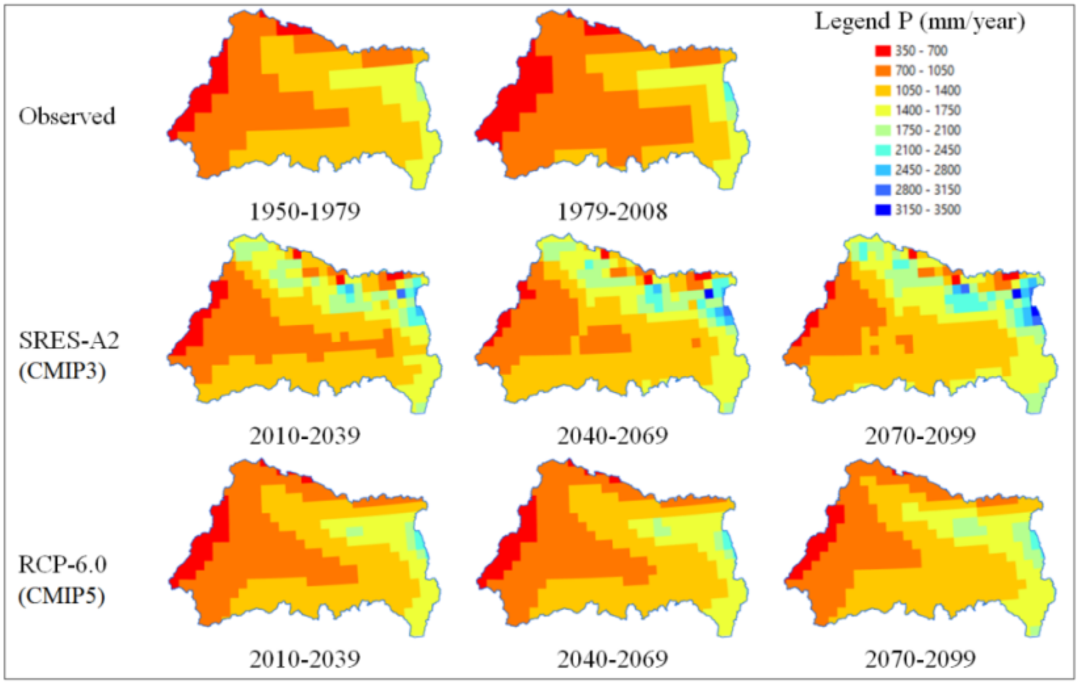


Figure 4: Plots showing spatial variation of tri-decadal means of observed (1950-1979 and 1979-2008) and projected annual precipitation (2010-2039, 2040-2069 and 2070-2099)

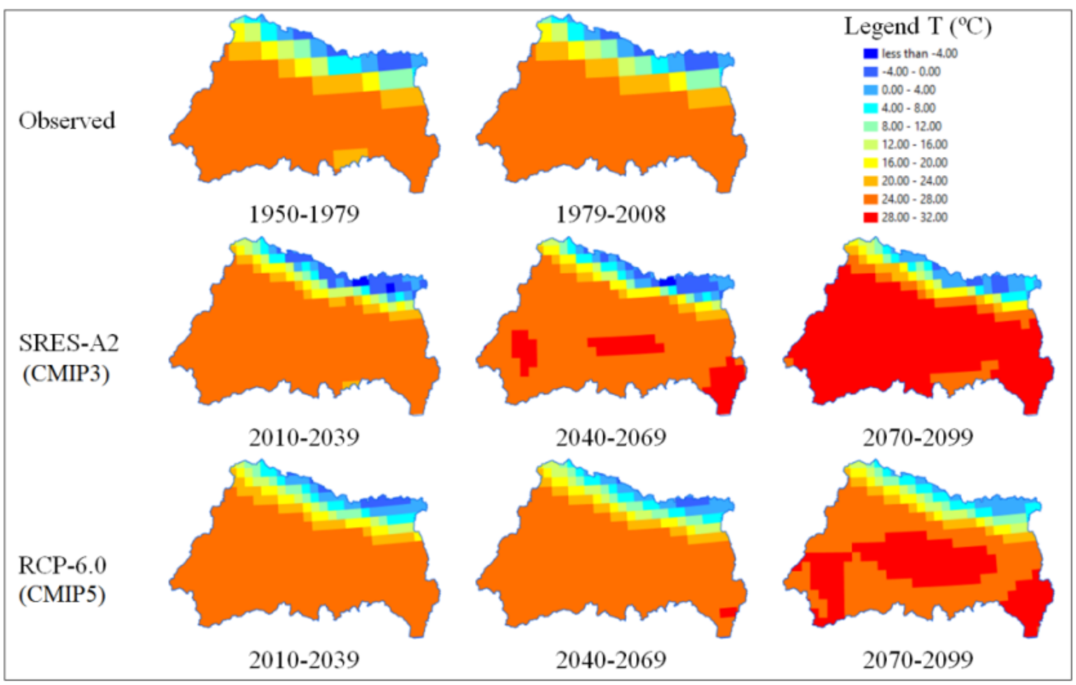


Figure 5: Plots showing spatial variation of tri-decadal means of observed (1950-1979 and 1979-2008) and projected mean Temperature (2010-2039, 2040-2069 and 2070-2099)

2.2.2 Data Used

- Observed District wise monthly precipitation data from 1901-2002 (102 years)

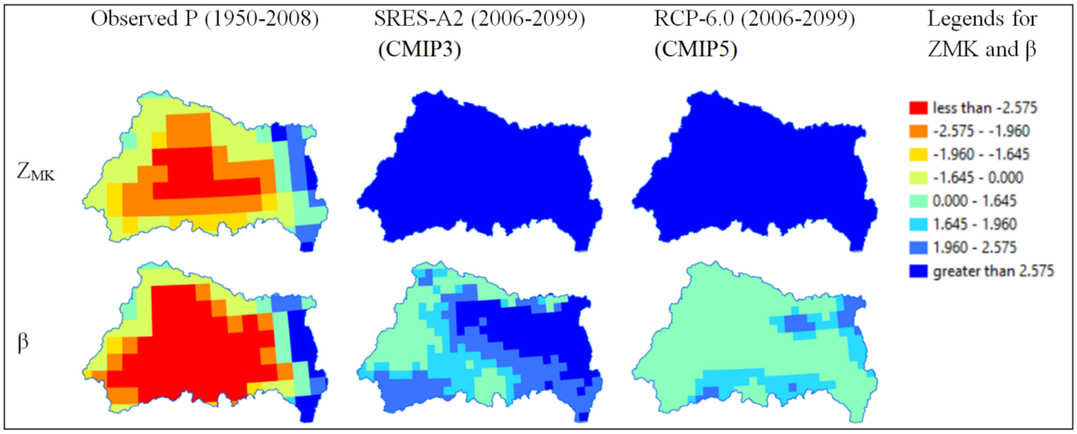


Figure 6: Plots showing spatial variation of tri-decadal means of observed (1950-1979 and 1979-2008) and projected mean Temperature (2010-2039, 2040-2069 and 2070-2099)

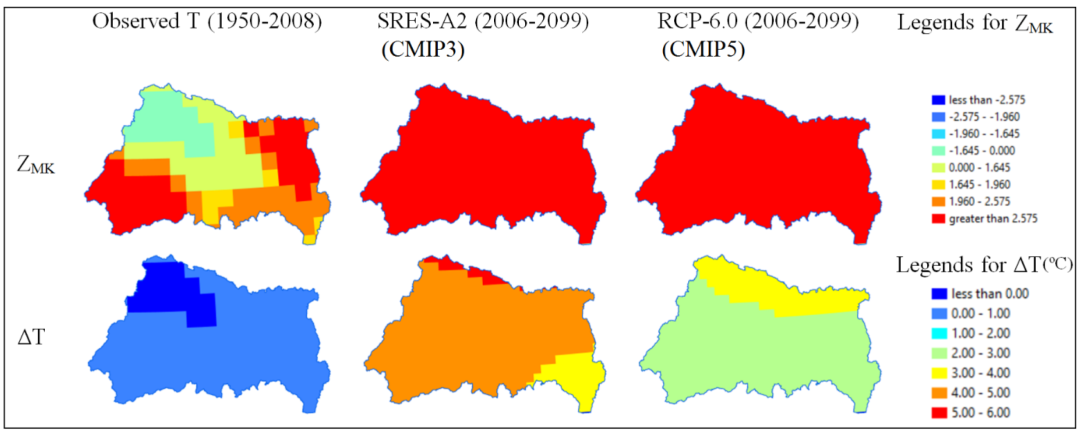


Figure 7: Plots showing spatial variation of trends in terms of (i) Mann-Kendall's statistic (ZMK), and (ii) Change in Temperature ($\Delta T = \beta \times$ length of data))

(available at http://www.indiawaterportal.org).

- Multi-model average of 16 GCMs CMIP3 gridded monthly precipitation data at grid interval of 0.5° latitute × 0.5° longitude for year 2006-2099 for three emission scenarios, i.e., A1B, A2 and B1.

- CMIP5 precipitation data: historical monthly (1950-2005) and for RCP2.6, RCP4.5, RCP6.0 and RCP8.5 monthly (2006-2100) which are multi-model average of 39 GCMs at grid interval of 0.5° latitute × 0.5° longitude.

2.2.3 Methodology

Standardized precipitation index (SPI) (McKee TB, Doesken NJ 1993) is used as drought index in this study. Two parameter-Gama distribution is fitted to precipitation data and transformed to standardized normal distribution to get SPI values. Following range of SPI are suggested by MCkee, 1993:

Table 1: SPI Values and Drought category

SPI values	Drought category
0 to -0.99	mild drought
-1.00 to -1.49	moderate drought
-1.50 to -1.99	severe drought
$\leq$ -2.00	extreme drought

2.2.4 Results and Discussions

Results and discussions are given here based on Figures 9 to 11. Overall, no significant trends in SPI values are found in observed data except some districts, which shows significant increasing trend. Annual and Monsoon

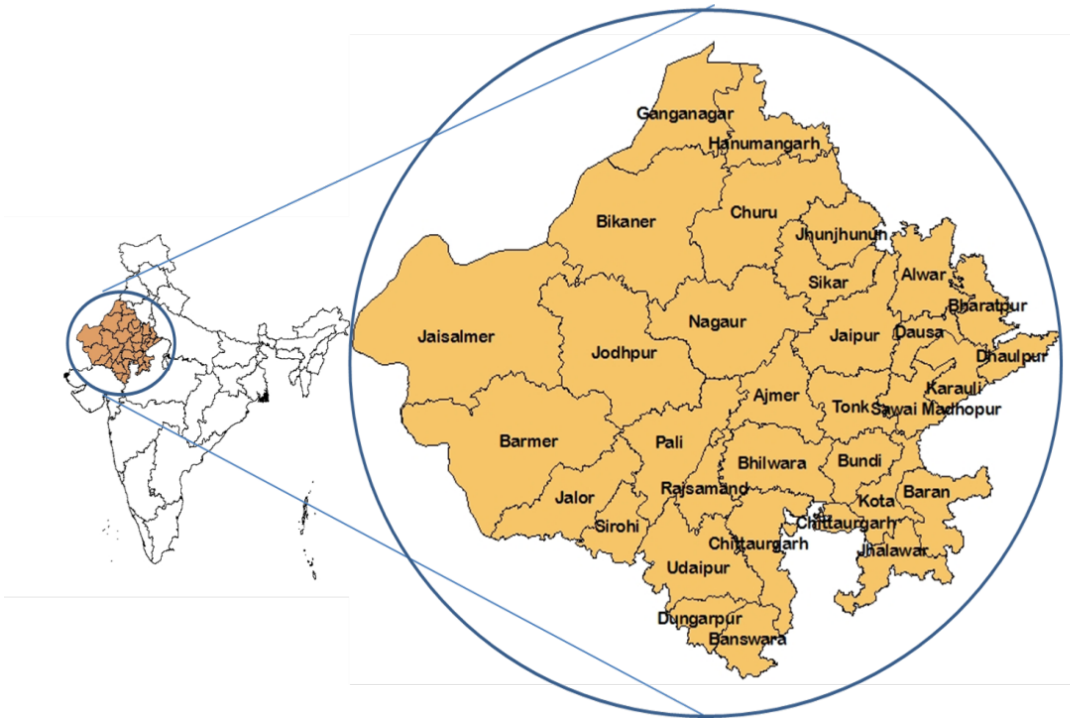


Figure 8: Study Area, Rajasthan, India

trends of SPI values for both CMIP3 and CMIP5 future scenarios are showing increasing trend, which indicates less severe drought events in future. Non-uniform spatial patterns can be seen in future scenarios of Non-monsoon SPI values. The study shows that, for CMIP5 data, Northern and Western part of Rajasthan will receive much lesser precipitation and Southern parts will receive higher precipitation in non-monsoon months.

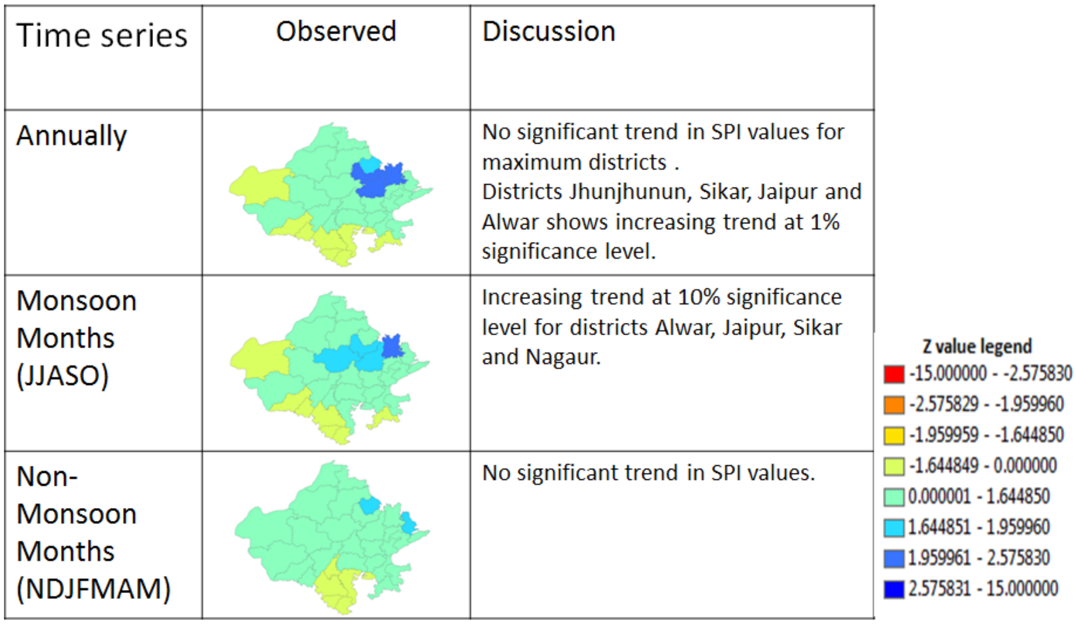
2.3 Case Study-3: Kedarnath Floods, Uttarakhand

In June 2013, Uttarakhand experienced worst flood event, which caused heavy damage to human life and property. More than 5700 person were presumed dead in the floods. Several studies attributed the flood event largely to human activities including hydropower projects, ever-increasing tourism, urbanization, and increased emission of greenhouse gases (GHGs) (Cho et al. 2015; Kansal et al. 2014).

3. Controlling CO_2 emissions (Carbon Budget)

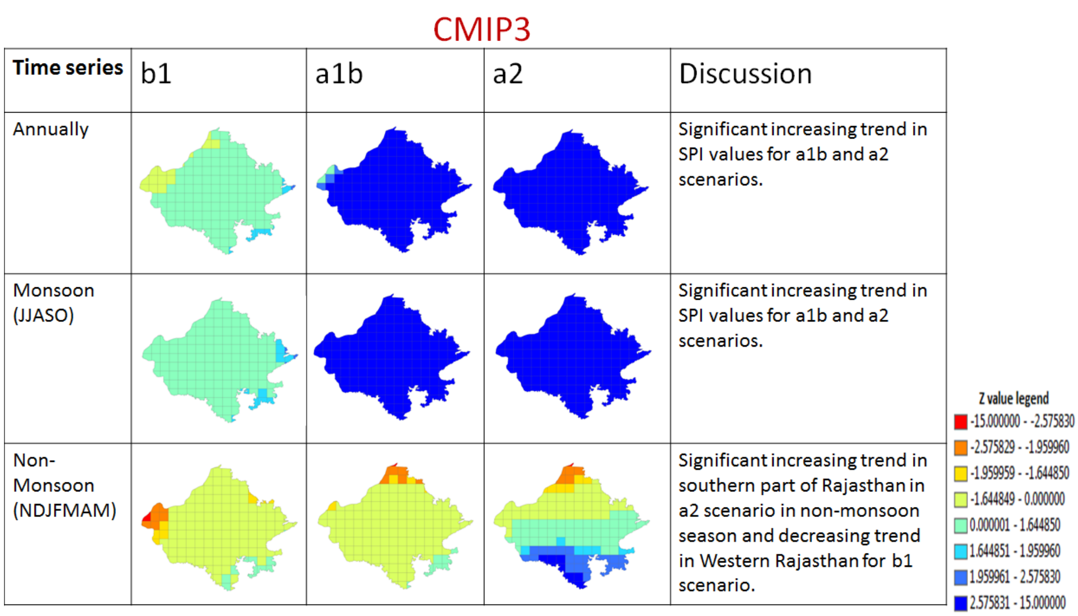
Carbon dioxide is a major contributor in the global warming which is the reason for the climate change in the last decades. According to 2014 UNFCCC Conference of the parties in Lima (Peru), in order to stay within the 2°C target at the end of the century of global warming, the amount of CO_2 to be emitted has to be limited (IPCC, Climate Change 2014). This 2°C target means, by the end of 2100 global temperature should increase by a maximum of 2°C from that of pre-industrial time, 1870 [21]. At 75% probability, the total carbon budget was estimated at 2900 Gt (gigatons) of CO_2 emissions for the period 1870-2100. But, till 2011 almost two-third (1900 $GtCO_2$) of this carbon budget has been used. This leaves us with only 1000$GtCO_2$ emissions for the period 2011-2100 for staying within the 2°C target.

However, this limit of 1000$GtCO_2$ emissions for the period 2011-2100 will be very difficult to achieve. Presently, fossil fuels contribute about three-fourth of the total global greenhouse gases emissions [22]. Figure 12 shows the global CO_2 emissions of the recent years by the use of fossil fuels only. In 2013, these fossil fuels



Time series	Observed	Discussion
Annually		No significant trend in SPI values for maximum districts . Districts Jhunjhunun, Sikar, Jaipur and Alwar shows increasing trend at 1% significance level.
Monsoon Months (JJASO)		Increasing trend at 10% significance level for districts Alwar, Jaipur, Sikar and Nagaur.
Non-Monsoon Months (NDJFMAM)		No significant trend in SPI values.

Figure 9: Trends of SPI values for observed precipitation

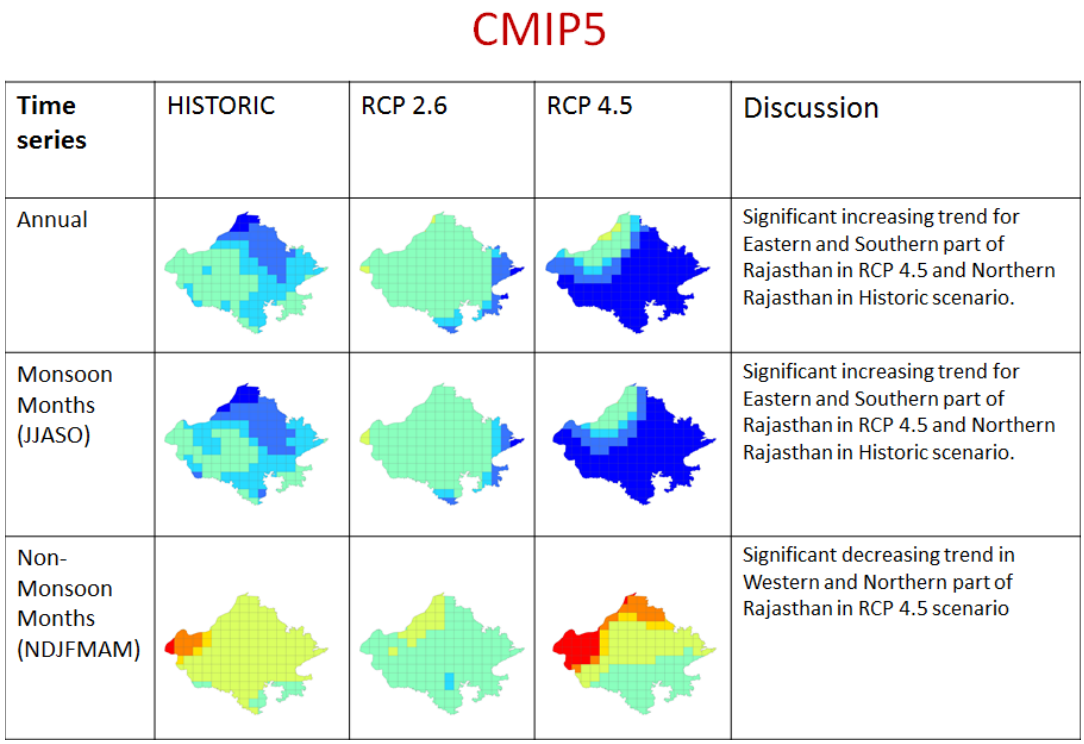


CMIP3

Time series	b1	a1b	a2	Discussion
Annually				Significant increasing trend in SPI values for a1b and a2 scenarios.
Monsoon (JJASO)				Significant increasing trend in SPI values for a1b and a2 scenarios.
Non-Monsoon (NDJFMAM)				Significant increasing trend in southern part of Rajasthan in a2 scenario in non-monsoon season and decreasing trend in Western Rajasthan for b1 scenario.

Figure 10: Trends of SPI values for observed precipitation

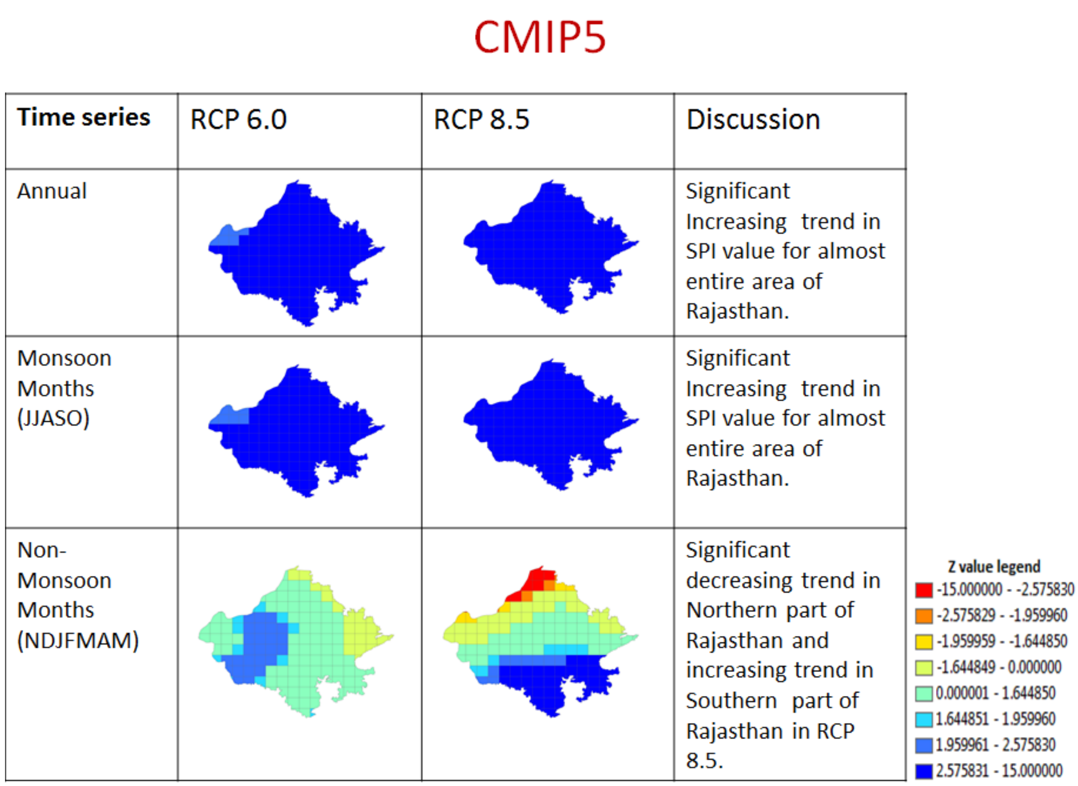
account for more than 35GtCO_2 per year and this rate is continuously increasing with the increasing use of the fossil fuels. At this rate, the remaining 1000GtCO_2 global budget will be exceeded in less than 25 years which is alarming. These proven and conventionally used fossil fuel reserves are still left in considerable amount. If fully used, these reserves will result in 3 times of the CO_2 emissions of the remaining carbon budget (Pulles, 2015). These fossil fuel reserves can be only utilized by using carbon capture and storage (CCS) technology if the 2°C target is to be met. All of coal and lignite and about two-fifth of the oil reserves should be combusted in units having 90% efficient CCS (Pulles, 2015). Carbon capture and storage is the process of capturing carbon dioxide formed as a result from the combustion of fossil fuels/ fuels from the point sources,



CMIP5

Time series	HISTORIC	RCP 2.6	RCP 4.5	Discussion
Annual				Significant increasing trend for Eastern and Southern part of Rajasthan in RCP 4.5 and Northern Rajasthan in Historic scenario.
Monsoon Months (JJASO)				Significant increasing trend for Eastern and Southern part of Rajasthan in RCP 4.5 and Northern Rajasthan in Historic scenario.
Non-Monsoon Months (NDJFMAM)				Significant decreasing trend in Western and Northern part of Rajasthan in RCP 4.5 scenario

Figure 11: Trends of SPI values for CMIP5 Data (Historical, RCP2.6 and RCP4.5)



CMIP5

Time series	RCP 6.0	RCP 8.5	Discussion
Annual			Significant Increasing trend in SPI value for almost entire area of Rajasthan.
Monsoon Months (JJASO)			Significant Increasing trend in SPI value for almost entire area of Rajasthan.
Non-Monsoon Months (NDJFMAM)			Significant decreasing trend in Northern part of Rajasthan and increasing trend in Southern part of Rajasthan in RCP 8.5.

Figure 12: Trends of SPI values for CMIP5 Data (RCP6.0 and RCP8.5)

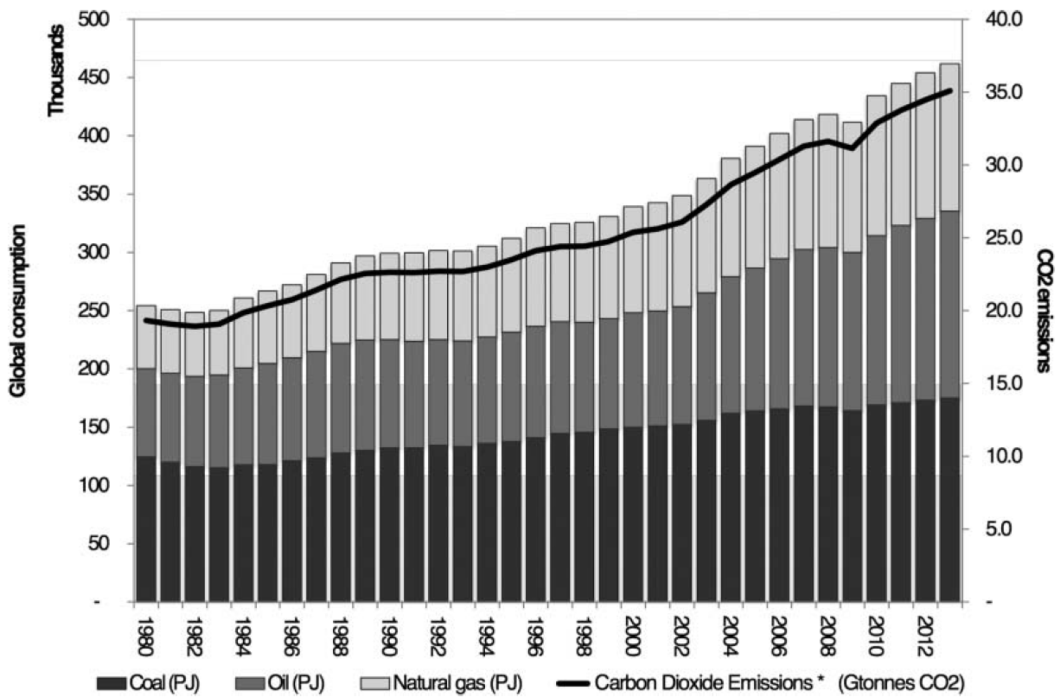


Figure 13: Year-wise global fossil fuel consumption in petajoules, PJ (left scale) and global CO2 emissions due to fossil fuels in GtCO2 (right scale)[22]

transferring and storing it to a site from where it cannot enter back in the atmosphere. So, in order to stay within the 2°C target, either the two-third of the proven fossil fuels has to be left unused or majority of them has to be used in CCS having 90

4. Sustainable water Resource Management

With the continuously rising global temperature and erratic climatic behaviour, the available water resources have become increasing limited. Also, with the economic advancements and rising population the consumption and usage of the water resources is continuously increasing. The sustainable management of the available water resources is thus of prime importance. Sustainable water resource management means meeting the need the water requirement of the present generation without hampering the ability of the future generations to meet their own needs. It describes how resilient the management system is during the face of change (SWRM, 2009). Principles of sustainable water resource management include environmental, social and economic considerations (SWRM, 2009).

The water resources should be neutral or restorative hydrologically and ecologically to satisfy the environmental considerations. Other reusable or recyclable water resource materials should also be neutral. Social considerations of water resource management include clean and abundant water supply which supports safe and secure food supply and clean and stable energy supply. Economic considerations include low life cycle costs and robustness (economically) on the face of changes of the water resource management infrastructure.

4.1 Components of sustainable water resource management

Sustainable water resource management consists of the following components (SWRM, 2009):

1. Integrated Planning
2. Regulatory and programmatic change
3. Community engagement
4. Management and financing

Integrated planning incorporates adaptive decision making and use of water management tools such as environmental, financial and social indicators, assessment tools for evaluation purpose, guidance manuals detailing the sustainable practices and participation of the stakeholder. Regulatory and programmatic change includes establishing minimum standards to address integrated planning needs. Development of ordinances and codes and forging policies also forms a part of this component. Management and financing includes integrated decision making approach which can identify the interconnections between the management at site to watershed to region to country to global levels. Market mechanisms, utilizes and service providers are structured so as to maximize the efficiency of the management.

4.2 Sustainable and integrated water resource management

While sustainable water resource management is the goal to attain sustainability, integrated water resource management (IWRM) is the strategy for pursuing this goal (SWRM, 2015). An often coined definition of IWRM is:"IWRM is a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems." (Global Water Partnership, 2000). However, the idea behind IWRM is well established but even at catchment level it faces some challenges that are required to be addressed before its implementation. They include understanding the specific catchment and adaptability of IWRM when conditions of the catchment change due to global change.

4.3 Agricultural water management

Water used for irrigation in agricultural is a major shareholder in the consumption of the available water resources. In agricultural intensive countries it accounts for about three quarters of the total water resources usage. This is why proper management of agricultural water is a key factor in sustainable water resource management. The usage of the available water resources can be elevated by improving the irrigation efficiencies in agriculture. Irrigation practices such as sprinkler irrigation, drip irrigation can be incorporated for increasing the irrigation efficiency. Further, research is being carried out to optimize the use of irrigation water so that amount of water can be minimized without any considerable affect in the crop yield. Deficit irrigation (Craciun and Craciun, 1999; Pandey et al., 2000); Shaozhong et al., 2000) and irrigation at a fixed moisture depletion level (maximum allowable deficit, MAD) are two of the approaches used in the literature for such optimization. Panda et al. (2003), Panda et al. (2004) and Gonita and Tiwari (2008) are some the research works that have accounted for the effect of irrigation treatment (MAD approach) on crop yield.

Also, drip irrigation can be improved and made more efficient by understanding the root water uptake patterns of the crops. Root structure of different crops is different. This is the reason that root water uptake patterns varies from crop to crop. Erie et al. (1965) enlisted consumptive use curves and layer-wise (soil layers of certain depths) soil moisture depletion data for a variety of crops. Various types of root water uptake models have been proposed by the researchers in the past to simulate the root water uptake patterns by some crops. Some illustrations are constant root water uptake model (Feddes et al., 1978), linear uptake model (Prasad, 1987), non-linear model (Ojha and Rai, 1996) and exponential model (Li et al., 2001).

Research work related to root water uptake patterns and agricultural water management has been carried out at I.I.T. Roorkee recently. Ojha et al. (1996), Ojha et al. (2009) and Shankar et al. (2012) are some of the illustrations. Also, the use of waste water for irrigation has been reported by Nema et al. (Nema et al. 2001) using SAT system at Sabarmati, Ahmadbad.

5. Conclusions

Climate change is inevitable due to continuously increasing anthropogenic activities which are harming nature. The footprints of climate change are also visible in observed data. Significant rising trend in observed temperature in Ganga basin shows increase in average temperature in most of regions. Future scenarios also show increase in temperature and precipitation in entire basin. Most of the previous studies have shown that rise in total amount of precipitation comes with more extreme events of rainfall due to climate change. Another case study of future SPI values in Rajasthan shows lesser severity in drought events annually and in monsoon months while, mixed pattern is found for non-monsoon months. Northern and Western part of Rajasthan will be more prone to severe droughts than southern part in pre-monsoon/ non-monsoon months. One of the most devastating effects of human activities and climate change was Kedarnath flood in June 2013. CO_2 emissions due to the combustion of fossil fuels account for almost 75% of the greenhouse gases emission. So, if we have to stay within the 2°C target of temperature increase from 1870-2100, unprecedented efforts and technological advancements in increasing the efficiency of CCS during/after combustion of fossil fuels are required.

Continuously increasing water demand and changing climate which will lower the available water resources in the long-term calls for the effective and sustainable management of the water resources which has to be done taking the environmental, social and economic considerations.

Acknowledgement

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References

[1] Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl. "An Overview of CMIP5 and the Experiment Design". EN. In: *Bulletin of the American Meteorological Society* 93.4 (2012), pp. 485–498. ISSN: 0003-0007. DOI: 10.1175/BAMS-D-11-00094.1.

[2] Reto Knutti and Jan Sedláček. "Robustness and uncertainties in the new CMIP5 climate model projections". In: *Nature Climate Change* 3.4 (2012), pp. 369–373. ISSN: 1758-678X. DOI: 10.1038/nclimate1716.

[3] M Beniston, H. F Diaz, and R. S Bradley. "Climatic change at high elevation sites: an overview". In: *Climatic Change* 36 (1997), pp. 233–251. ISSN: 0165-0009.

[4] Pratap Singh and Lars Bengtsson. "Hydrological sensitivity of a large Himalayan basin to climate change". In: *Hydrological Processes* 18.13 (2004), pp. 2363–2385. ISSN: 08856087. DOI: 10.1002/hyp.1468.

[5] C. Szczypta et al. "Impact of climate and land cover changes on snow cover in a small Pyrenean catchment". In: *Journal of Hydrology* 521 (2015), pp. 84–99. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2014.11.060.

[6] Céline Bonfils et al. "Detection and Attribution of Temperature Changes in the Mountainous Western United States". In: *Journal of Climate* 21.23 (2008), pp. 6404–6424. ISSN: 0894-8755. DOI: 10.1175/2008JCLI2397.1.

[7] Singh Dharmaveer, Sanjay Kumar Jain, and Gupta Rajan Dev. "Trend in Obsserved and Proojected Maximmum and Minimmum Temperature over N-W Himalayan Basin". In: *Journal of Mountain Science* 12.2 (2015), pp. 417–433.

[8] Manish Kumar Goyal, Chandra Shekhar Prasad Ojha, and Donald H. Burn. "Nonparametric statistical downscaling of temperature, precipitation, and evaporation in a semiarid region in India". In: *Journal of Hydrologic Engineering* May (2011), pp. 615–627. DOI: 10.1061/(ASCE)HE.1943-5584.0000479..

[9] Subimal Ghosh and P. P. Mujumdar. "Future rainfall scenario over Orissa with GCM projections by statistical downscaling". In: *Current Science* 90.3 (2006), pp. 396–404. ISSN: 00113891.

[10] B N Goswami et al. "Increasing trend of extreme rain events over India in a warming environment." In: *Science (New York, N.Y.)* 314.5804 (2006), pp. 1442–5. ISSN: 1095-9203. DOI: 10.1126/science.1132027.

[11] Arpita Mondal and P. P. Mujumdar. "On the basin-scale detection and attribution of human-induced climate change in monsoon precipitation and streamflow". In: *Water Resources Research* 48.10 (2012), pp. 1–18. ISSN: 00431397. DOI: 10.1029/2011WR011468.

[12] Praveen K. Gupta, Sushma Panigrahy, and Jai Singh Parihar. “Impact of Climate Change on Runoff of the Major River Basins of India Using Global Circulation Model (HadCM3) Projected Data”. In: *Journal of the Indian Society of Remote Sensing* 39.3 (2011), pp. 337–344. ISSN: 0255660X. DOI: 10.1007/s12524-011-0101-7.

[13] Walter Immerzeel. “Historical trends and future predictions of climate variability in the Brahmaputra basin”. In: *Int. J. Climatol* 28 (2008), pp. 243–254. DOI: 10.1002/joc.1528.

[14] P C D Milly, K a Dunne, and a V Vecchia. “Global pattern of trends in streamflow and water availability in a changing climate.” In: *Nature* 438.7066 (2005), pp. 347–350. ISSN: 0028-0836. DOI: 10.1038/nature04312.

[15] P. Sonali and D. Nagesh Kumar. “Review of trend detection methods and their application to detect temperature changes in India”. In: *Journal of Hydrology* 476.July 2015 (2013), pp. 212–227. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2012.10.034.

[16] Dwarika N. Dhungel and Santa B Pun. *The Nepal-India Water Relationship: Challenges, edited by Dhungel, D. N., Pun, S. B. and Shreshtha*. Springer Science & Business Media, 2009, p. 492. ISBN: 140208403X.

[17] NIH. *National Institute of Hydrology Website*. 2015.

[18] M.G. Kendall. *Rank Correlation Methods*. 4th. Charless Griffin, London, 1975, p. 272. ISBN: 0195208374.

[19] Henry B. Mann. “Nonparametric Tests Against Trend”. In: *Econometrica* 13.3 (1945), pp. 245–259.

[20] Pranab Kumar Sen. “Estimates of the Regression Coefficient Based on Kendall’s Tau”. In: *Journal of the American Statistical Association* 57.298 (1968), pp. 269–306.

[21] UNFCCC. *The Cancun Agreement*. 2010. URL: http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf.

[22] United States Environmental Protection Agency (USEPA). *Global Greenhouse Gas Emissions [Based on data from the World Resources Institute’s Climate Analysis Indicators Tool (CAIT)]*. 2014. URL: www.epa.gov/climatechange/pdfs/print_global-ghg-emissions-2014.pdf.

[23] Changrae Cho et al. “Anthropogenic footprint of climate change in the June 2013 northern India flood”. In: *Climate Dynamics* (2015). ISSN: 0930-7575. DOI: 10.1007/s00382-015-2613-2.

[24] IPCC. *Intergovernmental Panel on Climate Change, Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change, in Climate Change 2013: The Physical Science Basis, edited by T. F. Stocker et al.,* Cambridge Univ. Press, Cambridge, U. K., and New York., 2013.

[25] Mitthan Lal Kansal, Sandeep Shukla, and Tyagi Aditya. “Probable Role of Anthropogenic Activities in 2013 Flood Disaster in Uttarakhand, India”. en. In: *World Environmental and Water Resources Congress*. 2014, pp. 924–937. DOI: 10.1061/9780784413548.095.

[26] Edwin P. Maurer et al. “Fine-resolution climate projections enhance regional climate change impact studies”. In: *Eos, Transactions American Geophysical Union* 88.47 (2007), pp. 504–504. ISSN: 00963941. DOI: 10.1029/2007EO470006.

[27] Kleist J McKee TB, Doesken NJ. “The Relationship of Drought Frequency and Duration to Time Scales”. In: *Eighth Conference on Applied Climatology*. California, 1993, pp. 179–184.

[28] P Nema et al. “Techno-economic evaluation of soil-aquifer treatment using primary effluent at Ahmedabad, India”. In: *Water Research* 35.9 (2001), pp. 2179–2190. ISSN: 00431354. DOI: 10.1016/S0043-1354(00)00493-0.

[29] B D Santer et al. “Ocean variability and its influence on the detectability of greenhouse warming signals”. In: *Journal of Geophysical Research* 100.C6 (1995), pp. 10693–10725. ISSN: 0148-0227. DOI: 10.1029/95JC00683.

[30] S. Solomon et al. *IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 2007. ISBN: 0521705983.

[31] LJ Erie, Orrin F French, Karl Harris, et al. "Consumptive use of water by crops in Arizona". In: (1965).

[32] Reinder A Feddes, Piotr J Kowalik, Henryk Zaradny, et al. *Simulation of field water use and crop yield.* Centre for Agricultural Publishing and Documentation., 1978.

[33] NK Gontia and KN Tiwari. "Development of crop water stress index of wheat crop for scheduling irrigation using infrared thermometry". In: *Agricultural water management* 95.10 (2008), pp. 1144–1152.

[34] Rajendra K Pachauri et al. "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change". In: (2014).

[35] KY Li, R De Jong, and JB Boisvert. "An exponential root-water-uptake model with water stress compensation". In: *Journal of hydrology* 252.1 (2001), pp. 189–204.

[36] CS Ojha et al. "Evaluation of a nonlinear root-water uptake model". In: *Journal of irrigation and drainage engineering* 135.3 (2009), pp. 303–312.

[37] Chandra Shekhar P Ojha and Amaresh K Rai. "Nonlinear root-water uptake model". In: *Journal of irrigation and drainage engineering* 122.4 (1996), pp. 198–202.

[38] RK Pandey, JW Maranville, and A Admou. "Deficit irrigation and nitrogen effects on maize in a Sahelian environment: I. Grain yield and yield components". In: *Agricultural Water Management* 46.1 (2000), pp. 1–13.

[39] RK Panda, SK Behera, and PS Kashyap. "Effective management of irrigation water for wheat under stressed conditions". In: *Agricultural water management* 63.1 (2003), pp. 37–56.

[40] RK Panda, SK Behera, and PS Kashyap. "Effective management of irrigation water for maize under stressed conditions". In: *Agricultural Water Management* 66.3 (2004), pp. 181–203.

[41] Rama Prasad. "A linear root water uptake model". In: *Journal of Hydrology* 99.3 (1988), pp. 297–306.

[42] Tinus Pulles. "Will the world meet the climate change challenge?" In: *Carbon Management* 6.1-2 (2015), pp. 1–5.

[43] Vijay Shankar et al. "Model for nonlinear root water uptake parameter". In: *Journal of Irrigation and Drainage Engineering* 138.10 (2012), pp. 905–917.

[44] Shaozhong Kang, Wenjuan Shi, and Jianhua Zhang. "An improved water-use efficiency for maize grown under regulated deficit irrigation". In: *Field crops research* 67.3 (2000), pp. 207–214.

[45] I. Craciun and M. Craciun. "Water and nitrogen use efficiency under limited water supply for maize to increase land productivity". (1999). In: C. Kirda et al. *Crop Yield Response to Deficit Irrigation*. Kluwer Academic Publishers, The Netherlands, pp. 87–94.