CHAPTER 4

CLIMATE CHANGE AND PRECIPITATION

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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.

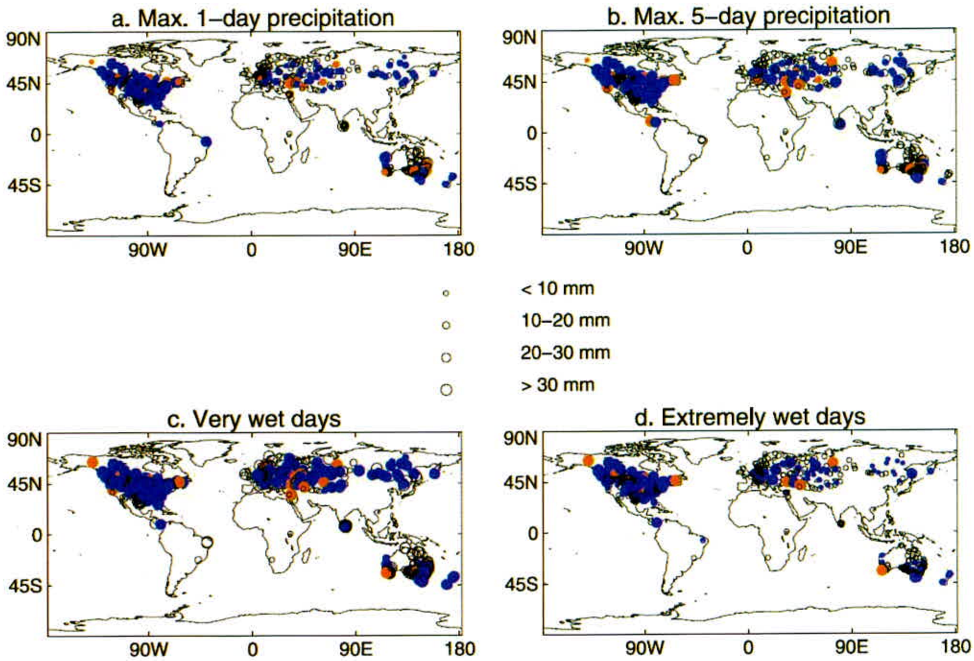

__Figure 4.1__. The 100-year trends for a selection of precipitation indices for the period 1901–2003 for a subset of stations with at least 80% complete data between 1901 and 2003. Black circles indicate anon-significant change. Blue (red) solid circles indicate a significant increase (decrease) at 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.

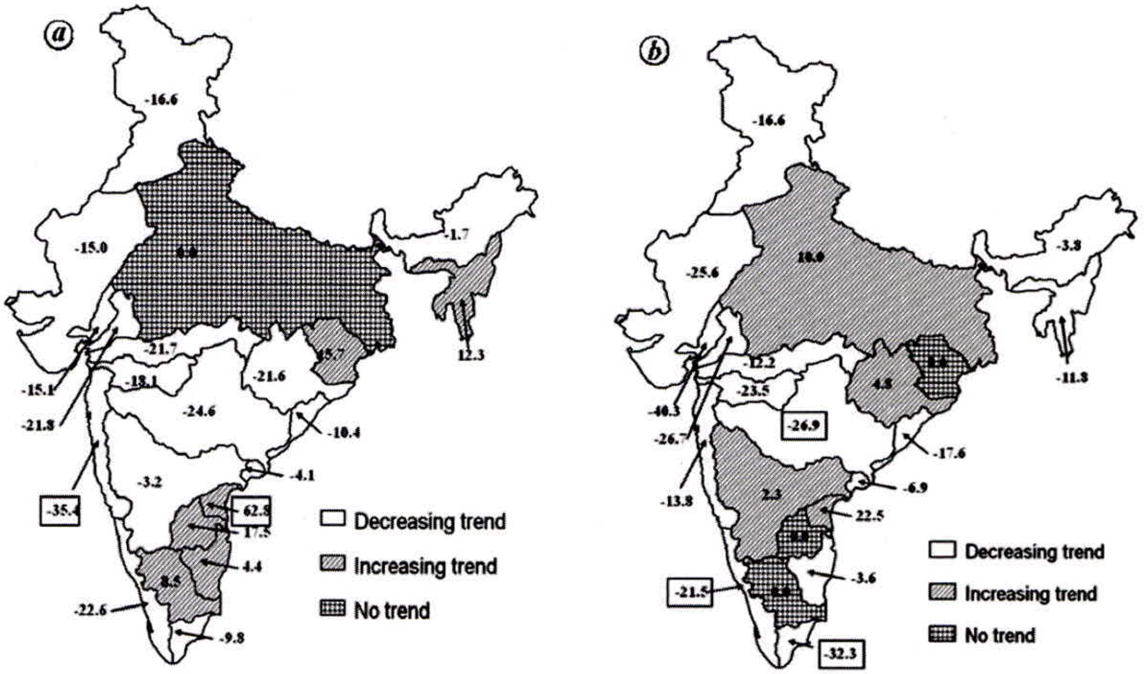

***Figure 4.2**. Trends and magnitude pertaining to rainfall changes for different river basins in India. Significant trends are displayed in boxes. (a)annual rainfall (% of mean/100 years); (b) annual rainy days (% of mean/100 years) (Source: Jain and Kumar, 2012).*

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.

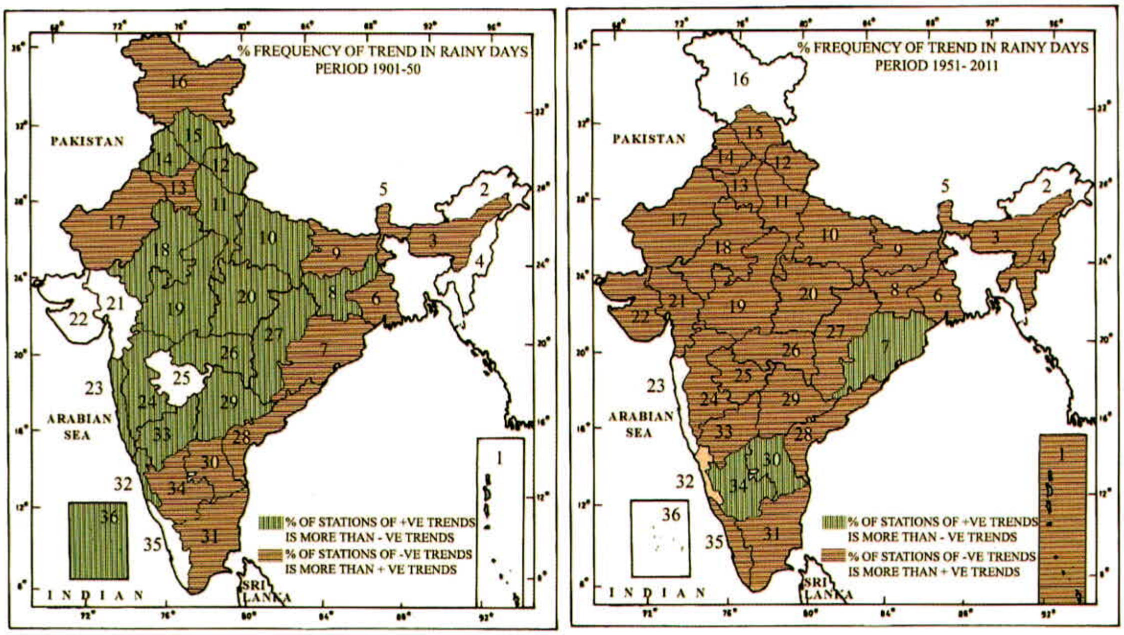

Figure 4.3. *Meteorological subdivisions showing frequency of stations having positive (increasing) trends more or less than negative (decreasing) trends in rainy days during the period (a) 1901 – 1950 and (b) 1951 – 2011 (Source: Guhathakurta et al., 2015).*

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 ≥ 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.

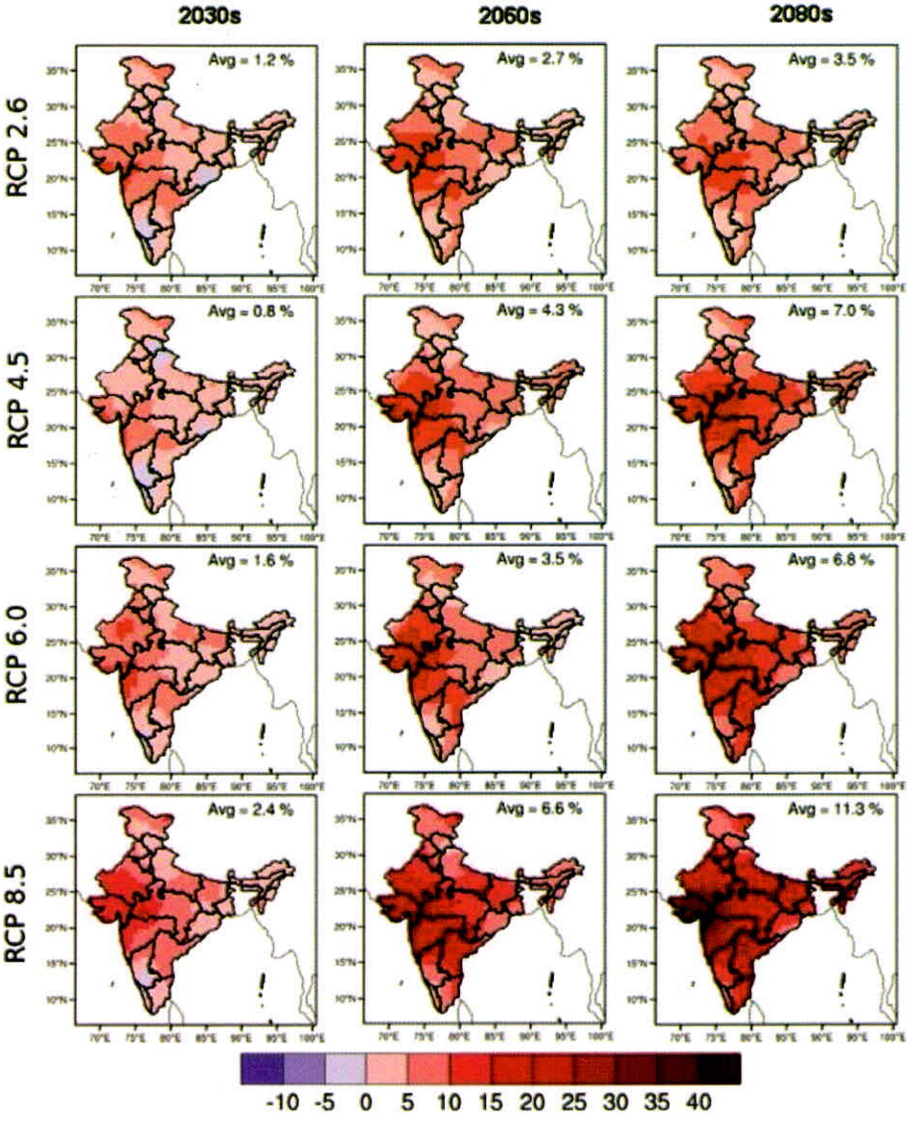

Figure 4.4. *CMIP5 model ensemble mean precipitation change (%) projected for 2030s (2021–2050), 2060s (2046–2075) and 2080s (2070–2099) relative to the pre-industrial period (1880s, i.e. over 1861–1900). (Source: Chaturvedi et al., 2012)*

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).

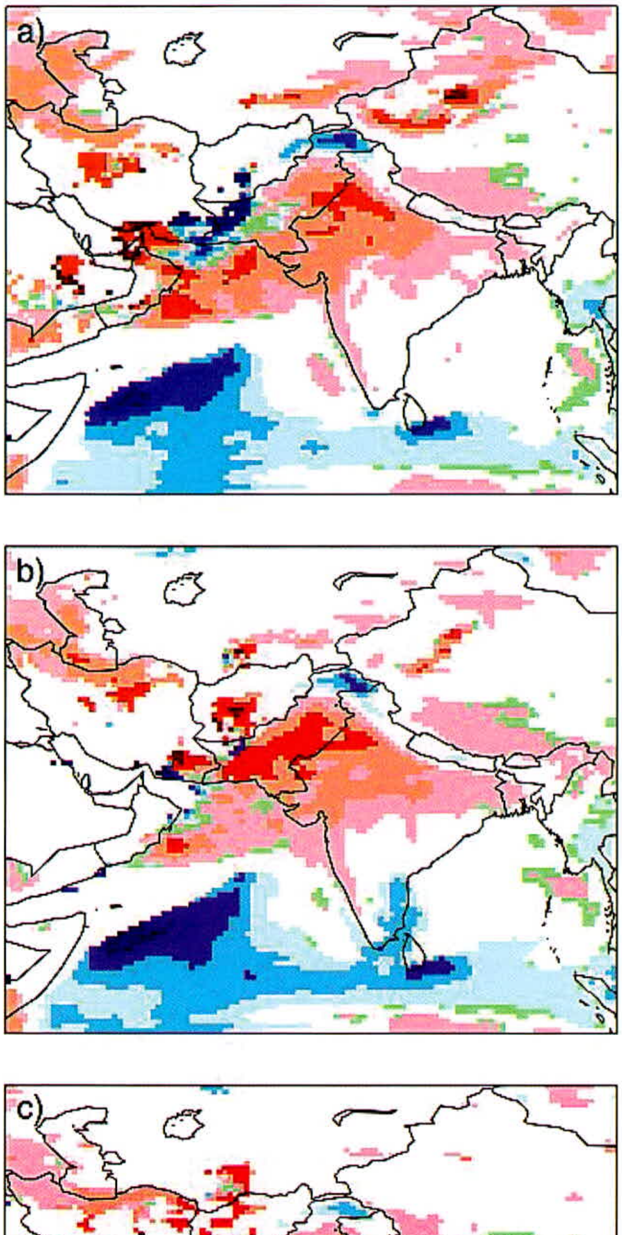

Figure 4.5. *Linear trends in monsoon rainfall (% / century) during the time period 1960 – 2100 in (a) the A2, (b) the A1B, and (c) the B1 COSMO-CLM runs. Colored areas show significant trends (at the 5% significance level). (Source: Dobler and Ahrens, 2011).*

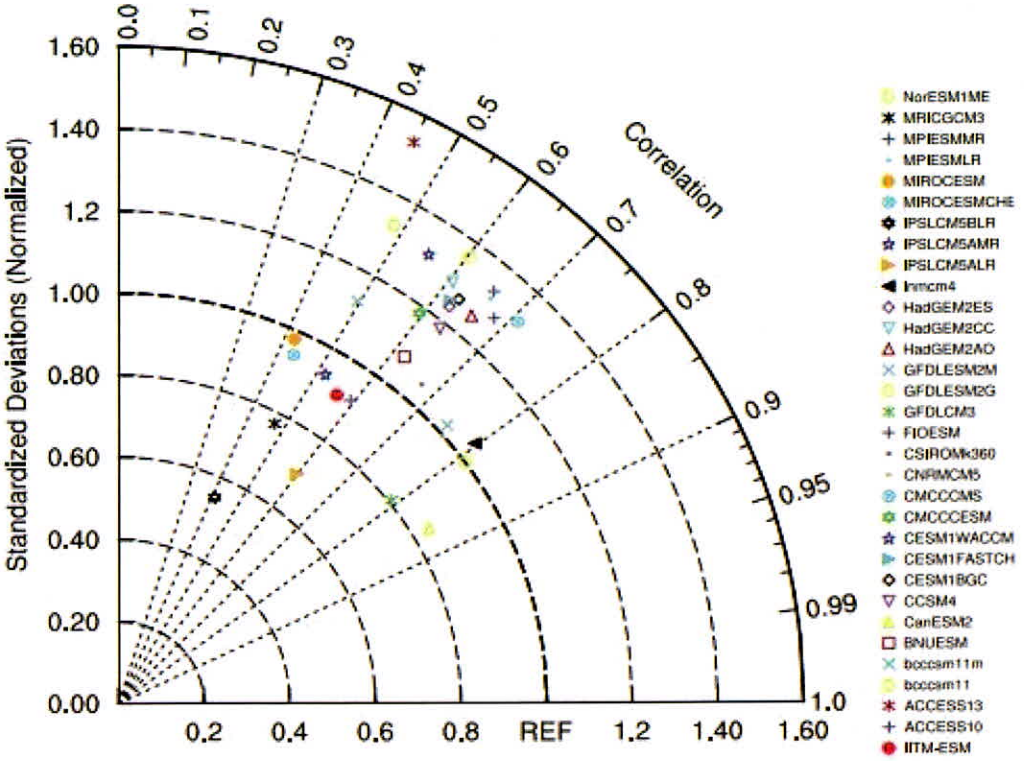

Figure 4.6*. Taylor diagram showing the spatial correlation and standard deviation of ISMR from IITM-ESMv2 and CMIP5 models. (Source: Swapna et al., 2018)*

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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