Chapter 2

Impacts of Climate Change on the Indian Summer Monsoon

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Abstract

Variability of the Indian summer monsoon has increased significantly since the 1950s. For several regions across India, this means an increase in long dry periods with low or no rainfall, intermittent with short, intense spells of rainfall. These changes are particularly significant for the western, central and eastern states of India where more than 55% of the cultivated area is largely rainfed and where the adaptive capacity is the lowest. The large-scale secular changes in monsoon rainfall are attributed to the increase in global emissions of greenhouse gases and air pollutants. At the same time, local changes through urbanization, land use changes and deforestation have brought in a non-uniform response in these rainfall trends. Changes in the onset, duration and intensity of the rainfall call for a reassessment of the crop calendar and climate resilient measures for the food-water-energy sectors of the country. Global warming has also altered the relationship between sea surface temperatures and other predictors of monsoon rainfall, introducing increasing challenges and uncertainties in the monsoon forecasts. Climate projections indicate a further increase in the monsoon variability and a shortening of the rainy season in the future, though there is considerable disagreement between model simulations.

2.1. Introduction

Every year during the summer from June to September, the southwesterly monsoon winds bring about 848 mm of rain for the 1.3 billion population of India. Considering the total area of India as 3 trillion m^2, the quantum of rain received during this season would equate to roughly 2,700 trillion litres, which translates to about 2 million litres of water per person. Almost half of this rainwater goes into the rivers, out of which half of the river water flows via the Ganges-Brahmaputra river basins at a rate of 37 million litres per second (Kumar et al., 2005). The summer monsoon rains bring more

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than 78% of annual rainfall to the Indian subcontinent. As such, any slight deviation in the rainfall could set off a cascade of events which can break or make the backbone of the society because the food, water and essentially the gross domestic product (GDP) of the subcontinent largely depend on these rains. The Indian summer monsoon exhibits variability on sub-daily and subseasonal to interannual and multi-decadal to centennial timescales. In this chapter, we will explore the monsoon variability along these timescales and how climate change is interacting among these scales. Human activities leading to increased greenhouse gas emissions, air pollution and deforestation are found to dominate the observed and projected changes in the monsoon, on sub-daily to multi-decadal timescales.

2.2. Changes in the Monsoon Variability on Subseasonal Timescales

The subseasonal variability, known as the monsoon intraseasonal oscillations (MISO), manifests as the active (wet) and break (dry) phases of the summer monsoon season. These intraseasonal oscillations originate as an ocean-atmosphere coupled event in the tropical Indian Ocean, propagate northward and depending on the phase of the oscillation, results in the wet and dry spells of the monsoon. The active phases are generally accompanied by heavy rainfall events while the break phases are characterised by low rainfall or occasionally long dry periods without any rains. This means that even if the seasonal mean rainfall is normal, the subseasonal variability can impact the food-water-energy sectors of the country. Generally, moderate rainfall is more useful for agriculture than very heavy rainfall—which has an adverse effect on the crops (Revadekar and Preethi, 2012). Recent studies show that the occurrence of prolonged breaks or heavy rains during a normal monsoon season can cause a reduction in kharif (summer) food grain yield (Preethi and Revadekar, 2013). In fact, most of the normal (and above normal) monsoon seasons years are associated with heavy-to-extreme rainfall activities while drought years are not associated with such intense rainfall activity (Preethi and Revadekar, 2013).

Since the initiation and propagation of MISO are tied to the ocean-atmospheric coupled evolution of sea surface temperatures (SST), winds and convection (Jiang et al., 2004; Roxy and Tanimoto, 2007; Zhou and Murtugudde, 2014), the basin-wide warming in the Indian Ocean has an impact on its characteristics in the recent decades. Recent studies using observations and atmospheric general circulation model experiments (Sabeerali et al., 2014b) indicate that the rapid increase in SST during the past decade (2001-2011) has changed the northward-propagating characteristics of the MISO, relative to the 1978-1988 period. They found that the MISO variance has increased in the recent period due to the SST rise. The warming of the equatorial region is also found to slow down the northward propagation, resulting in prolonged convection over the equatorial Indian Ocean (Sabeerali et al., 2014b).

Heavy-to-extreme rainfall events occur during active phases of the monsoon, and several studies point out a significant increase in the frequency of heavy and extreme rains across several regions of India (Singh et al., 2019). The rise in heavy rains coincides with a decrease in low or/and moderate rains (Goswami et al., 2006; Mishra et al., 2018; Rajeevan et al., 2008; Roxy et al., 2017; Singh et al., 2014), similar to the rainfall changes observed in other parts of the tropics (Lau and Wu, 2007) (Fig. 2.1). The increasing trend in extreme rainfall is homogenous across some regions like the central Indian region where the modulation of the monsoon westerlies is largely governed by global change (Roxy et al., 2017). However, there is a large regional variability over other regions across the country (Ghosh et al., 2012; Ghosh et al., 2016), and also localised changes in rainfall due to changes in land use land cover and urbanization (Ali and Mishra, 2017; Mondal and Mujumdar, 2015; Shastri et al., 2015).

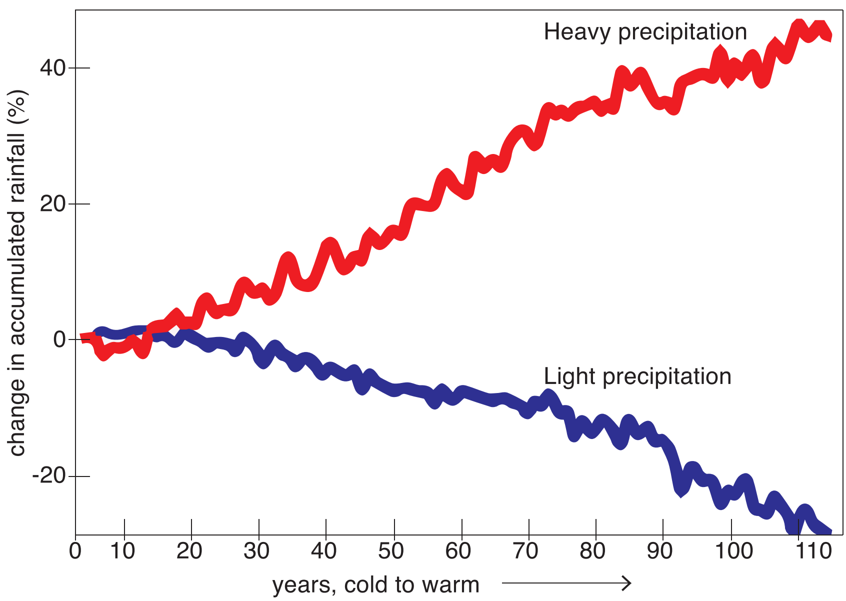

Figure 2.1. Seasonal changes in accumulated precipitation for heavy and light precipitation as a function of regional temperature over India, arranged from coldest to warmest years. Figure adapted from Mishra et al. (2018).

Rainfall data from the India Meteorological Department (IMD) for the period 1901-2014 shows a 12% increase in the number of active spells in the second half (1958-2014) (Pai et al., 2016). This increase in the active spells are mainly due to a shift towards more frequent occurrence in the short duration (3–6 days) spells compared to the long duration (≥13 days) spells (Dash et al., 2011; Pai et al., 2016; Singh et al., 2014). Meanwhile, another study using the IMD rainfall data for the period 1951–2013 suggests a decreasing trend in the strength of MISO (in the 20-60 days' timescale) over India (Karmakar et al., 2015), possibly attributed to a weakening of the local monsoon circulation. The study finds that the increase in extreme events is relatively more pronounced in the break phases than the active phases of MISO, which is suggestive of a flattening of the MISO during the past six decades (Karmakar et al., 2015). The changes in monsoon sub-seasonal variability are also felt in the major river basins over India. Analysis indicates that river basins located in central India show a significant increase in the intensity and area covered by heavy rains (Deshpande et al., 2016). At the same time, dry spells (days with no rainfall) are increasing in all the river basins except some parts of the Krishna and Peninsular river basins.

Analysis using IMD rainfall data for the period 1950-2015 indicate a threefold rise in extreme rainfall events which are widespread, covering a large area across the central belt of India, and last for a duration of about 3 days (Roxy et al., 2017). These widespread rainfall events are found to result in largescale floods and catastrophic loss for life and property across central and northern India–Gujarat, Maharashtra, Madhya Pradesh, Chhattisgarh, Telangana, Odisha, Jharkhand, Assam and parts of Western Ghats–Goa, north Karnataka and South Kerala (Roxy et al., 2017) (Fig. 2.2). There have been 285 reported flooding events in India over 1950-2017 affecting about 850 million people, leaving 19 million homeless and killing about 71,000 people (according to the International Disaster Data Base). The total damage during this period is about $60 Billion. Changes in the drainage patterns due to land use and land cover changes and increased settlement in low lying areas have raised the vulnerability to extreme rainfall events which, in turn, increases the devastation and economic loss every year. During the last decade, the damage due to floods alone has been about $3 Billion per year.

The largescale, widespread changes in extreme rainfall over the Indian subcontinent are largely dominated by dynamic responses of the atmosphere rather than thermodynamic factors. The trend in extreme events shows a negative correlation with the local temperatures over the central Indian region (Ali and Mishra, 2017; Roxy et al., 2017; Vittal et al., 2016). This is interesting because, across most of the tropics, the increase in local temperatures plays a major role in the rising frequency of the extreme rainfall events (Wang et al., 2017). The rise in widespread extremes is associated with increased variability of the low-level monsoon westerlies over the northern Arabian Sea driving surges of moisture supply, leading to extreme rain episodes across the entire central Indian belt (Mishra et al., 2018; Roxy et al., 2017). This is attributed to the increased warming north of the Arabian Sea which results in increased moisture and also large fluctuations in the monsoon westerlies (Roxy et al., 2017). The increased ocean warming is, in turn, a result of human activities leading to increased carbon dioxide emissions (Dong et al., 2014). Meanwhile, urbanization has also impacted the local rainfall distribution, inducing

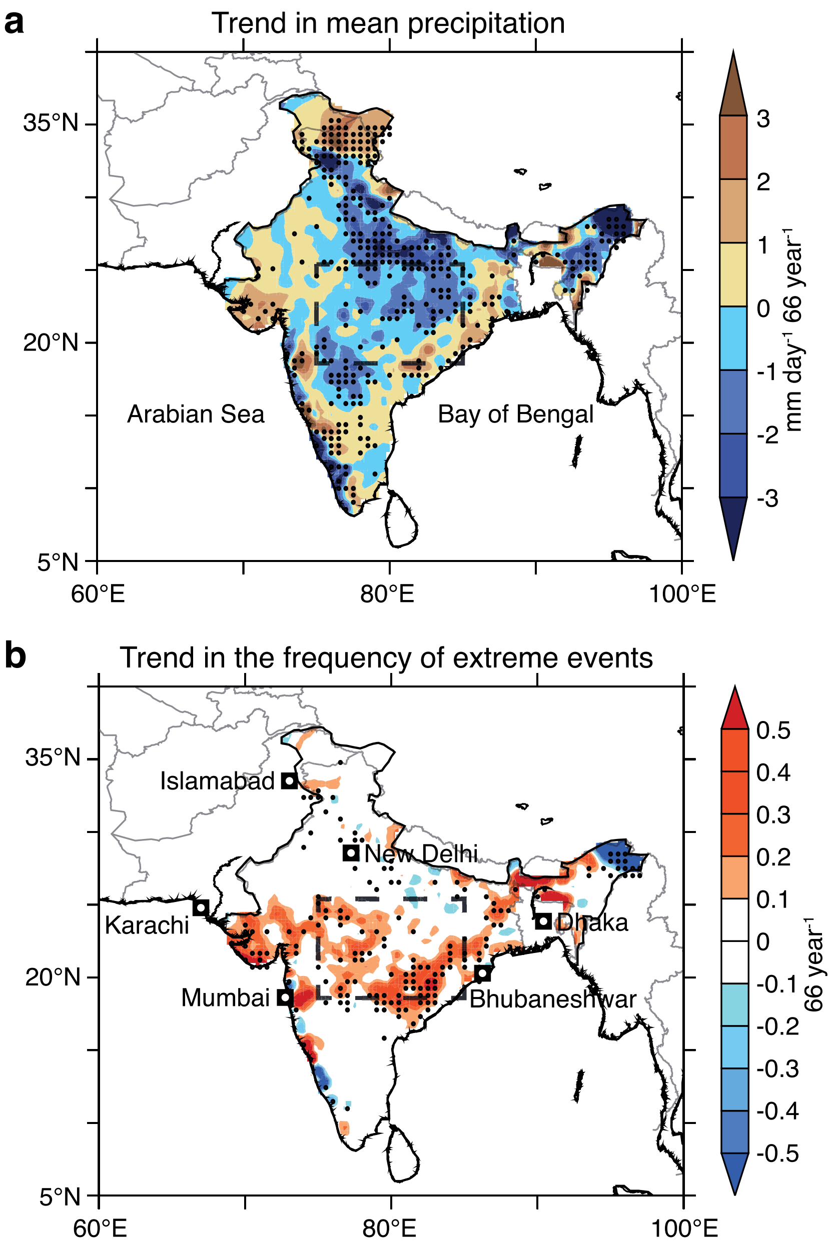

Figure 2.2. **The observed trend in summer (a) mean precipitation anomalies (mm day^{-1} 66 year^{-1}) and (b) the frequency (66 year^{-1}) of extreme precipitation events (precipitation ≥ 150 mm day^{-1}). Stippling indicates trend values significant at 95% confidence level. Mean precipitation for the season is 8.1 mm day^{-1}. Figure adapted from Roxy et al. (2017).**

nonuniformity in the observed changes of these extremes across India (Shastri et al., 2015). The impact of urbanization is visible in the southern, central, and western India. For example, urbanization has intensified the extreme rainfall in the metropolitan city of Mumbai, which is not visible in the nearby coastal town of Alibaug (Shastri et al., 2015).

Climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) project an increase in the monsoon variability at daily timescales, throughout the 21st century under the RCP 8.5 scenario, with a 13% to 50% increase by the end of the century (Menon et al., 2013). The active and break spells are projected to be more intense in the future climate, with an expansion in the area covered (Sharmila et al., 2015). These projections indicate an enhanced propensity towards short active and long break spells in the future. Short duration precipitation extremes, at sub-daily (3-hour timescales), are also projected to increase in the future. A rise of 1.5°C in the global mean temperatures (with respect to pre-industrial levels) is projected to results in a 20% increase in the sub-daily rainfall extremes, while a 2°C increase may result in a 25% increase (Ali and Mishra, 2018). However, the large spread among the CMIP5 monsoon simulations suggests low confidence in the projected changes in the monsoon and requires further investigation.

2.3. Changes in the Interannual and Multidecadal Variability of Monsoon

Though the year-to-year variability of the monsoon is generally within 10% of the average rainfall, the regional variabilities can be large, occasionally resulting in large-scale droughts. The onset and withdrawal dates are also different for each region and differ from year to year. El Niño Southern Oscillation (ENSO), characterised by a see-saw of ocean temperatures in the eastern Pacific, is a major factor influencing the monsoon variability by modulating the atmospheric circulation and the monsoon winds (Rasmusson and Carpenter, 1983). Hence generally, during El Niño conditions when the central-east Pacific temperatures are warmer than average, the monsoon circulation and winds are weak, and the rainfall over India is relatively low; and during La Niña conditions when the ocean temperatures are cool, the monsoon is strong. During 1901-2018, 12 out of the 25 monsoon droughts co-occurred with the El Niño events while 6 out of the 14 flood years were associated with the La Niña events (Fig. 2.3). This means that almost 50% of the monsoon drought and flood years are associated with the ENSO conditions in the Pacific Ocean. ENSO also influences the onset and withdrawal of the summer monsoon and in turn the length of the rainy season. An evolving El Niño reduces the tropospheric temperature gradient over the monsoon region and shortens the rainy season by delaying the onset and advancing the withdrawal (Goswami and Xavier, 2005).

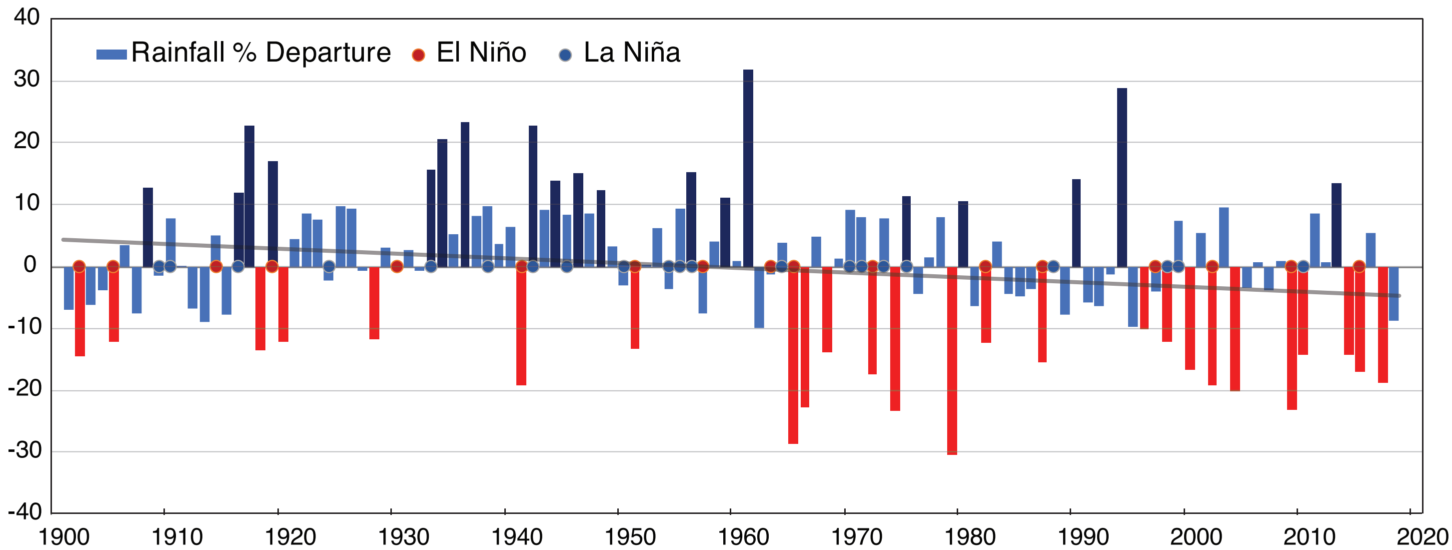

Figure 2.3. **Percentage departure of summer monsoon rainfall over central India (76-86°E, 19-26°N, box in Fig.2) during 1901-2018. Wet years (above 10% departure) are marked in dark blue colour and drought years (below -10% departure) are marked in red colour. El Niño and La Niña conditions for the summer season are marked using red and blue dots.**

However, during the last several decades, the frequency and intensity of monsoon droughts have increased, and some of these droughts were not linked to the El Niño (Fig. 2.3). Also, the El Niño-monsoon relationship exhibits a multi-decadal variability (Krishna Kumar et al., 1999), and may also depend on the temporal and regional evolution of El Niño in the Pacific (Ashok et al., 2007). Other than ENSO, the Atlantic also plays a role in influencing the monsoon interannual and decadal variability (Pottapinjara et al., 2014; Sankar et al., 2016; Yadav et al., 2018).

Nevertheless, the role of climate change is obvious in the observed changes in the interannual and multi-decadal variability of the monsoon. Observations show that Indian monsoon rainfall, particularly that over central and north India, has undergone a statistically significant weakening since the 1950s (Fig. 2.2). The secular decline in the mean rainfall is associated with a weakening of the local monsoon Hadley circulation. Several factors are attributed to the observed changes in the monsoon rainfall, one of them being the rapid warming in the Indian Ocean. It is suggested that the rapid warming in the Indian Ocean during the past six decades have reduced the meridional tropospheric temperature gradient, dampening the monsoon circulation (Gnanaseelan et al., 2017; Jin and Wang, 2017; Mishra et al., 2012; Roxy, 2017; Roxy et al., 2015). Deforestation, including conversion of forest land to cropland, have also contributed to the weakening of the monsoon, by decreasing the evapotranspiration and thereby the recycled component of rainfall (Paul et al., 2016). It is also argued that increased air pollution has played a role in changing the monsoon characteristics by reducing the meridional thermal gradient and by interacting with the convective processes (Guo et al., 2015)—though there is large uncertainty in these results due to lack of consistent, continuous observations and improper representation of aerosol effect in the models. Meanwhile, a recent analysis (Jin and Wang, 2017) suggests that enhanced land surface warming in the recent decade (2002-2014) has strengthened the meridional tropospheric temperature gradient, indicating a possible short-term revival of the monsoon.

Other than a weakening monsoon circulation, the onset of the monsoon over India has also experienced a delay in the recent decades (Sahana et al., 2015). The delay in the onset is attributed to a net decrease of moisture supply form the Arabian Sea in the post-1976 period. Hence, while the mean summer monsoon onset date was 1 June during 1948-1976, this has shifted to 5 June since 1976, suggesting a re-assessment of the crop calendar in India which depends on the monsoon onset dates. Global warming has also altered the predictor-predictand relationship in terms of monsoon forecasts. As a result, the skill in Indian monsoon seasonal forecasts has also reduced in the recent decades (Wang et al., 2015).

On a large scale, the rainfall over the northern hemisphere has shown substantial intensification during 1979-2011, with a striking increase of rainfall by 9.5% per degree of global warming (Wang et al., 2013). CMIP5 models project this to increase in the future, though there is low confidence in the simulations over the Indian monsoon region, due to large inter-model spread and coarse resolution of the model simulations (Sabeerali et al., 2014a; Saha et al., 2014). A study using selected CMIP5 models, which simulate the monsoon and Indian Ocean conditions, suggest a shortening of the rainy season in the future (Sabeerali and Ajayamohan, 2017). They attribute this to the rapid warming of the Indian Ocean which in turn dampens the meridional tropospheric temperature gradient. Another study indicates a weakening of the monsoon circulation due to a reduction in the large-scale meridional temperature gradient at upper tropospheric levels (200 hPa) over the Asian monsoon region, associated with increased heating over the equatorial Pacific in the future climate (Sooraj et al., 2015).

2.4. Changes in the Monsoon on Centennial Timescales

Centennial variability of the monsoon is inferred mainly from geological proxies such as stalagmites, stalactites, corals, marine and lake sediments (Chakraborty et al., 2012; Sinha et al., 2018; Zhisheng et al., 2015). A multi-centennial trend to drier and possibly cooler conditions in the Indus Valley region started around 4100 years ago. This coincided with a considerable decrease in the Northern Hemisphere temperature and Indus Valley deurbanization phase (about 3850–3300 years before present), as inferred from the speleothem oxygen isotope records from the Sahiya caves in north India (Kathayat et al., 2017). Oxygen isotope records based on stalagmite proxies from Kadapa caves in peninsular India also capture the wet and dry periods of the monsoon on decadal to centennial timescales (Fig. 2.4) (Sinha et al., 2018). These stalagmite records indicate an abrupt climate change, characterised by the decline of monsoon around 2800 years before the present time. This decline coincides with a sudden rise in the atmospheric carbon isotopes, indicative of reduced solar activity. It is noted that the declining trend of the monsoon follows the northern hemispheric summer insolation, which is known to influence the location and strength of the Inter Tropical Convergence Zone (ITCZ).

Studies show that the South Asian Summer Monsoon began to show a weakening trend from the mid-13th century, reaching a minimum in the mid-15th century and then peaking in the early 17th century. Upwelling proxy record from the Arabian Sea indicates that the monsoon strength reached a minimum around the year 1600 (Anderson et al., 2002). This weakening of the monsoon upwelling is reflected as drying over the subcontinent, especially over western-peninsula India during the period of 1580–1630 (Shi et al., 2018). Thereafter, the monsoon strengthened rapidly during 1630-1670. Following this, there has been a declining trend until the present (Shi et al., 2017; Shi et al., 2014). Such centennial variations may be partially attributed to changes in solar activity before the 19th century (Hiremath et al., 2015; Shi et al., 2017; Shi et al., 2014). Increased variability in solar radiation can increase the thermal contrast between land and sea (Hiremath et al., 2015), and lead to a northward shift of the intertropical convergence zone (Tierney et al., 2010) causing the monsoon to strengthen. Even though the solar radiation during four out of five of the solar activity sequences showed an increasing trend through the late 19th century, the monsoon continued to weaken (Shi et al., 2017). These mismatches may be related to the increased anthropogenic emissions in the 19th century (Bollasina et al., 2011; Guo et al., 2015; Krishnan et al., 2013; Roxy et al., 2015) because after the industrial era, the effect of natural forcings have decreased and that of anthropogenic emissions have increased (Bollasina et al., 2011).

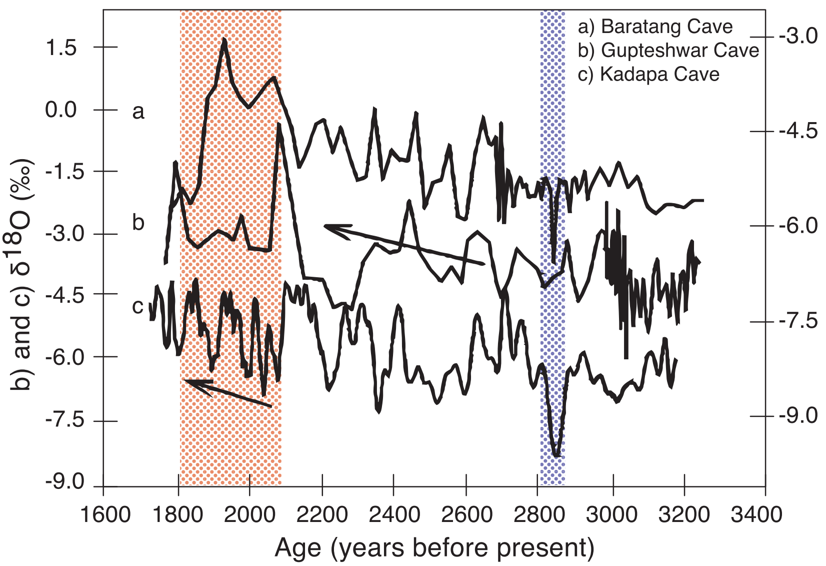

Figure 2.4. Variation of Oxygen isotopes at different caves across India, (a) Baratang Cave, (b) Gupteshwar cave and (c) Kadapa cave. The arrow shows an average declining trend in rainfall in all the records, during the warming period (red stippling) in Europe and the North Atlantic that ran from approximately 250 BC to AD 400. The blue stippling indicates the signature of enhanced monsoonal rainfall for a short period (about 2900–2850 years before present). Figure adapted from Sinha et al. (2018).

The Holocene age (the recent 10,000 years) saw large changes in the Earth's climate on a centennial scale. Weak summer monsoon winds correlate with reduced solar output—the variability as seen when going from a multidecadal scale to a centennial one. Studies indicate that over the past 11,100 years, the multidecadal to a centennial-scale decrease in summer monsoon intensity can be attributed to the intervals of reduced solar output and an increase in elevated solar output (Gupta et al., 2005). This link between the solar cycle and the monsoon appears to be via direct solar influence on the ITCZ that controls the monsoonal precipitation (Kodera, 2004). Meanwhile, it is indicated that the positive relation between monsoon rainfall and solar activity is mainly due to the effect of the Atlantic Multidecadal Oscillation, which is influenced by the changes in solar activity (Malik and Brönnimann, 2018). Also, it is argued that the strength of the relationship between monsoon rainfall and ENSO on interannual to centennial timescales is modulated by solar activity from 3 to 40 year timescales (Malik and Brönnimann, 2018).

2.5. Conclusion

Global changes resulting in warmer tropical oceans and local changes in land development, forest cover and air pollution have led to increased Indian summer monsoon variability during 1950-2018. Though non-uniform, the increase in variability is prominent with a significant weakening of the local monsoon circulation and rainfall, along with an increase in the frequency of short-duration extreme rainfall events. These changes are projected to increase further in the future, along with increased anthropogenic emissions. Using long-term data and high-resolution climate models, our understanding of these changes in monsoon rainfall has improved in recent decades. These observed and projected changes may be useful for the long-term management of the agricultural-irrigation sectors and efficient planning of the food, water and energy sectors of the region.

Short, extended range and seasonal monsoon forecasts have improved during the past decade due to advancement in monsoon research and development but more importantly due to the National Monsoon Mission which significantly raised the investment on high-performance computing, trained human resources and international participation (Abhik et al., 2017; Ramu et al., 2016; Sahai et al., 2013). However, state-of-the-art climate models still do not skillfully simulate the observed long-term climatic changes in monsoon rainfall, and there is low confidence in the projected changes in monsoon over South Asia. Besides, global warming has also introduced increasing challenges and uncertainties in the seasonal monsoon forecasts, which needs to be addressed (Wang et al., 2015). Hence, there is an urgent need to comprehensively understand the interactive roles of the land, ocean, atmosphere and biosphere on the observed changes and to incorporate them into the models for predicting the future changes (Swapna et al., 2015).

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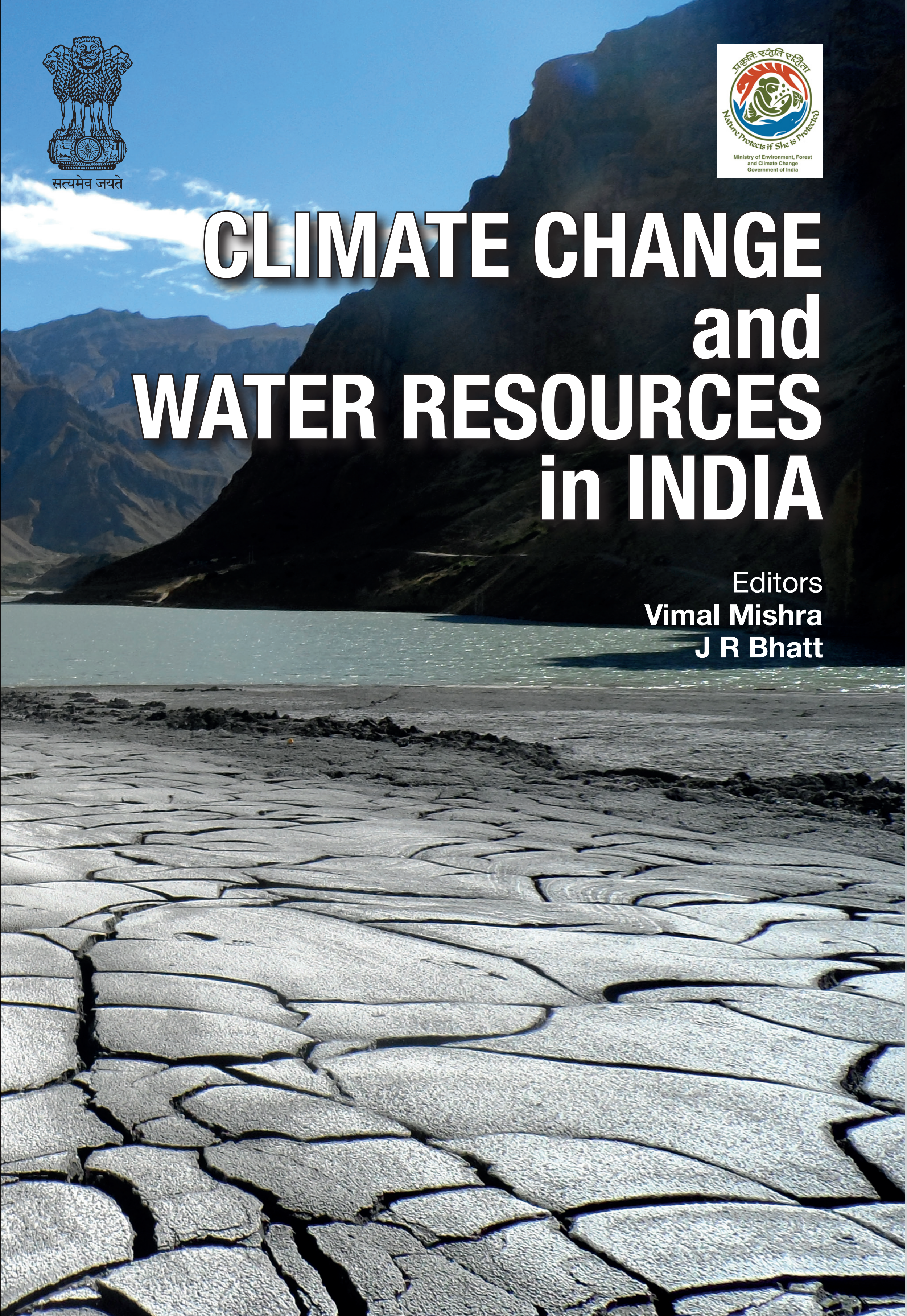

सत्यमेव जयते

प्रकृतिः रक्षति रक्षिता

Nature Protects if She is Protected

Ministry of Environment, Forest and Climate Change
Government of India

CLIMATE CHANGE and WATER RESOURCES in INDIA

Editors
Vimal Mishra
J R Bhatt

Climate Change and Water Resources in India

Understanding of changes in water resources in India in response to the warming climate is vital to ensure the food and freshwater security. Impacts of climate change are already visible in different sectors that affect socioeconomic conditions and livelihood of the people. However, climate change impacts on the water sector can have profound implications in the coming decades in India. This book provides a comprehensive assessment of the implications of climate change on water resources in the country. The book has ten chapters written by the expert authors that cover a wide-range of the topics. The book highlights the current state and the potential of surface and groundwater in India. Moreover, the book provides information on the projected changes in the Indian summer monsoon, streamflow, water availability, and water demands in the agriculture and industry sectors. The linkage between climate change and water quality of surface and groundwater resources in India is also explored. Overall, the book will be an excellent resource for policymakers, government and non-government organizations, and the scientific community working in the areas related to water resources.

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