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Indian Summer Monsoon Rainfall in a changing climate: a review

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ABSTRACT

Indian Summer Monsoon Rainfall (ISMR) is one of the most well-documented areas of hydrometeorology; however, the processes associated with ISMR are not well understood. This attributes to the complexities associated with ISMR at multiple spatio-temporal scales. This further results in inconsistencies across the literature to assess the impacts of global warming on the monsoon, though this has huge relevance as a huge population of South Asia is dependent on the same. Here, we review and assess the existing literature on the Indian monsoon, its variability, and its trajectory in a warming scenario. We further synthesize the literature on its impacts on the hydrology of major river basins in South Asia. We also identify a few research questions, addressing which will add value to the understanding of the Indian monsoon and the associated water cycle. We have highlighted that there is a significant lack of understanding of how different large-scale and regional factors affect ISMR at different timescales. These impacts, in turn, get translated into hydrology and water sector in India. There is a need to know where we stand to combat the impacts of climate change on ISMR, which can be translated to adaptation by policy-making processes and water management practices in India.

Key words: climate change, hydrologyl, indian summer monsoon rainfall, spatio-temporal variability

HIGHLIGHTS

- The study reviews the literature regarding the Indian monsoon in changing climate over time.
- Studies regarding the changing characteristics and the factors affecting the Indian monsoon have been reviewed.
- Few research questions are discussed that can be addressed to improve the understanding of the Indian monsoon.
- Study can be a guideline for future research regarding the simulation and prediction/projection of the Indian monsoon.

1. INTRODUCTION

Indian Summer Monsoon Rainfall (ISMR) is a large land–ocean–atmosphere coupled system. It occurs due to the transport of substantial amounts of moisture during June to September (summer) months across the Indian Ocean toward the Indian subcontinent (Webster *et al.* 1998). It reaches as far north as the southern Himalayas and as far northwest as Pakistan. India receives ~70% of the total moisture in the form of rainfall with which the socio-economic, agrarian, and water management reforms are intertwined tightly (Gadgil & Gadgil 2006). This is to the extent that even a few minor changes in its spatio-temporal patterns can bring substantial hardships to the region (Sinha *et al.* 2011). Western and central regions of India receive more than 90% of the annual precipitation during the June–September months.

On a global scale, the Inter-Tropical Convergence Zone (ITCZ) and tropical monsoons are quite related. The global circulation shifts toward the higher radiation received from the Sun, and the process largely drives seasons over the tropical region (Webster *et al.* 1998; Gadgil & Gadgil 2006). The zone of maximum solar influx energy is significantly wide over the region, defining the period of precipitation and strong seasonal rains. The southeast trade winds of the southern hemisphere cross the equator and start blowing southwest toward the Indian subcontinent under the influence of the Coriolis force. During the shift of the ITCZ, the Indian subcontinent is heated, which generates a low pressure drawing in moist air from the sea. The equatorial trough positions over the Ganga plain about 25°N of the equator, which is also known as the monsoon trough.

Along with the ITCZ, it was hypothesized that the Tibetan Plateau also drives the moisture transport over South Asia from the Indian Ocean while acting as a major heat source (Flohn 1968; Li & Yanai 1996). However, Boos & Kuang (2010) found the large-scale South Asian boreal monsoon is not affected by the existence of the Tibetan Plateau. In fact, the Tibetan Plateau acts as a broad desert producing shallow dry circulation, insulating the deep warm and moist air over the Indian subcontinent from the northern cold and dryness (Nie *et al.* 2010). It was later established that the non-elevated regions are more largely affected by surface heat fluxes than the elevated terrains, which act as thermal insulators (Wu *et al.* 2012; Boos & Kuang 2013). These overall impacts of global-scale circulations in boreal summer drive moisture from the ocean over the Indian subcontinent. The topography helps create a strong Indian monsoon from the rest of South Asia.

ISMR is also linked with the synoptic-scale systems over surrounded warm oceans, propagating into the land mass and causing convection (Gadgil 2003). Gadgil (2003) showed that low-pressure systems from the Bay of Bengal moving along the core monsoon zone significantly contributes to the Indian monsoon. The study also showed the significance of deep convection over the warm Indian Ocean could cause monsoon rainfall over India during boreal summer. The combined ocean–atmosphere interactions of the Indian and Pacific Oceans are also found to influence the Indian monsoon variability (Krishnamurthy & Kinter 2003).

In the early studies of the Indian monsoon, there was little understanding regarding its spatial variability. Moreover, the smaller network of rainfall stations also remained a challenge in determining Indian monsoon rainfall. ISMR has been historically calculated as total rainfall values over the Indian subcontinent. Blanford, in 1886, calculated the annual rainfall for the 19-year period from 1867 to 1885 and found that the annual mean rainfall varied from 90 cm in 1868 to 124 cm in 1878. Walker (1910) examined southwest monsoon (June to September) rainfall by considering all available rain gauge data to find the deficit rainfall decades during 1843–1860 and 1895–1907. Later, Mooley & Parthasarathy (1984) analyzed All India summer monsoon (June–September) rainfall for the earlier dataset to understand the interannual and long-term variability of the monsoon. The past statistics showed that India received 85.31 cm of mean monsoon rainfall, which is 78% of the annual rainfall. It was observed that there was a continuous rise in the 10-year mean rainfall from 1899 to 1953 (Mooley & Parthasarathy 1984). In the past century, the monsoon statistics have changed with the improved number of rain gauges and extrapolation of rainfall over India. In the past few decades, the Indian monsoon has observed more deficit rainfall years due to global warming (Roxy *et al.* 2017). The study of long-term trends within interannual variations can be of great implication if attended with spatial and temporal distribution due to huge uncertainty in both. Figure 1 shows the time series of ISMR by considering the spatial mean of rainfall values for the period 1901–2010. The time series is derived from the India Meteorological Department gridded dataset (Pai *et al.* 2014). The spatial variability of the mean and

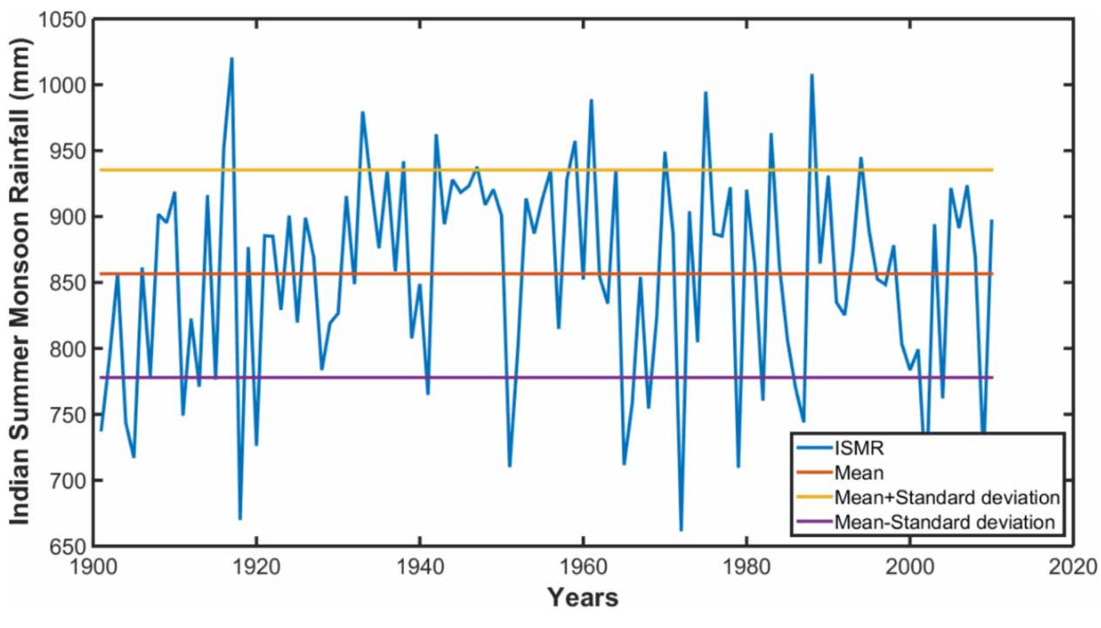

Figure 1 | Time series of ISMR for the period of 1901–2010 (110 years).

standard deviation of the Indian monsoon for the same period is shown in Figure 2(a) and 2(b), respectively. Many previous studies recorded these distributions using multiple classifications such as empirical orthogonal function (Krishnamurthy & Shukla 2000; Kulkarni 2017), principal component, and cluster analyses to classify regional variability within ISMR (Gadgil & Narayana Iyengar 1980; Kulkarni *et al.* 1992; Gadgil *et al.* 1993; Iyengar & Basak 1994; Azad *et al.* 2010; Sahastrabuddhe *et al.* 2019). Figure 2(c) shows nine spatial patterns (clusters/composites) of monsoon rainfall anomalies from the study by Sahastrabuddhe *et al.* (2019) for the period 1901–2010. They showed how large-scale hydroclimatic teleconnections from sea surface temperatures (SSTs) drive moisture over the Indian subcontinent causing a particular spatial pattern of ISMR.

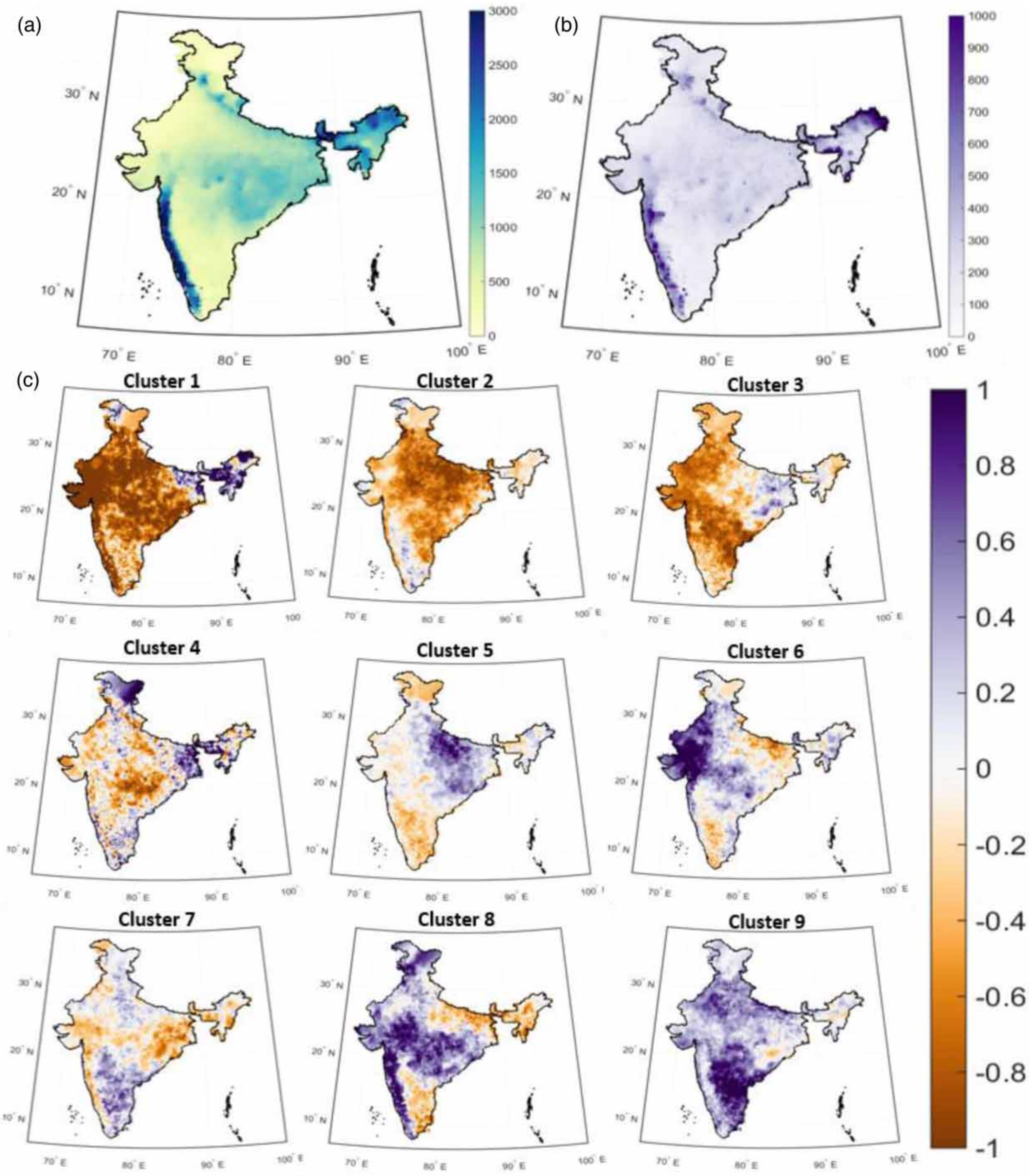

Figure 2 | Spatial distribution for (a) mean and (b) standard deviation of ISMR for the period 1901–2010. (c) Composites (Clusters) of standardized seasonal monsoon rainfall anomalies showing the spatial patterns obtained from the study by Sahastrabuddhe *et al.* (2019) for the given period.

1.1. Intraseasonal variability

Intraseasonal components are the building blocks of ISMR (Goswami & Ajayamohan 2001; Saha *et al.* 2021). The intraseasonal components, such as the synoptic system, include prominent westward and northward propagating synoptic system Monsoon Intraseasonal Oscillations (MISOs) (Krishnamurti & Bhalme 1976; Yasunari 1979; Sikka & Gadgil 1980). The intraseasonal variation has the fluctuations of two broad scales of 10–20 and 30–60 days. The 10- to 20-day variability was observed due to pressure, cloud cover, rainfall (Krishnamurti & Bhalme 1976), and in cloudiness data (Yasunari 1979), and the 40- to 50-day in a long record of daily rainfall (Hartmann & Michelsen 1989). Annamalai & Slingo (2001) estimated 10- to 20-day and 30- and 60-day fluctuations explain the total intraseasonal variability of about 25 and 66%, respectively. These analyses associate the intraseasonal variations to two prominent phases, i.e., active and break phases. However, Singh *et al.* (1992) found no connection between the intraseasonal variability of the Indian monsoon with either the total seasonal precipitation or the El Niño Southern Oscillation (ENSO) phenomenon. Krishnamurthy & Shukla (2000) used multichannel singular spectrum analysis of the daily rainfall anomalies to find two oscillations with periods of 45 and 20 days and three seasonally persistent components. However, the oscillations contribute little to the seasonal mean rainfall, apart from the seasonally persisting components, which have a very high interannual correlation with the seasonal mean rainfall.

Intraseasonal variability of ISMR has high frequency and is largely considered chaotic in nature, also called 'climatic noise' (Palmer 1994; Goswami 1998). Goswami & Xavier (2005a, 2005b) showed that the dominant noisy intraseasonal variability contributed to only around 50% of the predictability of ISMR. Several factors at the decadal and multidecadal scale contribute to the intraseasonal to seasonal variability of ISMR (Goswami 2004; Saha *et al.* 2019, 2021; Sahai *et al.* 2019). Several studies suggested that a significant part of intraseasonal variability is associated with the predictable mode of ENSO (Dwivedi *et al.* 2015; Saha *et al.* 2019). Saha *et al.* (2021) showed the contribution of intraseasonal variability of ISMR on an interannual to multidecadal scale. During 1901–2018, they found the in-phase relationship of synoptic variance with the seasonal ISMR varying from decadal to the multidecadal time scale. The systems were strongly in-phase around the 1940s and out of phase around the 1970s.

1.2. Interannual variability

SSTs are the prominent drivers of predictable components in Indian monsoon variability. Understanding the interannual variability of the Indian monsoon remains the most sought and intensively studied research area in climate (Kucharski & Abid 2017). In the earlier 20th century, ENSO was known to be the main driver of the Indian monsoon (Kumar *et al.* 1999). However, the study of Indian Ocean Dipole (IOD) (Saji *et al.* 1999; Yamagata *et al.* 2004) revealed the weakened relationship between ISMR and the El Niño phenomenon. Other large-scale SST forcings were established that directly or indirectly affected the Indian monsoon – such as SSTs over the Indian Ocean, Atlantic Ocean, and several areas over the Pacific Ocean. Lau & Nath (2000) showed the interrupted response of South Asian monsoon and tropical Pacific SST anomalies because of an anomalous response from the Indian Ocean. Hydroclimatic teleconnections between monthly summer monsoon rainfall from the Indian Ocean and tropical Pacific Ocean were discussed by Maity & Nagesh Kumar (2006). Arpe *et al.* (1998) indicated that western Indian Ocean SST could counteract the direct impacts of ENSO on the interannual variability of Indian monsoon rainfall. Along with these SSTs, Equatorial Indian Ocean Oscillation (EQUINOO), the fundamental output of IOD mode, was also registered (Gadgil *et al.* 2004). The physical interactions within these other forces could be constructive or destructive, with the ENSO impact further affecting the ENSO-induced predictable signal.

1.3. Multidecadal variability

ISMR observed multidecadal variability with less rainfall during the periods 1901–1930 and 1961–1990 and more rainfall during 1871–1900 and 1931–1960 (Parthasarathy *et al.* 1994). The variability is ~60 years of periodicity, which is presumed to be in phase with the Atlantic Multidecadal Oscillation (AMO) (Zhang & Delworth 2005; Goswami *et al.* 2006a, 2006b). Another multidecadal factor, Pacific Decadal Oscillation (PDO), governs the variability of ISMR. Goswami *et al.* (2016) showed 50–80 years of oscillations could be inherent variability of ISMR using Intrinsic Mode Function analysis. There is no established set of teleconnections provided, but much of the multidecadal variability arises from ocean–atmosphere–land interactions. Along with the impacts of SST, the multidecadal modulation from solar forcings is also studied with possible solar gradient proportional to ISMR (Bhattacharyya & Narasimha 2005, 2007). Agnihotri *et al.* (2002) observed a periodicity of 60 ± 10 years in both ISMR and solar activity. Recent studies also proved the impact of anthropogenic emissions and volcanic eruptions toward the long-term variability of ISMR. The epoch analysis by Anchukaitis *et al.* (2010) with coupled Global Climate Model (GCM) simulations also found dry conditions after volcanic eruptions in India. We have discussed important studies summarizing their findings, datasets used and their drawbacks in Table 1.

2. CHANGING CHARACTERISTICS OF ISMR

The human-induced climate change has immensely affected the magnitude of ISMR and its spatial variability recently. The impacts of global-scale greenhouse gas (GHG) emissions and aerosols and the local-scale changes such as urbanization and changes in land use have contributed largely to ISMR. Mooley & Parthasarathy (1984) studied the long-term variability of the Indian summer monsoon during the 1871–1978 years for decadal-scale statistics of rainfall and frequency of extremes. The first two decades of the 20th century showed a low average value of annual mean rainfall (~87 cm) for the period, which peaked progressively during the mid-1900s (~93 cm) and then again took a nosedive (~86 cm) during 1971–1980. They also recorded changes in occurrences of extreme rainfall during different decades of the twentieth century. Kumar *et al.* (2010) analyzed 135 years (1871–2005) and found an increasing trend of monsoon over northern India and decreasing over northeastern and central parts. Dash *et al.* (2007) reported increased pre-monsoon and post-monsoon precipitation averaged over India for the period 1901–2002, whereas summer monsoon precipitation decreased.

Roxy *et al.* (2015) showed the trend in precipitation over the South Asian region during the summer monsoon during the past century. The trends showed a weakening trend over the central-east and northern regions of the Indian subcontinent and south of the Western Ghats region. The spatial pattern featured a prominent horseshoe pattern showing the reduction in summer rainfall over central-east India during the past century. This could have socio-agrarian consequences as the agriculture in this region is still largely rain-fed. The positive rainfall trends are only seen in a small domain along the west coast of India.

Previous studies suggested that a decrease in global land monsoon rainfall is caused by warming trends over the tropical oceans, especially the Central-Eastern Pacific and the Western Indian Ocean. Although the Pacific Ocean does not show any significant warming trend, the western Indian and the Southern Indian Ocean have been warming in the past few decades (Roxy *et al.* 2015). Even after the warming of the Indian Ocean drives moisture over oceanic parts, it does not necessarily attract more moisture toward the subcontinent. In fact, the land–sea thermal gradient drops due to the warming over oceans, which could modulate the strength and flow of the monsoon circulation and the moisture-laded winds toward the South Asian subcontinent. The warming also contributes to the polarity of moisture transport over the northern and southern parts of the Western Ghats. But, the overall historical observation of ISMR since the 1950s shows a decreasing trend. Along with the weakening trend, there is evidence of extreme rainfall over the Indian subcontinent in the warming climate.

Rainfall events can be classified as short, long, dry or prolonged dry based on duration and low, moderate or heavy in terms of intensity. Based on a statistical analysis of observed data, a decrease in moderate and low rain days has been reported. Besides, it is also noted that long spells have declined. On the other hand, a short spell with heavy intensity and dry spells show an increasing trend (Dash *et al.* 2009). A decline in moderate-low intensity long spell events has also been reported (Dash *et al.* 2011; Singh *et al.* 2014; Kulkarni *et al.* 2020). Dash *et al.* (2011) showed that the contribution to total annual rainfall from short-spell events has increased from 1951 to 2008. In the future, the extreme wet and dry spells are projected to intensify (Sharmila *et al.* 2015) with more days of moderate to heavy rainfall (Katzenberger *et al.* 2022).

The assessment of extreme rainfall projections under future climate by Global Climate Models (GCM) represents poorly at a higher resolution (Shashikanth *et al.* 2018). The study used modified statistical methodology (MSD) to project the extremes for ISMR by two conventional extreme value theory approaches: Block Maxima (BM) and Peak over Threshold (PoT). The extreme projections showed significant improvement while projecting three different time windows, 2020, 2050 and 2080, using IPSL global climate model from Coupled Model Intercomparison Project Phase 5 (CMIP5). They found a heterogeneous spatial increase in rainfall extremes for future timescales. This is reflected in the future projections made by CMIP5 GCMs. Different Representative Concentration Pathway (RCP) scenarios provide more information regarding the future changes in ISMR and extreme events corresponding to each scenario.

Interannual variability of All India rainfall and the frequency distribution is analyzed from state-of-the-art coupled global climate models to derive robust signals within projected ISMR (Jayasankar *et al.* 2015b). CMIP5 models project the warming of Indian landmass at the end of the 21st century by 1.19 ± 0.79 °C for RCP2.6 and 3.99 ± 1.27 °C for RCP8.5. Due to vast intermodal bias, the Multi-model ensemble projected changes are 0.39 ± 0.79 mm/day for RCP2.6 and 0.95 ± 1.13 mm/day for RCP8.5. However, the seasonal cycle shows no consensus among the models, particularly for the early-stage monsoon

Table 1 | Summary of the relevant literature related to ISMR variability

Introduction to ISMR

References	Findings	Dataset used	Future scope
Walker (1910), Mooley & Parthasarathy (1984)	Calculating All India Monsoon Rainfall.	Rain gauge data.	The work includes an insufficient number of rain gauge stations and limited interpolation techniques. More rain gauge stations are needed for the improvement of analysis and better interpolation techniques need to be explored.
Pai *et al.* (2014)	Improved representation of ISMR spatial variability.	High-resolution data from 6,955 rain gauges.	Still require more number of rain gauge stations for higher resolution data.
Gadgil & Narayana Iyengar (1980), Kulkarni *et al.* (1992), Gadgil *et al.* (1993), Iyengar & Basak (1994), Krishnamurthy & Shukla (2000), Azad *et al.* (2010), Kulkarni (2017), Sahastrabuddhe *et al.* (2019)	Spatial variability of ISMR in terms of orthogonal function or mathematical representation.	India Meteorological Department (IMD) dataset (1°).	Lack of observed representation of spatial patterns. The spatio-temporal variability can be future scope of work.
Sahastrabuddhe *et al.* (2019)	Observed spatial patterns of ISMR.	High-resolution IMD dataset (0.25°).	The number of spatial rainfall composites will vary as the training period increases with passing time. Also, changes in spatial patterns due to intraseasonal variability of large-scale factors can be explored.
Krishnamurti & Bhalme (1976), Hartmann & Michelsen (1989)	10–20 days and the 40–50 days intraseasonal variability of ISMR.	IMD (1°) rainfall dataset; NCAR rainfall data.	Provided no information on the impacts of large-scale factors on intraseasonal variability.
Singh *et al.* (1992)	The intensity of MJO has no significant impact on ISMR. Found that there is no connection between ENSO on intraseasonal variability.	IMD (1°) dataset.	Understanding the triggering of ENSO events due to MJO is a potential study for the future.
Zhang & Delworth (2005), Goswami *et al.* (2006a, 2006b)	The in-phase variability of ISMR with the Atlantic Multidecadal Oscillation (AMO) with periodicity ~60 years.	IMD (1°) dataset, HadSLP1 sea level pressure data; a hybrid coupled model by replacing the dynamic ocean component of GFDL CGCM (CM2.0) with the motionless ocean.	Changes in sea level and the volume of ice sheets are not considered for the study of long-term climate change that can be further explored.
Goswami *et al.* (2016)	Showed 50–80 years of oscillatory variability inherent in ISMR.	ISMR values derived from proxies: Tree Ring Width Index chronology (RWI) from India (1481–2003); (b) RWI-Thailand (1558–2005) and I Oxygen isotopic composition.	The recent decreasing trend of ISMR needed further could not be explained.
Bhattacharyya & Narasimha (2005), Bhattacharyya & Narasimha (2007)	Proportionality of solar gradient to ISMR observed at the periodicity of 60 ± 10 years.	Annual rainfall over six homogeneous Indian rainfall zones, Solar activity index.	Unknown effects on the intensity of Walker circulation leading to changes in spatio-temporal patterns of ISMR can be future scope of research.

rainfall. This disparity leads to difficulty in quantifying future changes in ISMR and its variability. The study also professes an increase in the frequency of extreme rainfall, which is crucial not only for useful impact assessments and planning but for mitigation and adaptation too. The overall findings and drawbacks of changing characteristics of ISMR are discussed in Table 2.

3. FACTORS AFFECTING THE INDIAN MONSOON

There are several multi-scale factors having known relationships with the Indian monsoon; still, its spatio-temporal variability remains chaotic. The large heterogeneity in topography and the ever-changing Land Use Land Cover (LULC) have significantly played a role in the spatial variability of the Indian monsoon. Moreover, the global factors also show impacts on the characteristics of the Indian monsoon with the changes in the trend. However, it remains uncertain how the different RCP scenarios may affect rainfall in the ongoing century. The factors affecting the Indian monsoon are further discussed herewith and shown in Figure 3.

3.1. Intraseasonal scale

Atlantic Zonal Mode (AZM) is an important potential predictor of the Indian Monsoon (Kucharski *et al.* 2007, 2009; Sahastrabuddhe *et al.* 2019). The higher temperatures over the equatorial Atlantic peaking in boreal summer (i.e., June–August) cause the phenomenon. AZM has a short-living and weaker signal than ENSO (Lübbecke *et al.* 2010; Burls

Table 2 | Relevant literature on the changing characteristics of ISMR

Changing characteristics of ISMR

References	Findings	Dataset used	Future scope
Kumar *et al.* (2010)	Found an increasing trend of monsoon over northern India and decreasing over northeastern and central parts.	Sub-divisional monthly rainfall data of India prepared by the Indian Institute of Tropical Meteorology Pune for 135 years (1871–2005).	Clear identification of the spatial pattern of ISMR was not performed.
Dash *et al.* (2007)	Reported increased pre-monsoon and post-monsoon precipitation averaged over India, whereas summer monsoon precipitation as decreased.	Monthly maximum and minimum temperatures for the period 1901–2003 and rainfall for the period 1871–2002 from IMD, Reynold's Sea Surface Temperature (SST)values from National Climatic Data Centre (NCDC).	The human-induced changes to the monsoon rainfall can be further explored.
Roxy *et al.* (2015)	Showed the weakening trend over the central-east and northern regions of the Indian subcontinent and south of the Western Ghats region in the past century.	Precipitation datasets during the period 1901–2012 were obtained from IMD and Climate Research Unit (CRU), SST data for the same period from the HadISST1 dataset and the Extended Reconstructed Sea Surface Temperature (ERSST). For land–sea temperature gradient, surface temperatures from HadCRUT (1901–2012) and tropospheric temperature values from NCEP reanalysis (1948–2012) are used.	Individual contributions from components other than the Western Indian Ocean influencing the observed trend are further required.
Shashikanth *et al.* (2018)	The extreme projections showed a significant heterogeneous spatial increase in rainfall extremes while projecting three different time windows 2020, 2050 and 2080.	National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data and the gridded rainfall provided by Asian Precipitation – highly-resolved observational data integration toward evaluation (APHRODITE).	Using the same established statistical downscaling relationship for a future scenario as used for historical data. Another drawback is that the regional effects such as impacts of deforestation and urbanization have not been considered in this study.

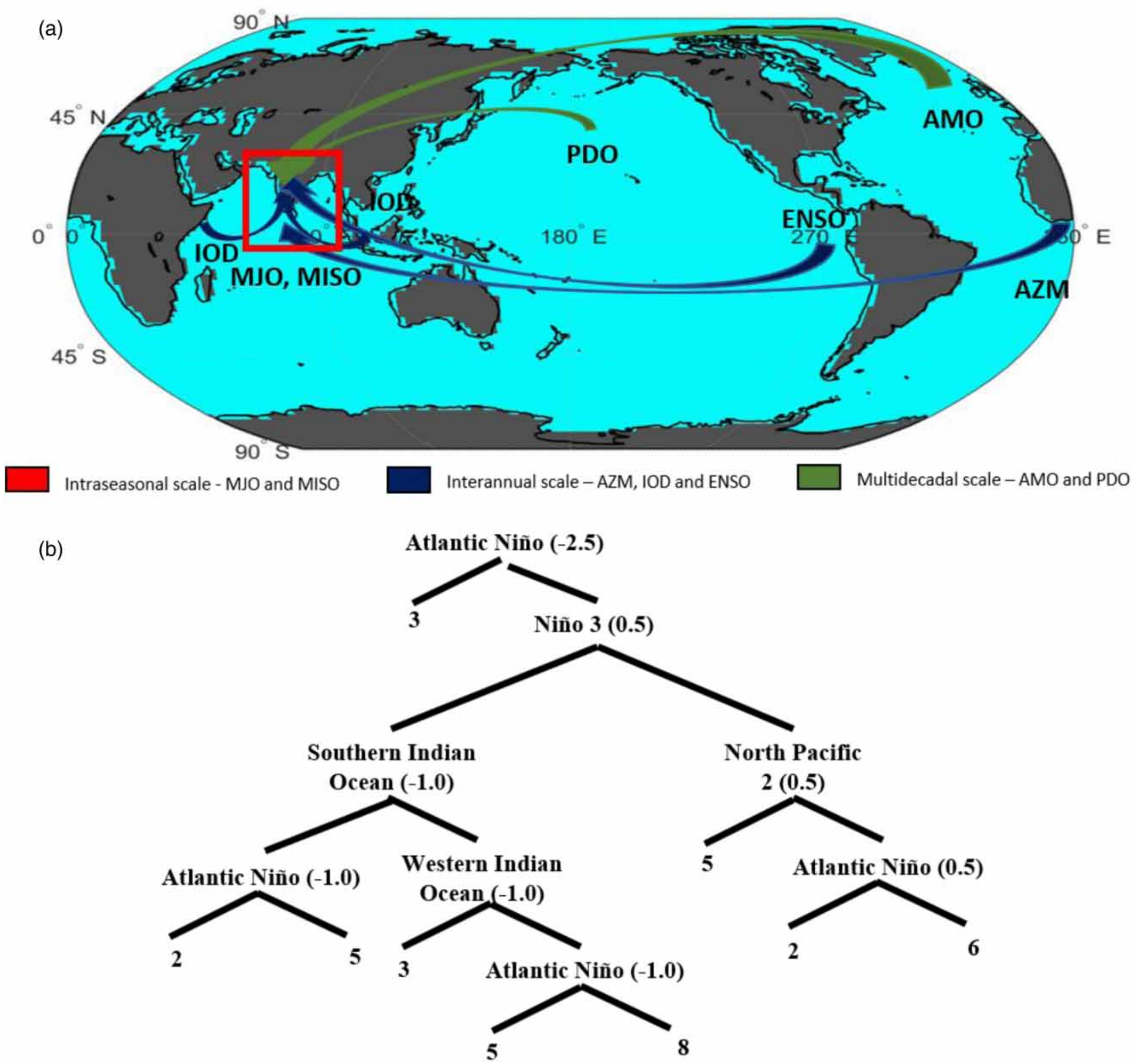

Figure 3 | (a) Factors affecting ISMR at different time scales. (b) Classification and Regression Tree from Sahastrabuddhe *et al.* (2019).

et al. 2012). The warm SST over the equatorial Atlantic decreases monsoon intensity over Central India (Kucharski *et al.* 2007; Pottapinjara *et al.* 2016; Sahastrabuddhe *et al.* 2019). The cold SST anomalies create cyclonic gyres over Central India, strengthening the Somali Jet and low-level convergence, thereby increasing monsoon rainfall (Matsuno-Gill). AZM peaks during the boreal summer, coinciding with monsoon rainfall over India.

The exchange of energy fluxes and teleconnections from SSTs also play an important role in the propagation of connection over India on intraseasonal timescales (Roxy *et al.* 2013; Gao *et al.* 2019; Konda & Vissa 2019, 2021; Karmakar & Misra 2020). Konda & Vissa (2021) found that the Boreal Summer Intraseasonal Oscillation (BSISO) are also one of the important features affecting South Asian summer monsoon at intraseasonal scale. They performed their study using CMIP5 models to show ISMR displaying strong intraseasonal variability propagating northward from the equatorial Indian Ocean to the foothills of Himalayas. However, the models showed significant spatial heterogeneity due to bias. In their further study (Konda & Vissa 2023), they used CMIP6 models to examine the simulations of excess/deficit ISMR and with air–sea interactions on intraseasonal to interannual timescales. However, the models failed to simulate large-scale SSTs and regional-scale convection over India. Recently, Jain *et al.* (2021) showed how the shifting of Somali Jet caused flood and drought over India. During droughts, the Somali Jet is weaker over the northern Arabian Sea and stronger over the southern Bay of Bengal, whereas reverse phenomena was observed during floods.

Another important tropical climate variability governing ISMR on an intraseasonal scale is the Madden-Julian Oscillation (MJO) (Madden & Julian 1972). It is modulated by a coupled ocean–atmosphere system having impacts upon global tropics. It is a large-scale convective anomaly developed over Indian Ocean with timescales of 30 and 60 days (Knutson & Weickmann 1987; Hendon & Salby 1994). The intraseasonal variability of the monsoon is due to spells of dry and wet conditions with a periodicity of 10–90 days (Goswami & Xavier 2005a, 2005b). Within the large timescale, the 10–20 days represent the westward propagating mode (Krishnamurti & Ardanuy 1980). There are eight phases of MJO affecting the Indian monsoon during active and break spells of the MJO life cycle, explaining the impact of MJO on the rainfall distribution over India (Pai *et al.* 2011). MJOs propagate eastward, originating over the Indian Ocean during boreal winter.

Another intraseasonal driver of ISMR associated with the active–break cycles is MISOs. During the boreal summer, the horizontal scale oscillations with a timescale of 30–60 days, larger than the Indian subcontinent with northeastward propagation with tropical convergence, help the convection and precipitation over the region (Sikka & Gadgil 1980; Goswami *et al.* 2011). MISO modulates synoptic activity by quasi-periodic oscillations of ISMR and influences interannual variability of the seasonal mean of ISMR (Goswami *et al.* 2006a, 2006b). These different factors over different timescales have a combined effect over the temporal and regional variability of ISMR (Table 3). They are further useful in developing various prediction schemes for spatio-temporal variability of ISMR.

Many studies (Sikka & Gadgil 1980; Goswami 2005) have suggested that between the two modes of intraseasonal oscillations, the active and break spells of monsoon rainfall are dominantly driven by the northward propagating 30–60-day mode. Also, some indicate that a significant amount of the northward propagating mode has no relation with the ward-moving mode (Wang & Rui 1990; Jones *et al.* 2004). However, Lawrence & Webster (2002) showed a large portion of northward propagation is related to the eastward-moving mode, along with some independent northward propagation. Dey *et al.* (2022) recently examined the combined phase propagation and amplitude of MISO and MJO for the period of 1998–2018. They showed that active/break spells are largely associated with MISO phases with more robust northward propagation than with MJO phases. They also studied phase composite, indicating the lead-lag relationship between MISO – MJO phases. On the spatial scale, MISO explains more variance compared to MJO with respect to reconstructed rainfall.

Ozone also participates in influencing ISMR through stratospheric intrusions at an intraseasonal scale. The stratospheric intrusions are caused due to Rossby wave breaking, resulting in the invasion of ozone-rich dry air mass between the lower extratropical stratosphere and upper tropical troposphere. When this phenomenon occurs over Tibetan Plateau, the ozone amounts increase in the upper troposphere over Tibetan Plateau along with North India (Fadnavis & Chattopadhyay 2017). The changes in an atmospheric radiative balance due to increased ozone radiative forcing (Fadnavis *et al.* 2019) can affect temperature distribution and circulation patterns (Roy *et al.* 2017). The formation of deep convective clouds is restricted by the cold and dry air associated with high levels of ozone intrusions. The prolonged intrusion inhibits monsoon convection leading to a dry spell over Tibetan Plateau and North India (Fadnavis & Chattopadhyay 2017).

3.2. Interannual scale

There is a famous empirical relationship between ENSO–ISMR, where the temperature rises over the Niño 3.4 region over the central Pacific is inversely proportional to the Indian monsoon (Sikka 1980; Pant & Parthasarathy 1981; Rasmusson & Carpenter 1983; Shukla & Paolino 1983; Parthasarathy & Pant 1985). The modulation of Walker circulation, causing the weakening of ISMR during El Niño, was further conceptualized by showing substantial changes in regional Hadley circulation modifying ISMR characteristics (Slingo & Annamalai 2000). The higher ascent over the equatorial Pacific enhances a low-level convergence zone and deprives the abundance of moisture circulation over Indian subcontinent. The higher surface temperatures over the central Pacific, called as El Niño-Modoki (Ashok *et al.* 2007), also cause deficit monsoon rainfall over India while following a different spatial pattern (Sahastrabuddhe *et al.* 2019). ENSO and Indian monsoon also have decadal and multidecadal teleconnection variability (Mann & Park 1993, 1994, 1996; Gershunov & Barnett 1998).

The higher SSTs over the western Indian Ocean and lower SST over Sumatra led to the ENSO independent event as a positive IOD (Saji *et al.* 1999). The strong positive IOD is known to counteract warm ENSO events bringing more moisture toward Indian subcontinent. The negative IOD has no significant impact on the Indian monsoon or not yet documented. The warmer western Indian Ocean creates a positive feedback mechanism, attracting more moisture toward India, and strengthening the regional Hadley circulation. Hrudya *et al.* (2020) explored changes in the ENSO-monsoon relationship during June,

Table 3 | Relevant literature on the factors affecting Indian monsoon

Factors affecting Indian monsoon

References	Findings	Dataset used	Future scope
Kucharski *et al.* (2007), Pottapinjara *et al.* (2016), Sahastrabuddhe *et al.* (2019)	The warm SST over the equatorial Atlantic decreases monsoon intensity over Central India.	ICTP AGCM and HadISST; HadISST; ERSST v3b for SSTs.	Insufficient input to the results regarding the trend and shift in climatology.
Goswami & Xavier (2005a, 2005b)	The intraseasonal variability of the monsoon is due to spells of dry and wet conditions with a periodicity of 10–90 days.	NCEP/NCAR reanalysis tropospheric temperature.	The relation between the amplitude of intraseasonal oscillations and the length of the rainy season is to be established.
Pai *et al.* (2011)	Eight phases of MJO affecting Indian monsoon during active and break spells of the MJO life cycle.	High-resolution IMD data and multivariate MJO indices RMM1 and RMM2.	No relation between MJO phases and the length of monsoon season developed.
Goswami *et al.* (2006a, 2006b)	Modulation of synoptic activity by quasi-periodic MISO of ISMR.		The dynamics of air–sea coupling of intraseasonal oscillations are unknown.
Sikka & Gadgil (1980), Goswami *et al.* (2011)	Horizontal scale oscillations with the timescale of 30–60 days, larger than Indian subcontinent, with northeastward propagation helping the convection over the Indian region.	Satellite imagery data of cloud band by NOAA.	Conclusions from cloud coverage, but conclusions to be made from the observed dataset.
Fadnavis & Chattopadhyay (2017)	Showed that the prolonged intrusion of ozone caused a significant reduction in ISMR, leading to a deficient monsoon.	ERA-Interim dataset.	More analysis can be performed for a longer time period to provide a better understanding of physics.
Sikka (1980), Pant & Parthasarathy (1981), Rasmusson & Carpenter (1983), Shukla & Paolino (1983), Parthasarathy & Pant (1985)	The famous inverse ENSO–ISMR relationship, where the temperature rise over the Niño 3.4 region is inversely proportional to the Indian monsoon.	IMD dataset available at the time.	Lack of knowledge regarding other global-scale factors intervening in the ENSO – ISMR relationship. That can be an active area of research.
Ashok *et al.* (2007)	The enhanced low-level convergence zone and deprivation of moisture circulation over Indian subcontinent due to higher ascent over the central equatorial Pacific, El Niño-Modoki.	HadISST data for SST, NCEP/NCAR data for SLP, geopotential height and wind	Impacts of El Niño-Modoki on spatial variability of Indian monsoon to be studied.
Saji *et al.* (1999)	Study of Indian Ocean Dipole (IOD) known to counteract warm ENSO event bringing more moisture toward Indian subcontinent.	GISST2.3b data set (1958–1998), the NCEP surface winds reanalysis (1958–1998), and the Xie–Arkin rainfall analyses (1979–1998).	Impacts on spatial variability of Indian monsoon to be studied.
Zhang *et al.* (1997)	The opposite effects of leading modes of PDO toward ISMR.	Comprehensive Ocean–Atmosphere Data Set (COADS), U.K. Meteorological Office Historical Sea Surface Temperature Dataset, Seasonal mean 500-mb height fields from National Meteorological Center.	

Lihua *et al.* (2007)	Impact of 11 years of solar period with the decadal-scale variations of ISMR.	Rainfall data from the Indian Institute of Tropical Meteorology, The annual sunspot relative number time series is obtained from the Sunspot Index Data Center (SIDC) of the Royal Observatory of Belgium.	No physical mechanism between the solar period and ISMR is explained.
Paul *et al.* (2016)	The impacts of recent Land Use Land Cover (LULC) changes in India on monsoon rainfall using the weather research and forecasting (WRF) simulations.	European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis data or ERA-I data with 6-hourly outputs over 30 pressure levels, NCEP Climate Forecast System Reanalysis, High-resolution IMD rainfall data.	Land surface representation at different scales on changes in Indian monsoon needs to be improved to be considered the role of LULC and land surface ET.
Devanand *et al.* (2019)	Sensitivity of Indian monsoon toward the choice of irrigation practices.	CFSv2 free run outputs, High-resolution IMD rainfall data.	More realistic representation of irrigation and the use of higher resolution simulations for improved topographical aspects are needed.
Shastri *et al.* (2015)	The influence of urbanization over the characteristics of monsoon rainfall in India.	Census of India for change in population, High-resolution IMD rainfall data; APHRODITE rainfall data.	Need to identify physical mechanisms regarding the impacts of increased urbanization on ISMR.
Konda &Vissa (2021)	Impacts of boreal summer intraseasonal oscillations (BSISO) on South Asian summer monsoon at intraseasonal scale.	CMIP5 GCM outputs for daily precipitation, Latent heat fluxes, Net heat fluxes, Sea Surface Temperatures, Downward surface solar radiation, U-wind at 850 hPa.	The models showed significant spatial heterogeneity due to bias. The bias can be removed using some statistical analysis.
Konda &Vissa (2023)	Examination of simulations of the excess/ deficit ISMR and the associated air–sea interactions from intraseasonal to interannual timescales.	CMIP6 outputs for daily precipitation, winds, specific humidity, SST, energy, and radiative fluxes.	The future scope can include removing the systematic biases from the model outputs.
Seetha *et al.* (2020)	ENSO–ISMR relationship that are attributed to the changes in the circulation features and associated oceanic warming.	Gridded rainfall data from Climate Research Unit, SST data from Hadley center.	More analysis is needed regarding the changing pattern of rainfall due to Indo–Pacific SST changes.
Falga & Wang (2022)	Long-term shifts in LULC play a crucial role in the prediction of the long-term trends of extreme precipitation events.	High-resolution IMD data, 20C Reanalysis Dataset Wind components, temperature and humidities.	Several other factors can also be critically analyzed to predict the trends of extremes.
Jain *et al.* (2021)	Examined the impacts of shifting of Somali Jet causing flood and drought over India.	High-resolution daily gridded rainfall data from IMD and wind data from ERA 20 C.	Reasons for the smaller changes in the precipitation and Somali Jet for future projections can be further explored.

July–August and September months of ISMR for the period 1951–2015. They found that during El Niño, there was a significant increase of rainfall over most of the Indian regions during June month. But, they found a significant decrease in rainfall during peak (July–August) and withdrawal (September) months. However, they also found that rainfall during La Niña events is significantly decreased for the study period over the monsoon core zone during all the months.

Apart from oceanic activities, solar activity also influences ISMR on an interannual scale. Lihua *et al.* (2007) showed 2–3 years of fluctuations using the Scargle periodogram with wavelet analysis. The fluctuations were high before 1900 and between 1930 and 1960. Although, they also suggested the peaks did not remain the same and differed most of the time. The changes in the appearance or energy output of the Sun are collectively termed as solar activity (Bhalme *et al.* 1981). One example of solar activity is the sunspots, temporary dark spots on Sun's surface. These are regions with a lower temperature than the surroundings. The more the number of spots, the more solar activity will be. The time period of this increasing and decreasing number of sunspots is roughly 11 years. The interaction between the solar cycle and ISMR is quiet complex involving several mechanisms (Claud *et al.* 2008). Higher solar activity leads to lower stratosphere warming, thereby reducing (enhancing) the convective activity in the equatorial (off-equatorial) region. Mean sea level pressure is also affected by the solar cycle. Over the Southern Indian Ocean, the SST is closely associated with the solar cycle. Greater solar activity is linked to more rainfall, which is more predominant in the central and west coast. Whereas the northeast and northwest regions are least responsive to this phenomenon (Bhattacharyya & Narasimha 2005).

3.3. Decadal and multidecadal scale

The Indian monsoon is known to have a periodicity of ~60 years, and presumptions are made that it is derived from AMO. AMO also has a coherent mode obtained from the North Atlantic Ocean with a period of ~55–80 years (Knight *et al.* 2006; Wei & Lohmann 2012). SST anomalies over the North Atlantic Basin (0°–80° N) are modes of AMO. Trenberth & Shea (2006) mentioned extracting the mode by detrending the subtracted global-mean SST anomaly time series obtained from the spatially averaged time series. The phases of AMO also show a positive correlation with ISMR (Goswami *et al.* 2006a, 2006b; Krishnamurthy & Krishnamurthy 2014, 2016). The ocean circulation generally modulates the lower frequency modes of AMO, and the subpolar gyre is identified as a key region for the variability (Zhang *et al.* 2016).

The PDO is a long-lived El Niño-like pattern derived from Pacific climate variability (Zhang *et al.* 1997). The leading mode of PDO, having periodicities of ~15–25 years and ~55–70 years, has the opposite effect toward ISMR. On contrary to AMO, PDO has inverse teleconnections with ISMR. Furthermore, the phases of PDO directly impact ENSO, which in turn affects the ISMR with the inverse relationship. Seetha *et al.* (2020) studied the changes in ENSO–ISMR relationship that are attributed to the changes in the circulation features and associated oceanic warming with the increased frequency of El Niño events.

We have demonstrated several studies where various large-scale factors affect ISMR at different temporal scales (Figure 3(a)). Sahastrabuddhe *et al.* (2019) demonstrated the potential prediction pathways for monsoon rainfall spatial patterns (Figure 2(c)). They implemented a seasonal prediction model based on Classification and Regression Tree (CART). SSTs over 12 important oceanic regions were used as predictors, and the cluster indices (Figure 3(c)) were used as predictands for the duration of 1901–2010 (We have pruned the CART model shown in Figure 3 for simple understanding). They showed that different sets of SST conditions could cause the same spatial monsoon rainfall pattern. More research on the combined effects of regional and large-scale predictors on monsoon variability at different time scales can be the potential future scope of work.

Due to 11 years solar period, the decadal-scale variations of ISMR are also observed with the solar activity (Lihua *et al.* 2007). The influence of activity was found to be weaker before 1930 and after 1985. It was found strongest around 1955 using wavelet analysis. However, along with these natural variability, humans have also apparently participated in the variability of climate variables. In the past few decades, the impacts of anthropogenic emissions on climate have gained momentum. The boom in the growth of technology was followed by industrial development, which consequently led to anthropogenic emissions.

Existing Indian inventories for different pollutants or climate-forcing agents are decided on the Intended Nationally Determined Contributions (INDCs) for policy-making purposes. GHG emission inventories are part of INDCs under the national communications of the United Nations Framework Convention on Climate Change (UNFCCC) (Garg *et al.* 2001, 2003). It has been reported that only about 12% of India's net GHG emissions comply with Tier III specified by the Intergovernmental Panel on Climate Change (IPCC 1997). These determined contributions of GHG emissions lead to climate warming, affecting global rainfall process. It has been observed these impacts have different consequences toward rainfall in different regions around the world. We discuss here its impacts on the Indian monsoon.

Warmer climate results in a higher moisture-holding capacity of the atmosphere, which in turn increases the rainfall. This follows the classical Clausius–Clapeyron relationship (Held & Soden 2006). This increase is observed worldwide, mostly in terms of extreme rainfall. For the Indian monsoon, there has been a decrease in mean rainfall over the last 50 years, and this is associated with the lowering of land–ocean thermal contrast. The western Indian Ocean showed a very high warming trend, whereas the Indian landmass showed a cooling pattern due to aerosols. This resulted in a decrease in historical ISMR (Bollasina *et al.* 2011; Roxy *et al.* 2014). However, the majority of the CMIP5 models have shown an increase in the historical seasonal rainfall, and this attributes to the failure of models in simulating monsoon-specific dynamics (Saha *et al.* 2014a, 2014b). The extremes over India have increased quite significantly, specifically over the core monsoon zone (Goswami *et al.* 2006a, 2006b; Rajeevan *et al.* 2008; Roxy *et al.* 2017), and this is well simulated by the models. As simulated by the models, the future projections show an increase in monsoon rainfall over India. There are several possibilities that we can speculate about. The increasing trend may be due to the model's overestimation of the rainfall trend (as seen in historical simulations) or the dominance of GHG effects over the aerosol effects in the future over the Indian landmass (Varghese *et al.* 2020). There is also a possibility that the historical experiments from models are not able to force the natural variability, which may lead to a possible indefinite trend of ISMR in the future.

3.4. Local factors affecting monsoon

Deforestation of forest cover significantly affects monsoon rainfall with changes in evapotranspiration (ET) with increasing drought intensity. The modeling of deforestation across the global monsoon region shows an 18% decline in precipitation in India (Devaraju *et al.* 2015). Paul *et al.* (2016) address the impacts of recent LULC changes in India on monsoon rainfall. They perform a sensitivity analysis using weather research and forecasting (WRF) simulations considering large-scale deforestation in recent decades. On comparing the 1980 and 2000s, the dominant LULC type earlier was woody savanna, mostly a forest land, found over central, Peninsular and Northeast India. However, due to the development and agricultural farm intensification, the regions were converted to cropland in 2005, which immensely affected monsoon precipitation. The differences between both simulations showed a strong decline in monsoon rainfall in Northeast India, the Ganga Basin, and some regions of Central India due to large-scale conversions. We also argue that land surface representation in climate models used for the simulation of monsoons at different scales needs to be improved to consider the significant role of LULC and land surface ET on the changing behavior of the Indian monsoon.

A sharp decrease was seen in daily moderate rainfall events from 1951 to 2005 (Halder *et al.* 2016). Moreover, the mean and extreme near-surface daily temperature during the monsoon season has also increased by 1–1.5 °C. The study used the simulations from the regional climate model (RCM), RegCM4, to demonstrate the changes in rainfall due to land use/land cover change (LULCC). The decrease in forest and increase in crop cover were the main reasons behind the scenarios. Results from these experiments corroborate our example of LULCC in the decrease in moderate rainfall events and increase in daily mean due to changes in ET.

The Indian monsoon is also found sensitive to the irrigation practices affecting the intraseasonal characteristics of the monsoon. India encompasses several river basins consisting of large areas of agricultural cultivation supporting a high-density of population. Although there is a heavy dependence of agriculture on rainfall, groundwater depletion due to rapid population suggests an increase in vulnerability growth and land use change (Singh *et al.* 2014). Using regional dynamical modeling, Devanand *et al.* (2019) demonstrate the sensitivity of the Indian monsoon to the choice of irrigation practices. The regional model revealed the irrigation practices dominating intraseasonal characteristics of Indian monsoon rainfall. They show how unmanaged irrigation facilities for paddy cultivation over northern India exhibit an increase in the late-season terrestrial monsoon. The study suggests that it is an imperative need for an accurate representation of irrigation practices to improve the healthy usage of water usage in India. The land use changes due to the vast population do not just lead to unmanaged irrigation in the agrarian economy but also the significant growth of urbanization over the region. This tremendously impacts the regional-scale monsoon rainfall and needs additional research to develop an understanding.

India has experienced an unparalleled growth rate of urbanization over the last three decades. Shastri *et al.* (2015) tried to understand the influence of urbanization over the characteristics of precipitation in India. They identify 42 hot spots using a computationally inexpensive black-box model to compare the extreme rainfall characteristics with the surrounding rural areas. The study revealed significant impacts of urbanization over the central and western regions of India. Quantile regression over station level data for Mumbai, India, with a nearby nonurban area, Alibaug disclosed the sensitivity of extreme rainfall events toward the increased urbanization. Universally, urban areas are reported to be warmer than the surrounding rural areas and the arrangement is known as Urban Heat Islands (UHI) (Oke 1982). The phenomenon leads to reduced ET, which needs climate adaptation, heat stress mitigation, and an understanding of urban micro-climates. A study by Singh *et al.* (2016) performed a non-stationary frequency analysis using the Generalized Additive Model for Location, Scale and Shape framework. They determined the global and local factors influencing non-stationary characteristics of ISMR extremes. They observed significant non-stationarity in extremes while transitioning from rural to urban than in completely urbanized or rural areas. Sudden changes in urbanization, irrigation practices, and land usage have brought discernible changes in regional rainfall over India. These local factors have shown an influence on the increase of mean daily rainfall (or possible extreme events). Falga & Wang (2022) found that long-term shifts in LULC, especially urbanization, play a crucial role in the prediction of the long-term trends of extreme precipitation events, particularly of the intensity of extremes using advanced models.

4. SIMULATIONS OF ISMR AND EVALUATIONS

Reliable simulations of ISMR are important for proper agricultural and water resource planning in India. In this section, we review the use of various Global and RCMs and compare their ability to assess precipitation changes over the Indian region (Table 4 and Table 5).

4.1. Global climate models

(CMIP climate models, developed around the globe by different modeling groups, are widely used to simulate and project changes in Indian monsoon rainfall. Evaluation of a large number of CMIP5 models showed that they were able to capture the broad climatological features of the Indian monsoon, including its mean and intraseasonal variability (Sabeerali *et al.* 2013). Their performance was found to improve when compared with older CMIP3 models (Sperber *et al.* 2013). However, they showed the limited performance in capturing the orographic effects. They were also unable to capture the trend in Indian summer monsoon rain. The inability of these models to capture rainfall trends was attributed to the misrepresentation of geophysical processes that modulate ISMR-like trends in SST of the Southern Indian Ocean and Mean sea level pressure over the Western Pacific Ocean (Saha *et al.* 2014a, 2014b). Increasing trends in the model were expected to be caused by the overestimation of convective rainfall with increasing temperature. These models were also unable to capture the strength of ENSO and the current monsoon climate, which eventually led to low confidence in projections for climate adaptation studies (Jourdain *et al.* 2013; Menon *et al.* 2013).

The latest CMIP6 models have shown improved simulation over the CMIP5 models, with a significant reduction in model bias (Gusain *et al.* 2020; Dutta *et al.* 2022). The better performance of these models was attributed to changes in convective parameterization schemes and better methods of estimating cloud fractions (Voldoire *et al.* 2019). These changes have led to an improved representation of total cloud fractions and their teleconnections with SSTs (Dutta *et al.* 2022). CMIP6 models have projected increased rainfall over India, particularly in the Himalayas and Northeastern parts of India (Katzenberger *et al.* 2020). They show increased robustness and a strong increase in ISMR when compared with CMIP5 models with reduced uncertainties. However, despite improvement over CMIP-5 models in seasonal climatology, CMIP6 models show no added value for the intraseasonal scale. The spatial pattern of observed ISMR still remains poorly described by these models as they fail to capture the orographic effects of rainfalls over Western Ghats (Konda & Vissa 2023). A recent study by Chowdary *et al.* (2023) showed that only 14% of CMIP6 models were able to simulate the summer rainfall anomalies during El Niño decay phases. The variations in active/break spells, too, remain inconsistent with observations in both CMIP5 and CMIP6 models.

While the CMIP5 and improved CMIP6 GCMs can simulate large-scale circulation and climate variables globally but being operated at high spatial grids, they fail to model local-scale processes. They generally fail to simulate the regional distribution of monsoon rainfall over India. This is because of their incapability to represent fine-scale processes like orography, convective precipitation, and land–atmosphere feedback. To overcome these limitations, downscaling (Figure 4) is done, which refers to determining the fine-resolution hydrologic data (predictand) using simulated large-scale climate variables (predictors).

Table 4 | Relevant literature on global and regional simulations of ISMR

ISMR: historical simulations and evaluations

References	Findings	Dataset used	Future scope
Saha *et al.* (2014a, 2014b)	Attributed the failure of CMIP5 models in capturing negative trends in ISMR to misrepresentation of trends in sea surface temperature of the Southern Indian Ocean and Mean sea level pressure over the Western Pacific Ocean.	Monthly simulations (1950–2005) of air temperature, wind speed, SST and Mean sea level pressure (MSLP) for 42 CMIP5 models.	The role of Anthropogenic forcings (Aerosols) in reducing ISMR for historical periods can also be explored.
Tripathi *et al.* (2006)	SVM based statistical downscaling approach generated using monthly rainfall which was a good fit with observed data and much better than older ANN-based downscaling techniques.	Observed Precipitation: IMD GCM: CGCM2 Reanalysis: NCEP/NCAR.	Needs to be extended to fine temporal resolution. Accounting for non-stationarity in a climate change scenario remains challenging.
Salvi *et al.* (2013)	Developed Kernel-based regression model to simulate ISMR at 0.5° resolution with high accuracy in capturing mean and spatial variability.	Observed: IMD GCM: CMIP3 GCM (CGCM3.1) output Reanalysis: NCEP/NCAR.	The model underperforms to capture temporal variability in rainfall. Methodology needs to be modified to capture rainfall extremes.
Shashikanth *et al.* (2018)	Modified transfer function-based statistically downscaled models by introducing a 2-stage regression and successfully captured historical rainfall extremes of ISMR.	Observed: APHRODITE Reanalysis: NCEP/NCAR GCM outputs: CMIP5.	Unreliable future projections based on stationarity assumption. The model does not include the effect of urbanization, changing land use and other local factors.
Pichuka & Maity (2018)	The time-varying downscale model outperforms statistically downscaled models and CORDEX RCMs.	Observed: IMD, GCMs: HadCM3, HadGEM2-ES and CanESM2.	Requires locations specific calibration and a large amount of historical data.
Mishra *et al.* (2014)	Ensemble mean of GCMs perform better in capturing extreme precipitation over India than CORDEX RCMs.	Observed Precipitation: APHRODITE RCMS: 4 CORDEX models GCMs: 32 CMIP5 models.	
Singh *et al.* (2017)	Evaluate 9 CORDEX RCMs and found no significant value addition to GCMs.	Nine regional CORDEX models, 9 CMIP5 GCMs.	
Devanand *et al.* (2018)	Coupling the regional land–atmosphere model with CFSv2 GCM can lead to better model performance with a significant reduction in model bias.	Observed data: IMD Reanalysis: ERA-interim GCM: CFSv2 RCM: WRFv3.8.1 coupled with CLM (WRF-CLM) and Noah (WRF-Noah)	Absence of representation of irrigation, which is needed to be explored.
Agrawal *et al.* (2021)	Regional climate model (RegCM V4.6) showed improvements in capturing the seasonal variabilities in ISMR as well as the active and break spells.	RegCM V4.6 model evaluated against ERA-5.	Model failed to determine the length and frequency of active/break spells.
Debnath *et al.* (2021)	Coupling the regional climate model with chemistry showed improvement in rainfall biases over conventional RCMs.	Coupled regional atmospheric chemistry transport model WRF-Chem. Evaluation against observations from IMD and TRMM.	Needs to be extended at longer timescales and evaluate its performance against interannual and inter-seasonal variabilities.

Table 5 | Relevant literature on future projections of ISMR

ISMR: future projections and impacts on hydrology

References	Findings	Dataset used	Future scope
Turner & Slingo (2009)	Increase in future extreme precipitation over India as an effect of increased CO_2 radiative forcing.	CMIP3 GCMs.	Some models show an increase in rainfall extremes exceeding CC rate (7%/K). The reasoning behind such an effect needs to be further explored.
Jayasankar *et al.* (2015b)	CMIP5 models project a reduction in light rainfall and an increase in high to extreme rainfall.	CMIP5 models RCP2.6 runs of 26 models RCP8.5 runs of 34 models.	Models project contrasting responses to changes in interannual variabilities.
Li *et al.* (2015)	Increase in future precipitation extremes as a dominant role of GHG forcing.	CMIP5 model simulations. 35 models, RCP8.5 emission scenario.	
Varikoden & Revadekar (2018)	Soil moisture response to precipitation.	ESA soil moisture, IMD precipitation.	More deeper soil depth can be considered.
Asoka *et al.* (2017, 2018)	Effect of monsoon precipitation on groundwater recharge.	GRACE TWS data, GLDAS surface storage data, ESACCI soil moisture, MODIS ET, India-WRIS groundwater well data, FAO's Global Map of Irrigation area, India Stat state level irrigation area.	More accurate estimates can be made with accurate observed data.
Ali *et al.* (2019)	Increased risk of extreme precipitation and flood.	IMD precipitation and temperature, NCEP/NCAR reanalysis wind speed, India-WRIS streamflow data, GFDL-CM3, GFDL-ESM2M, MIROC-ESM, MIROC-ESM-CHEM, and NorESM1-M daily precipitation and temperature.	
Joseph *et al.* (2018)	Uncertainty assessment of hydroclimatic projections.	SRTM DEM, UMD LULC, FAO soil data, IMD precipitation and temperature, streamflow from CWC, ESA soil moisture, MODIS ET, EC Earth, IPSL and MPI with RCP4.5 and RCP8.5.	Emission scenarios, and model structure uncertainty has to be considered.
Saha *et al.* (2022)	Projected daily extreme rainfall events to increase over North-East India, Central India and | Western Ghats.	12 CMIP6 GCMs under three scenarios: SSP1-2.6, SSP2-4.5 and SSP5-8.5.	Results were bias corrected. However the large model biases over Northwest and South east India were found and may affect the reliability in projections.
Ghausi *et al.* (2022)	Positive sensitivities of extreme precipitation to change in surface temperatures.	IMD, APHRODITE,TRMM and GSOD.	Further work is needed to explain the spatial variability in the sensitivities.

4.2. Downscaled models

The idea behind downscaled models is to capture the local variability in ISMR, which can then be used in regional planning and assessment studies for climate change. It can be done by developing statistical relationships between the large-scale historical variables and local-scale observations (statistical downscaling). Or by using more computationally extensive fine-scale land surface models, which can use the GCM outputs as boundary conditions (RCMs).

Several statistical downscaling models used to determine the variability in ISMR at fine scales are based on the Artificial Neural Network approach, Support Vector Machine approach (Tripathi *et al.* 2006), Sparse Bayesian learning, and relevance vector machine (RVM) (Ghosh & Mujumdar 2008), Conditional random field-based downscaling (Raje & Mujumdar 2009), Non-Parametric Kernel regression (Salvi *et al.* 2013) and Time-varying downscaling model (TVDM)

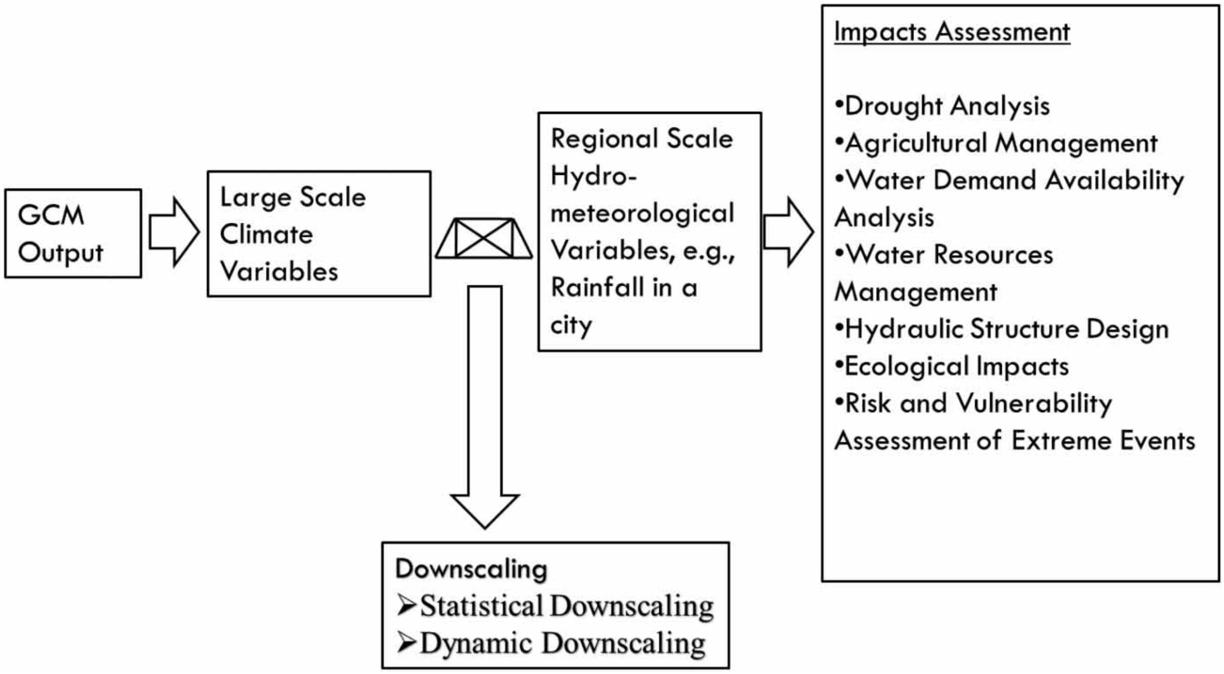

Figure 4 | Downscaling to bridge the gap between climate modeling and impact assessment.

(Pichuka & Maity 2018). While these models certainly add values to ISMR representation at fine scales and capture the spatial distribution, including the orographic effects better than GCMs, they had primarily two major limitations. The first is the failure to capture extreme precipitation, which reflects the inability of this approach to capture the essential physics of heavy rainfall events. Another limitation is that the relationship between predictors and predictands established during the historical period remains the same for future projections; hence, it cannot handle non-stationarity. Recent studies have tried to improve the latter by introducing a time-varying component that can handle non-stationarity (Merkenschlager *et al.* 2017; Pichuka & Maity 2018).

Dynamic downscaling, on the other hand, uses physics-based equations along with GCM outputs as boundary conditions and results in developing fine-resolution RCMs. With the advantage of being run at a higher resolution, they show improved simulations in terms of capturing small-scale weather systems, land–atmosphere feedback and improving the spatial variability associated with topographical changes. They also have shown improvements in capturing the seasonal variabilities and the active/break spells. However, the length and frequency of spells still remain challenging to model (Agrawal *et al.* 2021). RCM simulation strongly relies on the boundary conditions that are constrained using a GCM. Evaluation of these models for ISMR has revealed that the value addition using an RCM is very insignificant when compared with the parent GCM model (Racherla *et al.* 2012; Singh *et al.* 2017). While there have been improvements in simulating the mean distribution of regional rainfall, the RCMs have failed to capture the improved estimation of precipitation extremes (Kawazoe & Gutowski 2013).

Mishra *et al.* (2014) compared CORDEX RCMs and their respective CMIP5 GCMs and found that the ensemble mean of CMIP5 models provides better estimates of precipitation extremes than CORDEX RCMs. The land surface component in the regional models may improve the representation of land–atmosphere feedback. Yet, the lack of atmosphere–ocean coupling is one of the major reasons for its failure to reliably simulate Indian monsoon rainfall.

4.3. CFSv2 model

India Meteorological Department is currently using the NCEP-developed coupled ocean–atmosphere–land model, Climate Forecast System version 2 (CFSV2) for operational monsoon forecast. CFSV2 performs well in terms of improved intraseasonal monsoon variations and capturing the spatial changes of SSTs. Pillai *et al.* (2018) compared the performance of CFSV2 with US National Multi-Model Ensemble (NMME) seasonal prediction models. They found that although the SST forcings were not predicted very well by CFSV2, its ability to simulate better teleconnection patterns of ENSO and IOD makes it perform better for ISMR. However, a dry bias is observed over the Central India region, which limits the ability of this model to be reliably used for hydrological modeling and design (Saha *et al.* 2014a, 2014b). Reasons explored by studies to explain this dry bias include the inability of the model to capture the northward movement of the ITCZ (Pokhrel *et al.* 2013) and poor representation of land surface processes (Devanand *et al.* 2018). CFSV2 also fails in capturing AZM because of the inability of the model to forecast wind anomalies over the West Atlantic Basin (Sabeerali *et al.* 2019). Despite an improvement in monsoon predictability by the CFSV2 model, the reliability of predictions remains potentially low, and researchers are continuously improving its performance over the Indian region.

5. FUTURE PROJECTIONS

5.1. Changes in precipitation

There is a growing consensus in the science community that precipitation extremes in the future will intensify with warming. The primary argument arises from the Clausius–Clapeyron equation, which suggests a 6–7% increase in atmospheric moisture-holding capacity per degree rise in temperature. Assuming relative humidity to be constant, water vapor in the atmosphere will increase at a similar rate. The assumption of constant relative humidity in the future is likely to hold true based on model results and physical arguments (Held & Soden 2006). Extreme precipitation is influenced by the total moisture in the atmospheric column and hence is expected to increase at CC rates (Gorman & Schneider 2009; Ghausi & Ghosh 2020). Mean precipitation, on the other hand, is constrained by the earth's energy balance and is expected to increase at a much lower rate of around 2%/°C (Vecchi & Soden 2007). These arguments match well with observations and model projections over the Indian monsoon region. The increase in extreme precipitation has been found to be consistent with atmospheric moisture increase at the CC rate over the Indian region (Ali & Mishra 2017; Ghausi *et al.* 2022). However, there remains spatial variability in these sensitivities owing to the contribution of the dynamic response (Sengupta *et al.* 2022). Most studies have projected an increase in extreme rainfall over the Indian region and a decrease in the mean rainfall (Goswami *et al.* 2006a, 2006b). These results were also consistent in both RCMs (Preethi *et al.* 2011; Rao *et al.* 2014) as well as better-performing GCMs (Jayasankar *et al.* 2015a; Saha & Sateesh 2022). Observational evidence has also shown a decreasing trend in summer mean rainfall over northern India post-1950, while a threefold rise in extreme precipitation over the Central Indian region (Roxy *et al.* 2017). The decrease in mean ISMR has been mainly attributed to increased warming over the Indian Ocean, which reduces the land–sea thermal gradient and subsequently results in a weakened monsoon circulation. While the warming in the ocean is expected to weaken the monsoon circulation by reducing land–sea thermal gradients (Ueda *et al.* 2006), it also increases the atmospheric temperature above the South Asia landmass leading to more evaporation and increasing the local atmospheric moisture. This leads to enhanced moisture convergence, which further results in increased extreme rainfall. This contrasting response further increases the complexities associated with future projections of ISMR. Despite the weakening of monsoon circulation, an increase in local atmospheric moisture with the climate change act is expected to act as a dominating factor for projecting an increase in monsoon rainfall across all state of art climate models (Endo & Kitoh 2014, 2016).

Still, there exists a large disparity among models in projecting future changes in ISMR (Jayasankar *et al.* 2015a). Trends in future rainfall are associated with inconsistent variation of rainfall and large spatial variability (Shashikanth *et al.* 2018). Inadequacy in the representation of monsoon processes further adds to the problem. A better understanding of atmospheric processes and land–sea interactions are essential for predicting a certain and reliable future.

5.2. Changes in hydrology

The regional rainfall patterns during the monsoon are significantly affected by feedback from land surface processes like soil moisture and ET (Pathak *et al.* 2014). Besides, it is also important to estimate the future water availability for water resources planning and management. Therefore, understanding the response of the land surface hydrology to climate-induced changes in the precipitation pattern is critical. Hydrological models are important tools for examining the changes in streamflow, soil moisture and groundwater recharge with changes in precipitation. Hydrological modeling for climate change impact assessment broadly includes three steps: simulating the changes in climate by employing GCMs, downscaling the coarse resolution outputs to basin scale and running a hydrological model using the downscaled variables as meteorological forcing. Numerous basin-wise studies have been performed to analyze the combined effect of changes in precipitation and temperature on the water balance components. Gosain *et al.* (2006) conducted the climate change impact assessment for 12 river basins in India using the SWAT@@ model. Severe drought and flood were predicted in the Mahanadi and Krishna basins, respectively. In the above basins, the ET, water yield, and river flow were observed to be positively correlated to the changes in precipitation. However, in the basins of Narmada and Kaveri, the runoff revealed an opposite trend compared to precipitation. An overall reduction in runoff was observed in this study. Mishra & Lilhare (2016) analyzed the sensitivity of hydrological variables to climate change for 18 river basins in India. They concluded that the sensitivity of river runoff to the changes in precipitation was more predominant than ET over Ganga and Godavari basins. Shah *et al.* (2016) performed a similar study using the VIC model over the Indian subcontinent for a period of 1901–2012 and found that in 11 out of 18 basins, monsoon precipitation showed a decline, subsequently reducing the water availability and ET. Another study carried out by Nilawar & Waikar (2019) over the Purna River Basin employing the SWAT model showed an increase in runoff and sediment concentration for RCP4.5 and 8.5 scenarios. This increase was attributed to the increased projected precipitation. Soil moisture exhibits a strong positive correlation with precipitation during the monsoon season (Varikoden & Revadekar 2018). Therefore, the changes in precipitation are replicated in soil moisture as well. Studies performed to evaluate the changes in groundwater levels with climate change show incoherent results. The analysis by Asoka *et al.* (2017) revealed a decline in groundwater levels in northern India due to decreased precipitation. The two reasons identified were reduced groundwater recharge and escalated groundwater extraction. Asoka *et al.* (2018) reaffirmed the dependence of groundwater recharge on monsoon precipitation. MacDonald *et al.* (2016) utilized in-situ groundwater observation data and showed contradictory results. Their study demonstrated an increase in groundwater level over northern India with a few exceptions.

Another important aspect is how the changes in precipitation lead to the occurrence of extreme events. Indian region is highly vulnerable to droughts and floods because of the large variability in monsoon. The changes in antecedent hydrologic conditions, like soil moisture and changing snow cover, play a significant role in determining the changing patterns for flood extremes. In recent decades studies have shown a decline in monsoon rainfall whereas a heavy increase in rainfall extremes (Guhathakurta *et al.* 2011; Singh *et al.* 2014). Roxy *et al.* (2017) revealed that extreme events have increased threefold in the past 60 years. Although extreme events are increasing in magnitude and frequency, they are spatially non-uniform with large spatial variability (Ghosh *et al.* 2012). Ranger *et al.* (2011) analyzed the climate change implications of flood risk over Mumbai and concluded an increased likelihood of floods in the future. Ali *et al.* (2019) performed a study over the Indian river basins using the Noah MP model for the RCP2.6 and RCP8.5 emission scenarios and found a rise in multi-day extreme rainfall and flood events. Monsoon drought frequency has increased over the past years (Dai 2013; Kumar *et al.* 2013; Salvi & Ghosh 2016). Mishra & Liu (2014) concluded that prolonged dry spells and the number of dry days have increased, thereby increasing drought risk in India. The variation in the onset and withdrawal of monsoon coupled with reduced streamflow due to a decline in precipitation makes the dry land more vulnerable (Prabhakar & Shaw 2008).

Hydroclimatic modeling is often tricky. As regards Himalayan rivers, which are also fed by glacier melt, untangling the impact of each climate variable can be challenging (Moors *et al.* 2011). In addition to climate change, several other factors like LULC changes, and anthropogenic activities like irrigation and groundwater extraction influence hydrology and hence have to be separately considered. Chawla & Mujumdar (2015) isolated the impacts of LULC and climate change on the streamflow of the Upper Ganga Basin and concluded that climate change effects dominated. Chanapathi & Thatikonda (2020) reported that the changes in LULC offset the effect of climate change over the Krishna River Basin. We must also note that all the above analysis are associated with uncertainties at each step of regional hydrological modeling (Raje & Krishnan 2012; Joseph *et al.* 2018).

6. DISCUSSION AND WAY FORWARD

Climate studies have been a well-sought-after area of research for scientists, especially after the evidence of climate change due to global warming. The climate of the earth pertains large-scale processes such as SSTs, atmospheric circulations, etc. which influence moisture transport, vegetation and precipitation processes. Precipitation is one of the most important geophysical processes which impacts the huge economy of countries such as India. The majority of the Indian population depends on the ISMR which occurs over the period of June–September. ISMR is one of the most complex geophysical processes in climate systems where understanding long-term variability and predictability has remained challenging. The country's economy, agricultural activities and several policy-making processes are decided by the monsoon rainfall occurring over the country. However, there exists vast spatial heterogeneity in the occurrence of the seasonal rainfall over the country. There have been studies largely focussing upon the influence of SST predictors upon All India Summer Monsoon Rainfall, viz., total summer monsoon rainfall over India. However, they added no significant value toward regional-scale rainfall or its prediction over India. Studies like Sahastrabuddhe *et al.* (2019) can be considered a benchmark to help improve the knowledge of the spatio-temporal variability of the Indian monsoon. They pointed out that identifying changing intraseasonal monsoon patterns due to large-scale and regional-scale teleconnections has a vast scope of potential research. Modeling the high spatial heterogeneity of the Indian monsoon within regional rainfall patterns can also be further explored.

The outline of the research mentioned in the earlier sections regarding the impacts of large-scale factors affecting the observed characteristics of ISMR and its spatio-temporal variability can be critical. Moreover, understanding the impacts of hydroclimatic teleconnections among the large-scale dynamics (including, but not only ENSO connections) on the Indian monsoon variability remains challenging. Also, mining more potential predictors of ISMR and its spatio-temporal variability in changing climate (Wang *et al.* 2015) can be another motivational area of study. However, these studies have primarily focussed on the impacts of large-scale teleconnections on regional-scale monsoonal systems. There exists a caveat in research on feedback from local disturbances to large-scale and associated energy exchanges can be a novel area of study. Also, a causal connection among global monsoonal systems, separately and individually, and the interconnections with the Indian monsoon is another crucial wide area of research.

Understanding the long-term variability of the Indian monsoon also has a huge potential for future research where the dynamical models, viz., CMIP5 models, have not been able to simulate the decreasing trend in ISMR for the years post-1950 so far (Saha *et al.* 2014a, 2014b). While there have been continuous efforts and significant advancements in the modeling frameworks, the state-of-the-art climate models still struggle to simulate ISMR accurately at various spatial and temporal scales. GCMs are inherently developed with the objective of capturing global climatological features and often fail to simulate regional rainfall patterns, particularly when there is an increased contribution from land surface feedback. Using RCMs that are typically designed for conditions suited to western countries does not solve the problem either and further results in biases and wrong conclusions. To increase the accuracy of regional ISMR projections, we need to take into account surface conditions relevant to the Indian region, including the land use changes and irrigation strategies, and accordingly, tune the model parameters. This will, however, also require the need to increase field observations.

Another challenging feature to simulate ISMR is capturing extreme rainfall. Both GCMs and RCMs have shown poor performance in capturing the heavy rainfall events over India. While it is partly to do with the small timescale of convective systems and the complexities in its dynamics which remain unclear, it is also sensitive to the boundary conditions and parameterization schemes used. The use of convection-permitting RCM simulations at regional scales may help to better predict changes in extreme rainfall. There is also a need to fill the gap between model complexity and model understanding to understand the different features of ISMR and to identify their responses in a changing climate. This can be done by creating a hierarchy of idealized models with varying complexity to understand the predominant drivers of regional changes in rainfall and temperature.

Myriad of GCMs show disagreement among themselves that becomes more pronounced on downscaling depending on the method chosen. The lack of proper calibration data for hydrological models further exacerbates the complexity. Contradictory results and disagreements in different analyses further make their interpretation unreliable for policymakers. For instance, Ghosh *et al.* (2016) performed hydrological simulations using the VIC hydrological model that revealed increased (decreased) water yield over water deficit (surplus) basins. This was in contrast to the general impression of 'wet getting wetter and dry getting drier' from previous studies. The widely suggested adaptation strategies like inter-basin transfer are questionable under such circumstances. Continuous efforts are underway to perceive the hydrological implications of changing climate. A better understanding of different atmospheric processes and land–sea–atmosphere interaction is required to improve the simulation and interpret future changes.

These vast areas of potential future research can also be extended to address sector specific problems and predictions contributing to socio-economic activities. Solving the problems of grass-root stakeholders (common person) are pertinent while we delve into research. For example, meteorological forecasts for agriculture may not directly help to understand and prioritize the health sector of a region. This requires more knowledge of societal needs and the implications of our research on these sectors. Such coupled natural-human systems need more understanding through research, and tuning such predictive models incorporating uncertainty is vital.

7. SUMMARY

We have provided a detailed review of the literature related to ISMR and the water cycle of South Asia associated with it. As summarized, the Indian monsoon is still viewed as a large-scale process driven by atmospheric and oceanic circulations, and significant research has been done on the same. They have also been incorporated into the operational models. However, the region has very strong land–atmosphere feedback characteristics, which are neglected. Further to this, we are now in Anthropocene, when anthropogenic interventions are significant in the water cycle in terms of water use, irrigation, water diversion, etc. Monsoon science neglects its feedback in operational models, though literature suggests they have their own importance. Monsoon is part of an extensive Earth System, where a perturbation in any of the components may result in propagation to other components through forcing and feedback links. Understanding these dynamics is essential for projecting the monsoon rainfall in a changing environment. This may be achieved in the near future with much improved Earth System models taking care of all the spheres, hydrosphere, atmosphere, biosphere, and lithosphere.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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