Indian summer monsoon: Extreme events, historical changes, and role of anthropogenic forcings

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OVERVIEW

Indian summer monsoon: Extreme events, historical changes, and role of anthropogenic forcings

Deepti Singh[1,2] | Subimal Ghosh[3] | Mathew K. Roxy[4,5] | Sonali McDermid[6]

[1]School of the Environment, Washington State University, Vancouver, Washington

[2]Lamont-Doherty Earth Observatory, Columbia University, New York City, New York

[3]Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India

[4]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India

[5]NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington

[6]Department of Environmental Studies, New York University, New York City, New York

Correspondence
Deepti Singh, School of the Environment, Washington State University, Vancouver, WA.
Email: deepti.singh@wsu.edu

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South Asia is a complex coupled human-natural system that poses unique challenges for understanding its evolution alongside increasing anthropogenic activities. Rapid and substantial changes in land-use, land-management and industrial activities over the subcontinent, and warming in the Indian Ocean, have influenced the South Asian summer monsoon. These might continue to be significant drivers in the near-term along with rising global greenhouse gas emissions. Deciphering the region's vulnerability to climate change requires an understanding of how these anthropogenic activities, acting on a range of spatial scales, have shaped the monsoon spatially and temporally. This review summarizes historical changes in monsoon rainfall characteristics, associated mechanisms, and the role of anthropogenic forcings, focusing on subseasonal variability and extreme events. Several studies have found intensified subseasonal extremes across parts of India and an increase in spatial variability of rainfall despite an overall weakening of seasonal rainfall in the monsoon core. However, understanding these changes remains challenging because of uncertainties in observations and climate models. The mechanisms and relative influences of various anthropogenic activities, particularly on subseasonal extremes, remain relatively underexplored. Large biases in the representation of relevant processes in global climate models limit the ability to attribute historical changes and make reliable projections. Nevertheless, recent advances in modeling these processes using higher-resolution modeling frameworks provide new tools to investigate the Indian summer monsoon's response to various anthropogenic forcings. There is an urgent need to understand how these forcings interact to shape climate variability and change in this vulnerable region.

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KEYWORDS

anthropogenic forcings, climate change attribution, extreme events, South Asian monsoon, subseasonal variability

1 | INTRODUCTION

South Asia is one of the world's most densely populated regions, with a large fraction of people dependent on monsoon-related activities for their livelihood. The summer monsoon season is the prime agricultural season for most of South Asia and the yields of the major cereal crops are highly sensitive to seasonal temperature and precipitation variability (DeFries et al., 2016). Recent studies have also highlighted the substantial impacts that subseasonal precipitation variability has on crop yields (Auffhammer, Ramanathan, & Vincent, 2012; Fishman, 2016; Gadgil & Kumar, 2006; Prasanna, 2014; Preethi & Revadekar, 2013; Revadekar & Preethi, 2012; A. Singh, Ghosh, & Mohanty, 2018). Further, the intensity of rainfall is closely linked to the recharge of groundwater resources (Asoka, Wada, Fishman, & Mishra, 2018). Therefore, changes in the timing and magnitude of monsoonal rains can have particularly severe impacts on the region's agriculture, surface water and ground water resources (Asoka, Gleeson, Wada, & Mishra, 2017; Barnett, Adam, & Lettenmaier, 2005; Gadgil & Gadgil, 2006; Russo & Lall, 2017). Changes in the timing of the monsoon can also have non-local impacts such as over the Tibetan Plateau, where a trend toward early Indian monsoon onset has been associated with enhanced precipitation and greening since the 1970s (W. Zhang, Zhou, & Zhang, 2017).

Subseasonal rainfall variability also has severe hydrological impacts including flooding that are often associated with substantial economic and humanitarian costs (De, Dube, & Rao, 2005; Gadgil & Gadgil, 2006; Mooley & Parthasarathy, 1982; Mooley, Parthasarathy, Sontakke, & Munot, 2018). The severity of these impacts can be gathered from recent events across South Asia including the Mumbai floods in 2005 (Bohra et al., 2006; A. Kumar, Dudhia, Rotunno, Niyogi, & Mohanty, 2008), Pakistan floods in 2010–2012 (Rahman & Khan, 2013), Uttarakhand floods in 2013 (D. Singh, Horton, et al., 2014), and floods across Nepal, Bangladesh, and northern India (Gettleman, 2017), each affecting millions of lives. Further, heavy rainfall events alone are associated with approximately 50,000 fatalities in India since the 1980s (Figure 1), exemplifying the severity of their impacts.

To minimize the vulnerability of the region's population to such impacts, it is critical to understand how the monsoon system has changed and how it will evolve in coming decades to inform disaster-risk management and adaptation planning. Over the late 20th century, South Asia has experienced substantial changes in three major anthropogenic climate forcings—well-mixed greenhouse gases (GHGs), anthropogenic aerosol emissions, and land-use land-cover change (LULCC). Global anthropogenic activities (primarily fossil-fuel burning and agricultural activities) have contributed to increases in GHG, which constitute the dominant global-scale radiative forcing (Myhre et al., 2013). South Asia's 20th century agricultural development has been among the most rapid and intensive globally, with ~50% of the total geographic area under agriculture (Roy et al., 2015), demanding large amounts of inputs and resources (Ramankutty, Evan, Monfreda, & Foley, 2008; Wada & Bierkens, 2014). Changes in surface albedo, surface roughness, heat fluxes, and modulation of the water cycle associated with agricultural expansion and irrigation activities (Figure 2a,b) constitute the LULCC forcing, which is relatively small on a global-scale but significant on regional scales (Cook, Shukla, Puma, & Nazarenko, 2015). Additionally, industrialization, urbanization, and agricultural activities, have increased emissions of aerosols, including sulfate, black carbon, and organic carbon over the region, which constitute the diverse and complex anthropogenic aerosol forcing (Figure 2c, Ramanathan et al., 2005; Ramanathan & Carmichael, 2008).

Unlike most other regions where GHG are likely to be the dominant forcing in the future, South Asia will continue to experience these multiple, diverse, and spatially heterogeneous forcings (Figure 2), which have likely already influenced several characteristics of the monsoon (Bollasina, Ming, & Ramaswamy, 2011, 2013; Douglas, Beltrán-Przekurat, Niyogi, Pielke, & Vörösmarty, 2009; Guo, Turner, & Highwood, 2015; Lau & Kim, 2010; Z. Li et al., 2016; Meehl, Arblaster, & Collins, 2008; Paul, Ghosh, Oglesby, Pathak, & Chandrasekharan, 2016; Puma & Cook, 2010; Ramanathan et al., 2005; Ramanathan & Carmichael, 2008; Salzmann, Weser, & Cherian, 2014; Shukla, Puma, & Cook, 2014; D. Singh, Bollasina, Ting, & Diffenbaugh, 2018). Regional aerosols are projected to increase for at least the next few decades and agricultural activities will

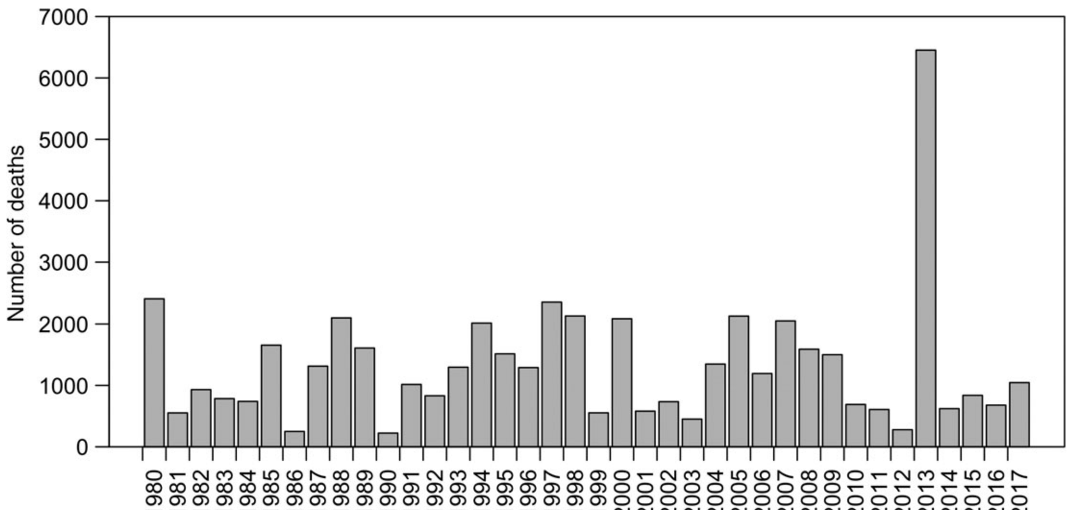

FIGURE 1 Annual number of deaths associated with flooding events in India. Data from EM-DAT: The CRED/OFDA International Database (Guha-Sapir, Below, & Hoyois, 2018)

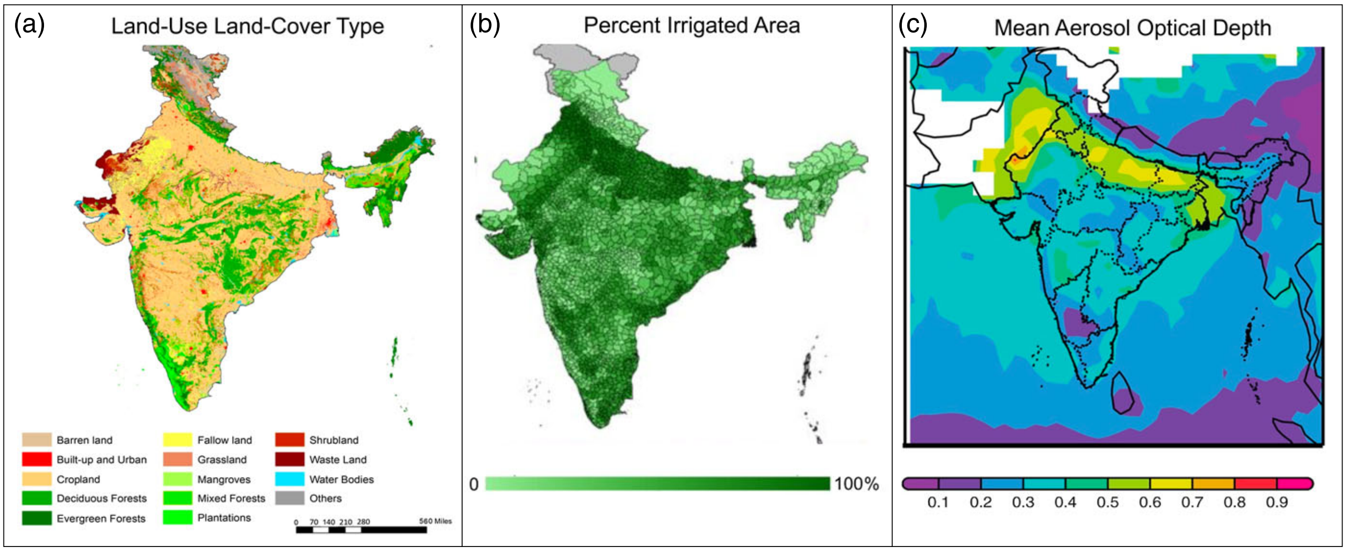

FIGURE 2 External forcings affecting South Asia (a) land-use and land-cover map of India for 2005 based on multiple satellite remote sensing data and extensive ground truthing, and following the International Geosphere Biosphere Program classification scheme (Reprinted from Roy et al. (2015) under Creative Commons Attribution 4.0 International License.); (b) percent irrigated area in 2015 (Reprinted from Ambika et al. (2016) under Creative Commons Attribution 4.0 International License.); and (c) MODIS-derived annual mean mid-visible aerosol optical depth (Reprinted with permission from Srivastava (2017). Copyright John Wiley and Sons)

continue to intensify, to meet the rising food and energy demands of the growing population (Defries, Bounoua, & Collatz, 2002; R. Kumar et al., 2018; Tilman et al., 2001; van Vuuren et al., 2011). Therefore, making reliable climate projections for the future requires a complete understanding of the relative and combined influence of these forcings.

Understanding the monsoon response to anthropogenic climate forcings has so far been crippled by the limited ability of global climate models to skillfully simulate the monsoon circulation and rainfall (Ashfaq, Rastogi, Mei, Touma, & Ruby Leung, 2017). Improvements in the accuracy of simulating the timing and spatial characteristics of the Indian Monsoon over the last two generations of the Coupled Model Intercomparison Project (CMIP) have been marginal, with persistent biases in several characteristics including the onset, extent and subseasonal variability (Sperber et al., 2013). While finer spatial resolution regional and global models provide some improvements (Mishra et al., 2014), they still have heavy computation requirements that limit the number of simulations that can be conducted. This limitation further inhibits the utility of large ensemble simulations, which are required to capture the full range of internal variability that is critical on intraseasonal to decadal timescales (Deser, Phillips, Bourdette, & Teng, 2012). Planned modeling efforts for the CMIP6 with higher resolution, global climate models (Eyring et al., 2015) have the potential to overcome some of these limitations and provide an improved suite of experiments to study the response of the summer monsoon to external forcings on various spatiotemporal scales. In particular, the Global Monsoons Model Inter-comparison Project (GMMIP; Zhou et al., 2016) will improve our process-level understanding of these sources of variability in monsoon precipitation and their response to external forcings.

Various dimensions of the Asian monsoons have received abundant scientific attention including the response of the seasonal monsoon to climate change (Turner & Annamalai, 2012) and the interactions between aerosols and the monsoon (Z. Li et al., 2016). Given their potential for substantial societal impacts, there has been a flurry of recent research on subseasonal processes associated with extreme events. Here, we review advances in the state of knowledge of the South Asian summer monsoon seasonal and subseasonal processes and their interactions with different anthropogenic forcings. Our review largely focuses on the historical period for which several uncertainties remain on how and why the monsoons have changed. Section 2 provides an overview of the processes associated with South Asian monsoon subseasonal variability and extremes on a range of spatial and temporal scales, and the interactions across these scales. Section 3 discusses the observed changes in seasonal and extreme precipitation and their associated physical processes, and their attribution to various anthropogenic forcings. Section 4 evaluates the uncertainties in observed changes in extreme precipitation measures among various key datasets to highlight observational constraints. Section 5 summarizes the performance of global and regional climate models in simulating precipitation characteristics and their physical processes. Section 6 focuses on their projections in response to enhanced GHG in the 21st century. We conclude by highlighting the robust results and key uncertainties in understanding the influence of these diverse anthropogenic activities in shaping changes in high-impact subseasonal rainfall processes within this highly vulnerable region in Section 7. While most regions are likely to experience the greatest impacts from rising GHG emissions, climate over South Asia, at least in the near-term, is likely to be influenced by the other regional anthropogenic drivers that need careful consideration in designing mitigation and adaptation efforts.

2 | SOUTH ASIAN SUMMER MONSOON AND EXTREME RAINFALL PROCESSES

2.1 | South Asian summer monsoon

The South Asian summer monsoon that brings rainfall to the countries lying within the Indian subcontinent and the Indo-China Peninsula, is the most extensively studied among the global monsoon systems and arguably one of its strongest elements (J. Li & Zeng, 2003; Trenberth, Stepaniak, & Caron, 2000; B. Wang & Ding, 2008; B. Wang, Liu, Kim, Webster, & Yim, 2012). These monsoonal systems are typically characterized by seasonal reversals of the circulation and associated precipitation, driven by changes in the meridional temperature gradient between the hemispheres and differential heating of the land and oceans (Trenberth et al., 2000; B. Wang & Ding, 2008; B. Wang et al., 2012). In particular, the temperature gradient at the upper tropospheric levels (200–500 hPa), driven by solar heating and amplified by convective latent heating over land, has a stronger control over the monsoon strength relative to the gradient in the lower troposphere (850–500 hPa) due to the larger magnitude of its mean and variations (Dai et al., 2013). As a consequence, monsoonal climates have a well-defined peak rainfall season during which a majority of the annual rainfall occurs. The South Asian summer monsoon provides approximately 80% of the region's annual rainfall (Cane, 2010; Gadgil, 2003; Turner & Annamalai, 2012).

The global unified monsoon systems can be viewed as the seasonal migration of the Intertropical Convergence Zone (ITCZ), a region of intense boundary layer convergence associated with deep atmospheric convection, which brings precipitation to the subtropical land regions (Gadgil, 2003; Privé & Plumb, 2007). The distribution of precipitation associated with the ITCZ is influenced by the distribution of moist static energy (MSE), a function of moisture availability and temperature, below the cloud level (Boos & Kuang, 2010; Bordoni & Schneider, 2008; Cane, 2010; Chou & Neelin, 2003; Privé & Plumb, 2007; Turner & Annamalai, 2012). Over South Asia, the maximum in this quantity occurs south of the Himalayas coincident with the region of precipitation maximum, suggesting that their presence modulates the precipitation associated with the large-scale monsoon circulation (e.g., Boos & Kuang, 2010; Chakraborty, Nanjundiah, & Srinivasan, 2006; Hahn & Manabe, 1975; Wu et al., 2012). One theory suggests that the Himalayas act as a physical barrier preventing the mixing of cold, dry extratropical air with the warmer, moist air over the Indian subcontinent (Boos & Kuang, 2010; Cane, 2010). Another suggests that the sensible heating over the Himalayas and the Tibetan Plateau influences the tropospheric temperature contrast between the land and surrounding oceans, which influences the strength of the monsoon (Meehl, 1994; Webster et al., 1998; Wu et al., 2007, 2012). Reversal of this thermal contrast is closely associated with the onset of the monsoon over the Indian subcontinent (C. Li & Yanai, 1996). Therefore, either by thermal or mechanical forcing, the region's large-scale topography is important in shaping the monsoon's characteristics. Further, the finer-scale topographic features of the Western Ghats also dramatically affect the spatial distribution of monsoonal precipitation.

In addition to topography, fine-scale processes such as soil moisture feedbacks have a notable influence on the South Asian monsoon due to the strong land–atmosphere coupling in the region (e.g., Dirmeyer, 2011; Halder, Dirmeyer, & Saha, 2015; Koster et al., 2004). This means that soil moisture conditions have a substantial influence on evapotranspiration and therefore, regional precipitation. Evaporation or recycling of local moisture during the peak of the monsoon season contributes on average ~20–30% to precipitation (Mei, Ashfaq, Rastogi, Leung, & Dominguez, 2015; Pathak, Ghosh, & Kumar, 2014). Soil moisture conditions can also influence surface temperature through altering the partitioning of net surface energy into latent and sensible heat fluxes (e.g., Diffenbaugh, 2009; Douglas et al., 2006; Halder, Saha, Dirmeyer, Chase, & Goswami, 2016; Hirsch et al., 2015; Lee et al., 2009; McDermid, Mearns, & Ruane, 2017; Pielke et al., 2011; Quesada, Arneth, & de Noblet-Ducoudré, 2017; Yamashima, Matsumoto, & Takahashi, 2015). As a consequence, the timing, strength, and intensity of the monsoon are sensitive to soil moisture conditions (Mei et al., 2015; Pathak et al., 2014; Paul et al., 2016). Therefore, changes to land-surface conditions that modulate soil moisture and transpiration such as agricultural expansion and intensification, can either have direct effects on the monsoon through land–atmosphere feedbacks or indirect effects through modulating the thermal and moist-static energy gradients. Together, these elements highlight the collective role of land–atmosphere–ocean interactions in shaping the overall monsoon characteristics.

2.2 | Low-frequency subseasonal variability: Active and break spells

The summer monsoon experiences substantial subseasonal variability associated with oscillations of the ITCZ, commonly referred to as monsoon intraseasonal oscillations (MISOs). This subseasonal variability manifests as wet and dry periods (Figure 3), often referred to as active and break phases of the monsoon (e.g., Gadgil, 2003; Gadgil & Joseph, 2003; Krishnamurti, Jayakumar, Sheng, Surgi, & Kumar, 1985; Rajeevan, Gadgil, & Bhate, 2010; Sikka & Gadgil, 1980; Webster et al., 1998). These oscillations occur on quasi-biweekly (10–20 days) and submonthly (30–50 days) timescales associated with westward propagating modes of convection anomalies originating in the western Pacific and northward propagating modes originating in the equatorial Indian Ocean, respectively (Annamalai & Slingo, 2001; V. Krishnamurthy & Shukla, 2007, 2008;

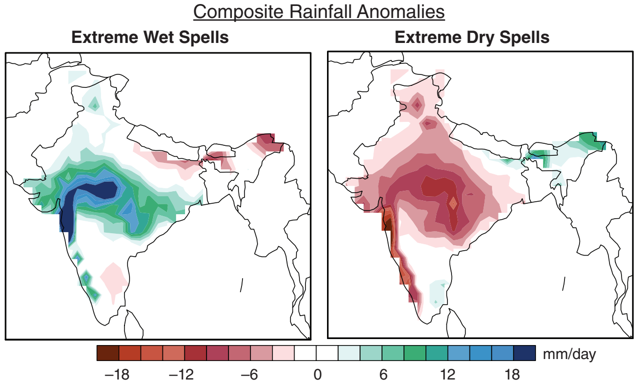

FIGURE 3 Composite precipitation anomalies from the July–August 1951–2011 mean for all extreme wet/dry spells in 1951–1980. Wet/dry spells are defined as events with rainfall anomalies over Central India exceeding $\pm 1\sigma$ for a minimum of three consecutive days (Reprinted with permission from D. Singh, Tsiang, Rajaratnam & Diffenbaugh (2014). Copyright 2014 Springer Nature; Nature Climate Change)
Note: Depiction of political boundaries in these maps may not be accurate.

T. N. Krishnamurti & Ardanuy, 1980; T. N. Krishnamurti & Bhalme, 1976; T. N. Krishnamurti et al., 1985; B. Wang, Webster, Kikuchi, Yasunari, & Qi, 2006).

This monsoon subseasonal variability occurs as an ocean–atmosphere coupled phenomenon. Warm sea surface temperatures (SSTs, above 28.5°C) over the tropical Indian Ocean and west Pacific increase MSE—destabilizing the lower atmospheric column and promoting convective activity over the equatorial Indian Ocean. This manifests as northward propagating convective bands, bringing rains over much of the Indian subcontinent (Roxy & Tanimoto, 2007; B. Wang & Rui, 1990). The ocean-atmospheric evolutions of winds, convection and SST anomalies over the northern Indian Ocean mutually complements the processes related to the northward propagation of the intraseasonal oscillations (Jiang, Li, & Wang, 2004; Kemball-Cook & Wang, 2001; Lawrence & Webster, 2001; Roxy, Tanimoto, Preethi, Terray, & Krishnan, 2013; Sharmila et al., 2013).

Active and break spells resulting from these propagating modes of variability modulate rainfall on relatively large spatial scales. Traditionally, such spells are defined based on rainfall variability over the central Indian core-monsoon region. Active spells lead to coherent, widespread wet conditions across much of central India and dry conditions across the Himalayan foothills and peninsular India, whereas break spells are associated with the opposite spatial pattern of rainfall anomalies (V. Krishnamurthy & Shukla, 2008; Rajeevan et al., 2010). Pacific and Indian Oceans SST variations are found to influence such intraseasonal activity on seasonal and subseasonal timescales (e.g., Liu, Zhou, Ling, Fu, & Huang, 2016; Narapusetty, Murtugudde, Wang, & Kumar, 2017; Pathak, Ghosh, Kumar, & Murtugudde, 2017; Prasanna & Annamalai, 2011; Rajeevan et al., 2010; Xi, Zhou, Murtugudde, & Jiang, 2015). Several other processes including land–atmosphere feedbacks (S. K. Saha, Halder, Suryachandra Rao, & Goswami, 2012), atmosphere–ocean interactions (e.g., Misra, Mishra, & Bhardwaj, 2018; Narapusetty et al., 2017), cloud–radiation feedbacks (Prasanna & Annamalai, 2011), natural (Vinoj et al., 2014), and anthropogenic aerosols (Dave, Bhushan, & Venkataraman, 2017) can initiate or modulate the characteristics of the active/break phases over India. The role of these factors highlights the potential influence that land-surface changes and changing atmospheric constituents can have on these subseasonal events.

2.3 | Widespread daily-scale extremes: Monsoon depressions

On daily timescales, large- and fine-scale rainfall extremes can result from synoptic-scale systems, mesoscale convective systems, and local convection events. Synoptic-scale systems such as monsoon lows and depressions, collectively referred to as low pressure systems (LPSs) occur across the global monsoon regions and contribute substantially (~40–80%) to the overall continental summer monsoon precipitation (Hurley & Boos, 2015). Indian monsoon LPS have spatial scales of over 1,000–2,000 km and are referred to as lows, depressions, and deep depressions (or cyclonic storms) depending on their wind speeds (Godbole, 1977; Hurley & Boos, 2015). The largest number of the Indian monsoon LPS form over the northwestern Bay of Bengal and adjoining land areas (Figure 4), with a small number of shorter-lived storms developing over the Arabian Sea during June–September (Godbole, 1977; Hunt, Turner, Inness, Parker, & Levine, 2016; Hurley & Boos, 2015; V. Krishnamurthy & Ajayamohan, 2010). These systems have timescales of 3–6 days and occur with an average frequency of 13–15 storms a season (Godbole, 1977; Hurley & Boos, 2015). LPS that originate near the Bay of Bengal region, propagate northwestward, bringing heavy precipitation over hundreds of kilometers across central India (Godbole, 1977; Hunt, Turner, & Parker, 2016; V. Krishnamurthy & Ajayamohan, 2010). The heaviest precipitation associated with these systems occurs to the west or southwest of their centers and often exceeds 300–400 mm in 24 hr (Godbole, 1977; V. Krishnamurthy &

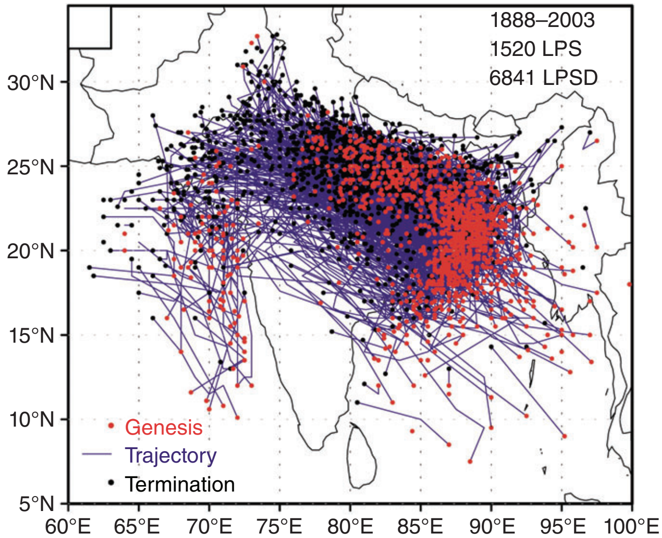

FIGURE 4 Tracks (blue lines) of low pressure systems formed during the JJAS monsoon season in the period 1888–2003. The genesis (red dots) and termination (black dots) locations are represented. (b) Seasonal (JJAS) climatological mean of mean sea level pressure (hPa) for the period of 1948–2003 (Reprinted with permission from Krishnamurthy & Ajayamohan (2010). Copyright American Meteorological Society)

Ajayamohan, 2010). Some LPS have recorded precipitation rates exceeding 68 mm/hr (Hunt, Turner, & Parker, 2016; Hunt, Turner, Inness, et al., 2016), which highlights their potential for causing severe impacts.

LPS activity can be modulated by natural processes acting on various timescales. On subseasonal timescales, active and break spells in the monsoon can influence the frequency and intensity of LPS. Active phases of the monsoons are associated with ~3.5 times more LPS and 7 times more depression days than break phases (Goswami, Ajayamohan, Xavier, & Sengupta, 2003; V. Krishnamurthy & Ajayamohan, 2010; V. Krishnamurthy & Shukla, 2007). Monsoon depressions during active phases are typically more intense than during the break phases (Hunt, Turner, Inness, et al., 2016; Hunt, Turner, & Parker, 2016). In addition, LPS genesis locations and tracks are clustered toward the northern Bay of Bengal along the monsoon trough during active phases but are more disperse during break phases (Goswami et al., 2003).

On longer timescales, oceanic conditions can influence LPS activity. For instance, monsoon depressions are more likely to form and have heavier core-region precipitation during El Niño conditions than during La Niña conditions. However, depressions are associated with heavier rainfall away from their core during La Niña conditions (Hunt, Turner, Inness, et al., 2016; Hunt, Turner, & Parker, 2016). In contrast, there is little difference in the total number of depressions or LPS days during these conditions (Hunt, Turner, & Parker, 2016; Hunt, Turner, Inness, et al., 2016; V. Krishnamurthy & Ajayamohan, 2010). Further, only one study has examined the influence of Indian Ocean dipole (IOD) conditions on LPS activity and found little evidence for any robust relationships. However, IOD conditions could influence moisture availability over the western Indian Ocean and therefore, contribute to the rainfall associated with these systems.

The influence of these various processes on LPS characteristics remains an understudied area. Additional studies are required to establish the robustness and causality of the relationships between subseasonal oscillations and oceanic conditions with the characteristics of LPS. The few existing studies are based on a relatively short observational record of daily data. While the observational record is limited for robustly identifying such relationships, controlled modeling experiments could help systematically evaluate the influence of different conditions on LPS activity.

2.4 | Intense fine-scale precipitation events: Tropical-midlatitude interactions

Occasionally, these moisture-rich, monsoon lows and depressions propagate northwards toward the Himalayas, where interactions with extratropical disturbances and strong orographic forcing create conditions for intense convection, resulting in extreme precipitation events and subsequent flooding in parts of Pakistan, Northern India, and Nepal (Bohlinger, Sorteberg, & Sodemann, 2017; Hunt, Turner, & Shaffrey, 2018; Priya, Krishnan, Mujumdar, & Houze, 2017; Vellore et al., 2016). Their catastrophic impacts generated substantial interest in understanding the underlying mechanisms contributing to such intense events and their predictability (e.g., Bohlinger et al., 2017; Houze, Rasmussen, Medina, Brodzik, & Romatschke, 2011; Joseph et al., 2015; A. Kumar, Houze, Rasmussen, & Peters-Lidard, 2014; Lau & Kim, 2012; Martius et al., 2013; Priya, Mujumdar, Sabin, Terray, & Krishnan, 2015; Ranalkar, Chaudhari, Hazra, Sawaisarge, & Pokhrel, 2016; Rasmussen & Houze, 2012; D. Singh, Horton, et al., 2014; Vellore et al., 2016; Webster, Toma, & Kim, 2011).

These recent studies have identified three key ingredients working across spatial scales that incite such events across the Himalayas (Figure 5). First, central to the occurrence of these events is the presence of low-pressure systems in either the Bay of Bengal or the Arabian Sea that carries moisture into the region at the lower atmospheric levels (Bohlinger et al., 2017; Hunt et al., 2018; Martius et al., 2013; Vellore et al., 2016). Second, large-scale forcing from the equatorward extrusions of midlatitude troughs in the mid to upper troposphere, associated with wave-breaking downstream of the blocking over western Eurasia and ridging over the Tibetan Plateau, is required to orient moisture flow toward the Himalayas (Bohlinger et al., 2017; Martius et al., 2013; Vellore et al., 2016). Third, convection triggered by orographic lifting associated with the steep Himalayan terrain forces condensation of this moisture and consequently, causes precipitation (Bohlinger et al., 2017; Houze et al., 2011; Martius et al., 2013; Vellore et al., 2016). The contribution of these ingredients can vary for individual events as noted by Houze, McMurdie, Rasmussen, Kumar, and Chaplin (2017) and across different locations of the Himalayas as shown by Bohlinger et al. (2017).

In addition to these ingredients, several other factors could contribute to the occurrence and intensity of such extreme precipitation events. For instance, wet soil moisture conditions, sometimes associated with active phases, could provide additional moisture to the associated convective systems to intensify them (Bohlinger et al., 2017; Houze et al., 2017; Martius et al., 2013) as local moisture recycling can account for over 50% of the moisture associated with these events (Bohlinger et al., 2017; Martius et al., 2013). Break phases of the monsoon could create conditions favorable for such extremes in certain regions of the Himalayas (Bohlinger et al., 2017). SST conditions in the Indian and Pacific Ocean basins could influence such events through induced circulation changes (Priya et al., 2015). Further, warming in parts of the Indian Ocean that contribute moisture for such events (Bohlinger et al., 2017; Hunt et al., 2018; Martius et al., 2013) could intensify them through increased moisture transport.

The studies discussed here focus on specific events, with a few exceptions (Bohlinger et al., 2017; Hunt et al., 2018; Vellore et al., 2016). The large societal impacts of such events have inspired recent research into the causes and occurrence of such events and several aspects require more comprehensive investigations. In particular, a better understanding of the influence of oceanic conditions and subseasonal oscillations on the large-scale circulation patterns associated with such events, genesis and propagation mechanisms of monsoon LPS, and moisture availability conducive to these events, could facilitate better predictability. Another aspect that requires attention is the influence of land–atmosphere feedbacks on the interactions between the large-scale, fine-scale, and convective processes that cause such events. This will provide useful insights for the

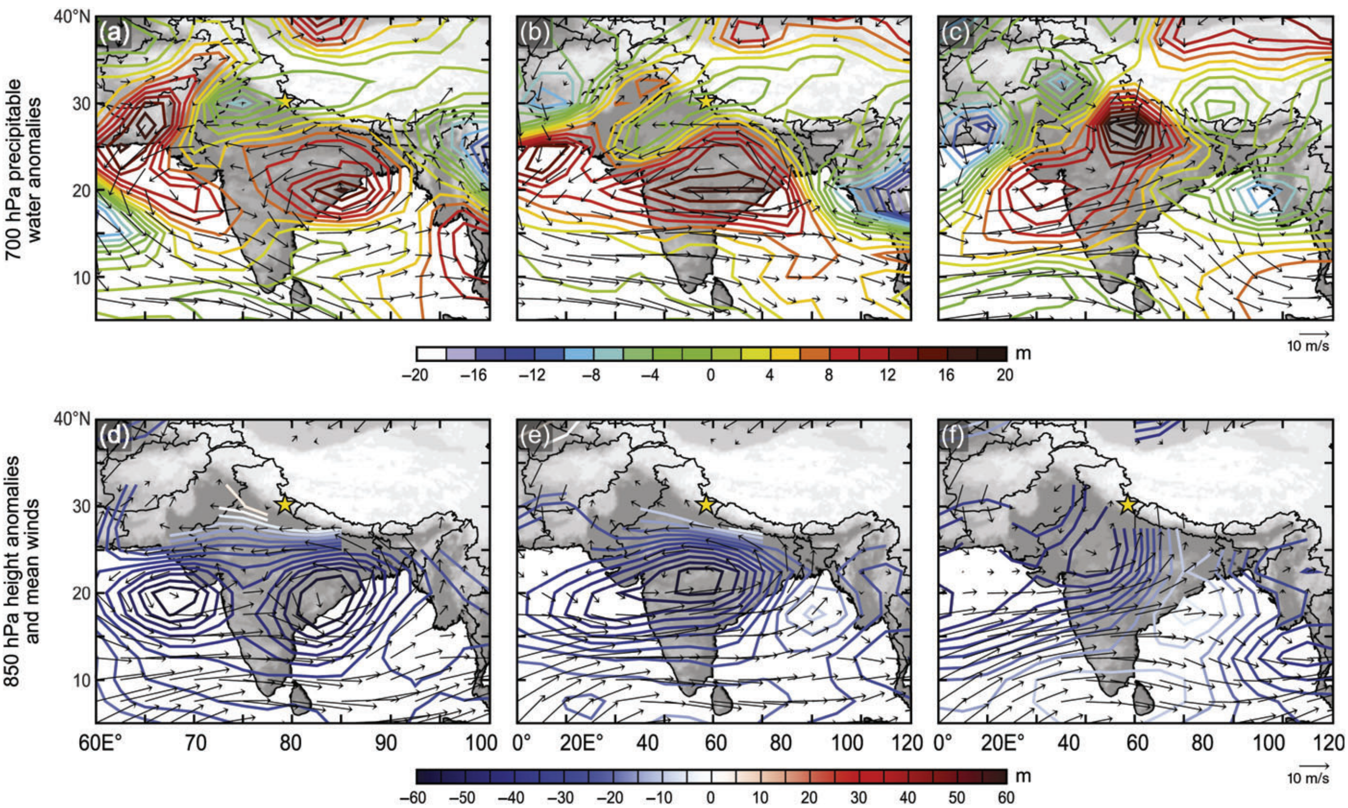

FIGURE 5 Midlatitude–tropical interactions. Synoptic maps showing the 700-hPa precipitable water anomalies (mm) and mean 700-hPa winds (m/s) during the Uttarakhand flooding disaster in 2013, (a) 13 June, (b) 15 June, and (c) 17 June 2013. (d)–(f) As in (a)–(c), but for synoptic maps of 850-hPa height anomalies (m) and mean 850-hPa winds (m/s) (Reprinted with permission from Houze et al., 2017. Copyright American Meteorological Society)

potential for internal variability (such as active/break spells) and external factors (such as irrigation) to influence the characteristics of such high-impact precipitation events.

3 | OBSERVATIONS CHANGES IN PRECIPITATION PROCESSES AND THEIR ATTRIBUTION TO ANTHROPOGENIC FORCINGS

3.1 | Changes in seasonal precipitation

Rainfall across South Asia shows substantial spatial variability with heaviest rainfall along the Western Ghats and the Himalayan foothills due to interactions of the monsoon flow with the orographic features, and over central India due to the maximum convergence of the monsoon low-level circulation. Therefore, rainfall over central India is a good indicator of the overall strength of the synoptic-scale monsoon circulation. In addition, central India experiences the largest and most widespread effects of subseasonal and interannual variability (V. Krishnamurthy & Shukla, 2008; Rajeevan et al., 2010). Therefore, long-term trends in summer monsoon rainfall characteristics across central India have been extensively studied along with All-India rainfall trends (e.g., Bollasina et al., 2011; Goswami, Venugopal, Sengupta, Madhusoodanan, & Xavier, 2006; Jin & Wang, 2017; Ramanathan et al., 2005; D. Singh, Tsiang, Rajaratnam, & Diffenbaugh, 2014). While there is little change in the All-India rainfall average, multiple datasets confirm that the mean June–September rainfall over central India has significantly weakened over the second half of the 20th century (Bollasina et al., 2011; Jin & Wang, 2017; Mishra, Smoliak, Lettenmaier, & Wallace, 2012). This weakening is primarily driven by a strong declining trend (~10%) in the peak months (July–August) of the monsoon season (D. Singh, Tsiang, et al., 2014; Figure 6). Since the early 2000s, this trend has reversed in multiple observational datasets except in the Indian Meteorological Department (IMD) dataset in which it has stabilized (Jin & Wang, 2017).

The longer-term weakening of the monsoon is linked to a reduction in the tropospheric thermal contrast that is associated with the warming of the Indian Ocean and concurrent cooling over land (Roxy et al., 2015). The subsequent revival is associated with a reversal of the surface and lower-level (850 mb) meridional thermal gradient in the pre-monsoon and monsoon seasons, driven by an uptick in warming over the Indian subcontinent relative to the tropical Indian Ocean, which has continued warming. Observational studies and modeling experiments have attributed the weakening of the Indian monsoon to a combination of other factors including LULCC (Paul et al., 2016), irrigation (Cook et al., 2015; Shukla et al., 2014), and

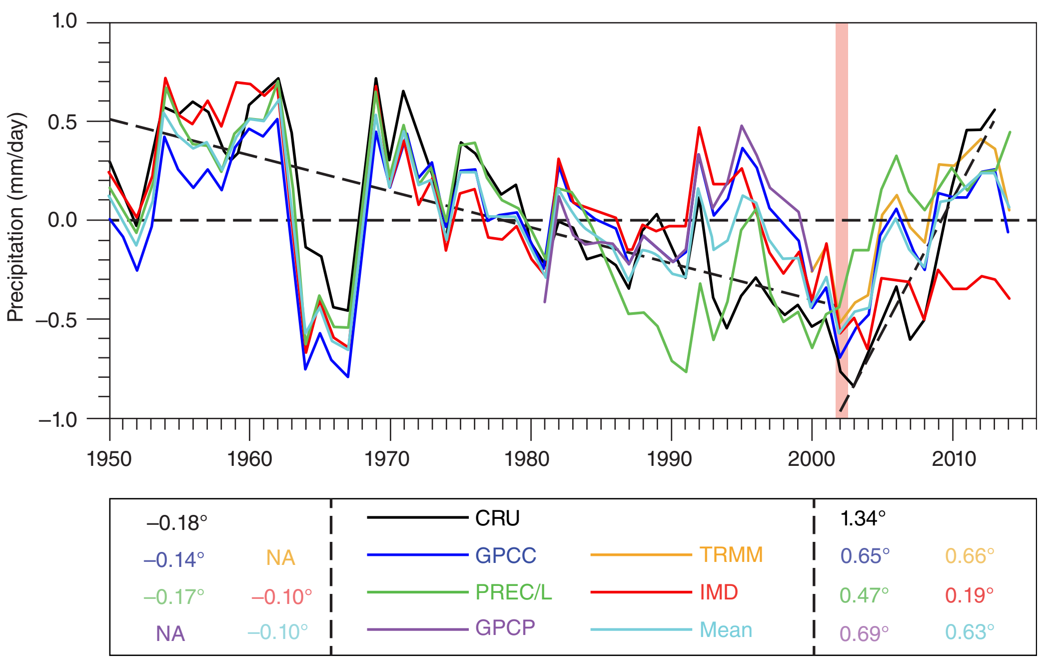

FIGURE 6 Time series of 5-year running means of the Indian summer monsoon precipitation anomalies (mm/day) relative to the 1950–2013/2014 base period. The precipitation is area-averaged over northern central India (20–28°N, 76–87°E). The various colors represent various datasets, that is, colors of black, blue, green, purple, orange, red, and cyan corresponding to the datasets of CRU, GPCC, PREC/L, GPCP, TRMM, IMD, and the ensemble mean, respectively. The legends of the figure are in the lower box and the numbers in the first and third columns of the box represent the linear trends of precipitation in 1950–2002 and 2002–2013/2014, respectively. The numbers in the box followed by a star '*' denote trends significant at the 95% confidence level (Reprinted with permission from Jin & Wang (2017). Copyright Springer Nature; Nature Climate Change)

increased anthropogenic aerosol content in the atmosphere (e.g., Bollasina et al., 2011; Guo et al., 2015; Krishnan et al., 2016; Z. Li et al., 2016; Patil, Venkataraman, Muduchuru, Ghosh, & Mondal, 2018; Ramanathan et al., 2005; Ramanathan, Crutzen, Kiehl, & Rosenfeld, 2001; Salzmann et al., 2014). These forcings have changed simultaneously over the 20th and early 21st century, and some of these forcings such as aerosols and GHG, have had competing effects on the monsoon and on SSTs (e.g., Bollasina et al., 2011; Dong & Zhou, 2014; Guo et al., 2015; Lau & Kim, 2017; X. Li, Ting, Li, & Henderson, 2015; Z. Li et al., 2016; L. Zhang & Li, 2016). Further, some forcings such as land-surface changes have had a stronger influence over land, while the others have influenced both land and ocean temperatures, both of which determine the overall response of monsoons to these combined forcings. We discuss the influence of each of these factors below.

3.1.1 | GHG and Indian Ocean warming

The tropical Indian and Pacific oceans have a dominant role in regulating monsoon variability (B. Wang, Lee, & Xiang, 2015). The monsoon weakening over the second half of the 20th century is associated with warming over the tropical Indian Ocean and the western and central-eastern tropical Pacific (Deser, Phillips, & Alexander, 2010; Zhou, Yu, Li, & Wang, 2008). Warming has been particularly pronounced over the Indian Ocean during 1950–2015 and has extended into the upper troposphere due to enhanced latent heating aloft from convection (Roxy et al., 2015). Therefore, the Indian Ocean warming results in a weakened meridional tropospheric temperature contrast, which directly influences the strength and location of the continental monsoon. This warming has been linked to natural and anthropogenic causes, with the latter contributing over 95% to the trend since the 1950s (Dong & Zhou, 2014; Dong, Zhou, & Wu, 2014; Roxy, Ritika, Terray, & Masson, 2014). Over recent decades, aerosol forcing has likely dampened the GHG forced warming of the Indian Ocean (Dong & Zhou, 2014). This warming of the Indian Ocean has an asymmetric pattern, with the western equatorial part experiencing enhanced warming relative to the eastern part (Zhou, Yu, et al., 2008). The asymmetric warming pattern is likely associated with feedbacks between ocean temperatures and the weakened monsoon flow, where the lower-level monsoon jet (known as the Somali jet) typically induces upwelling-related cooling along the coast of Africa (Swapna, Krishnan, & Wallace, 2014).

In addition to GHG-induced warming, changes in the Pacific Ocean might have contributed to the Indian Ocean warming trend. On interannual timescales, El Niño Southern Oscillation (ENSO) is the major driver of monsoon variability (Rasmusson & Carpenter, 1983). El Niño events influence the monsoon via modulating the Walker circulation. El Niño warming in the tropical Pacific generates enhanced convection in the central-east Pacific and anomalous subsidence over the Indian Ocean, leading to warming of the western Indian Ocean (Roxy et al., 2014). These changes dampen the monsoonal winds and suppress rainfall over land. Hence, typically, an El Niño year may be characterized by a dry monsoon over a large region over the subcontinent, while a La Niña might denote a wet monsoon year (Figure 7; K. K. Kumar, Rajagopalan, Hoerling, Bates, & Cane, 2006; Roxy et al., 2017). Therefore, more frequent El Niño events in the second half of the 20th century relative to the earlier part, might in part, have contributed to the asymmetric warming pattern of the Indian Ocean (Roxy et al., 2014) and the overall drying of the Indian Monsoon over land.

Concurrent with the warming of the tropical Indian Ocean during the late 20th century, there has been cooling or absence of warming over the Indian land mass in the pre-monsoon season, further weakening the meridional thermal gradient (Figure 8). Meanwhile, Jin and Wang (2017) note that emergence of land surface warming, likely associated with emergence of the GHG signal over the competing effect of other forcings, in recent years (2002–2014) has resulted in an increase in the

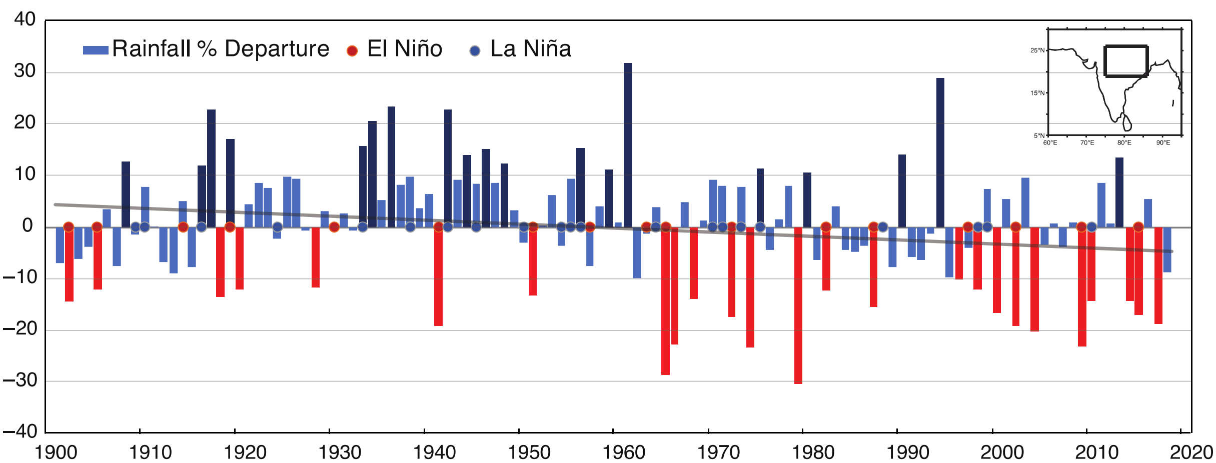

FIGURE 7 Summer monsoon (June–September) rainfall departure (in %) over central India (75–85°E, 19–26°N), during 1901–2018. Wet years (above 10% departure) are marked in dark blue colors and drought years (below −10% departure) are marked in red colors. El Niño and La Niña conditions for the same season are marked using red and blue dots, respectively. Rainfall data is from the Indian Meteorological Department

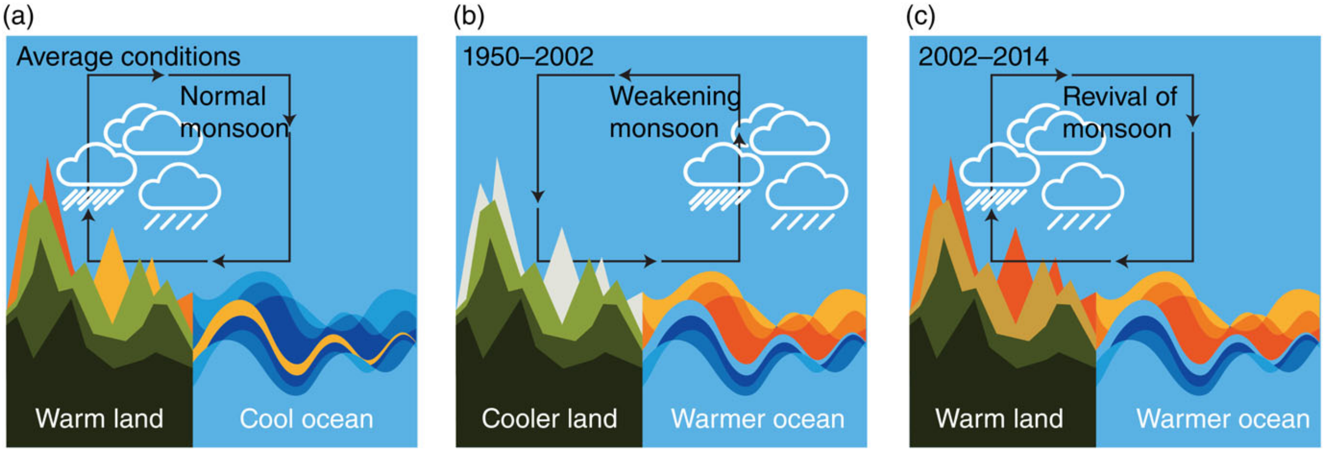

FIGURE 8 Schematic illustration of changes in the Indian summer monsoon (Roxy, 2017) (Reprinted with permission from Roxy (2017). Copyright Springer Nature; Nature Climate Change)

meridional tropospheric temperature gradient in the lower troposphere. This provides a mechanism for the possible revival of the monsoon Hadley circulation and rainfall since the early 2000s. Nevertheless, the years 2014 and 2015 witnessed back-to-back droughts over the Indian subcontinent, which do not reflect in the analysis of Jin and Wang (2017). Further, an extension of the SST trends up to 2017 suggest that the Indian Ocean continues to warm as a response to increased GHG, which indicates that the strength of the monsoon may depend on the competition between the land and ocean—on which warms faster than the other (Figure 8). A recent study by Sabeerali and Ajayamohan (2018) using CMIP5 projections based on a subset of CMIP5 models that simulate the large-scale thermodynamics and Indian Ocean warming, demonstrates that continued increase in anthropogenic CO_2 emissions result in the monotonous warming in the Indian Ocean. The continued Indian Ocean warming weakens the upper-tropospheric thermal gradient and is associated with a shortening of the rainy season by the end of the 21st century (Sabeerali & Ajayamohan, 2018). CMIP5 models robustly project enhanced monsoonal precipitation in the 21st century despite a weakening of the thermal gradient and a shorter rainy season. The projected enhancement of rainfall is consistent with the revival of the monsoon since the early 2000s although the projected trends in the thermal gradients are not (Figure 6). Further, the accuracy of these projections is questionable because the CMIP5 models are unable to capture historical trends in the upper-level thermal gradients (Jin & Wang, 2017).

3.1.2 | Influence of aerosols and LULCC

The land-surface cooling in the second half of the 20th century has largely been attributed to the direct (i.e., solar dimming) and indirect (i.e., aerosol–cloud interactions) effects of sulfate aerosols that have masked GHG-induced warming (e.g., Bollasina et al., 2011, 2013; Guo et al., 2015; Krishnan et al., 2016; Lau & Kim, 2017; Lau et al., 2017; Z. Li et al., 2016). There is strong consensus between multiple models that the reduction in these thermal gradients and suppressed moisture availability over the oceans (e.g., Bollasina et al., 2011; Guo et al., 2015; X. Li et al., 2015; Z. Li et al., 2016; Salzmann et al., 2014), attributable to anthropogenic aerosols, have weakened the monsoon (Figure 9), consistent with observations of the late-20th century (Figure 6). Among the models that include explicit representations of aerosol-indirect effects, there is also agreement on the predominant role of aerosol–cloud interactions (commonly referred to as indirect effects) in the overall drying over South Asia (Bollasina et al., 2011; Guo et al., 2015; Ramanathan et al., 2001). These aerosol indirect effects refer to increases in solar reflectance of clouds due to increase in cloud fraction and cloud droplet size over northern and central India, collocated with the region of largest increase in aerosol loading during the monsoon season (Guo et al., 2015).

In addition to their large-scale effects, aerosols can weaken monsoonal rains through more localized effects such as increasing atmospheric stability, which along with near-surface cooling, reduces convective potential over land (Lau et al., 2017; Z. Li et al., 2016; Niyogi et al., 2007; Ramanathan et al., 2005). These local-scale changes can feedback to influence the larger-scale thermal gradients through influencing tropospheric temperature due to the strong land–atmosphere coupling. Despite the strong model agreement on the role of aerosols in weakening the monsoon, there is still considerable uncertainty in the magnitude of aerosol effects on the Asian monsoon due to lack of long-term observations of aerosols, simplified representation of aerosols, underestimation of black carbon effects, overestimation of aerosol indirect effects, and uncertainties in the representation of physical processes such as cloud physics and their interactions with aerosols (Lau et al., 2017; Z. Li et al., 2016).

While aerosols and GHG have been the most widely-studied external forcings on the South Asian summer monsoon, the role of widespread agricultural expansion and intensification in driving the 20th century weakening are starting to get attention

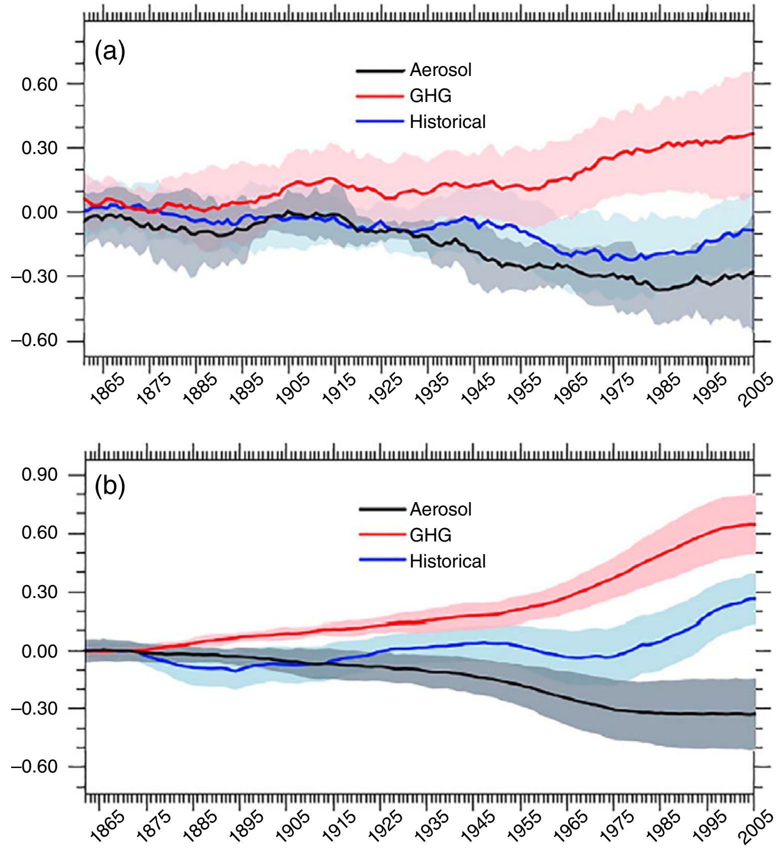

FIGURE 9 (a) JJAS rainfall from 1861 to 2005 averaged over South Asia (10–35°N, 70–90°E) in the CMIP5 all-forcings historical experiment (blue), greenhouse gas (GHG)-only historical experiment (red) and the aerosol-only historical experiment (black). The thick lines show the multi-model ensemble means with a 21-year running mean applied, while the pale envelope indicates the range from the mean. Only eight models are used in constructing this figure (see Section 2): CanESM2, CCSM4, CSIRO-Mk3.6.0, GFDL-CM3, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and NorESM1-M. The curves are centered around zero by removing the mean rainfall from pre-industrial control runs (piControl) of the same models. Units are mm/day. (b) Same as (a) but for the global mean and annual mean land–sea surface temperature contrast from 1861 to 2005. Units are K (Reprinted from Guo et al., (2015) under Creative Commons Attribution 3.0 License)

(Krishnan et al., 2016; Lee et al., 2009; Niyogi, Kishtawal, Tripathi, & Govindaraju, 2010; Paul et al., 2016; Shukla et al. 2018; D. Singh, McDermid, et al., 2018). Recent studies have shown the potential for land-cover change from agricultural expansion to contribute to the weakening of the monsoon. This can occur through an increase in planetary albedo (crops have higher albedo than the natural vegetation, mostly forests, that they replace in this region) that weakens the monsoon (Krishnan et al., 2016) and a decrease in evapotranspiration and convection that reduces the amount of recycled moisture (Paul et al., 2016), whose contribution to mid- and late-monsoon season precipitation can exceed 25% over parts of India (Mei et al., 2015; Pathak et al., 2014, 2017). These studies have shown that land-cover forced changes to the monsoon have notable effects even in the presence of other external forcings. Early observational evidence suggests that winter season and pre-monsoon vegetation increases associated with agricultural intensification are linked to suppression of rainfall during the pre-monsoon season (Lee et al., 2009; Niyogi et al., 2010). Modeling studies also support the idea that agricultural intensification in the form of irrigation, could weaken rainfall over parts of India by reducing lower-level temperatures through evaporative cooling by altering the surface energy balance and consequently weakening the monsoon due to weakened thermal contrasts (Cook, Puma, & Krakauer, 2011; Douglas et al., 2009; Guimberteau, Laval, Perrier, & Polcher, 2012; Puma & Cook, 2010; Sacks, Cook, Buenning, Levis, & Helkowski, 2009; Shukla et al., 2014).

Therefore, observational and modeling evidence highlights the potential for substantial effects of land-cover changes and agricultural intensification, particularly irrigation, on historical changes in the region. However, the magnitude of these effects relative to other external forcings is still quite uncertain since most studies only examine the isolated effects of land-cover change (e.g., Douglas et al., 2009; Niyogi et al., 2010; Paul et al., 2016) or are limited to single models (e.g., Cook et al., 2015; Puma & Cook, 2010; Sacks et al., 2009; Shukla et al., 2014). While the effects of atmospheric constituents have received extensive attention, this calls for further attention to role of land-surface changes and their interactions with other forcings.

3.2 | Changes in subseasonal extremes

Given the societal impacts of short-lived, high impact, extremes, such events have received considerable scientific attention over the last decade although studies dating back to the 1990s have reported significant changes in parts of the subcontinent. These studies use a range of metrics, datasets, study domains, and methodologies based on applications (such as water resource management), physical processes (such as synoptic-scale circulation) or geographical features (such as river basins). Using these multiple dimensions for defining extremes can lead to seemingly conflicting results (D. Singh, Tsiang, et al., 2014; Vinnarasi & Dhanya, 2016), which are expected given the dramatic spatial heterogeneity in rainfall across India and its increase in recent decades (Ghosh, Das, Kao, & Ganguly, 2012). Below, we reconcile some of these differences and highlight the emerging consensus on changes in various rainfall measures across different subregions. Table 1 summarizes the metrics and findings of the major studies that are discussed below.

Rainfall variability and extremes result from the interactions of intraseasonal oscillations on various timescales. Since the late 1970s, daily rainfall variability within the monsoon season has significantly increased over western, central, and northeastern India (Sabeerali et al., 2014; D. Singh, Tsiang, et al., 2014). Increased rainfall variability is associated with enhanced moisture convergence due to increased humidity associated with Indian Ocean warming and slower progression but increased amplitude of the northward propagating MISO (Sabeerali et al., 2014; C. Singh, 2013b). Weakened vertical wind shear over the equatorial Indian Ocean and reduced meridional moisture gradient across the monsoon domain are probable causes of the slower phase speed of the northward propagating MISO (Sabeerali et al., 2014; D. Singh, Tsiang, et al., 2014). Using SST-forced experiments, Sabeerali et al. (2014) showed that these changes are largely related to the enhanced warming in the western equatorial Indian Ocean.

Changes in rainfall variability and characteristics of intraseasonal oscillations have also influenced the characteristics of active and break spells, which refer to multiday periods of above or below normal rainfall (defined as an exceedance of a certain anomaly threshold) across central India (Annamalai & Slingo, 2001; Gadgil & Asha, 1992; Pai et al., 2016; Rajeevan et al., 2010; D. Singh, Tsiang, et al., 2014). Break (dry) spells, particularly short durations ones lasting ~3–7 days, have increased significantly since the 1950s (C. Singh, 2013b; D. Singh, Tsiang, et al., 2014), consistent with slower propagation of the northward propagating MISO (C. Singh, 2013b). While their frequency has increased (Figure 10), their severity (measured as the average rainfall anomaly) has reduced due to enhanced convective potential in a warmer and wetter climate that favors more rainfall (D. Singh, Tsiang, et al., 2014). In contrast, the overall frequency of active spells remains largely unchanged over this period although their intensity has increased (D. Singh, Tsiang, et al., 2014; Figure 10). Despite no change in their overall frequency, there is, however, a shift toward more frequent occurrence of shorter duration (4–7 days) active spells at the expense of longer duration ones (Pai et al., 2016; C. Singh, 2013a; D. Singh, Tsiang, et al., 2014). Shorter but more intense active spells are a response to increased moisture convergence (D. Singh, Tsiang, et al., 2014) and are consistent with the effect of atmospheric warming on precipitation (e.g., Allan & Soden, 2008; Allan, Soden, John, Ingram, & Good, 2010). In addition, these increases in shorter duration active spells are correlated with an increase in the number of days with monsoon lows (Pai et al., 2016).

Using IMD ($1^\circ \times 1^\circ$) daily gridded data for the period 1901–2004, Neena and Goswami (2010) indicate that the potential predictability of active and break spells of rainfall has increased during 1980–2004. They suggest that the potential predictability of active spells have increased from 1 week to 2 weeks while that for break spells has increased from 2 weeks to 3 weeks over this period. Further, they point out that the rapid increase in break predictability is associated with the rapid surface warming over Indian Ocean, which enhances the air–sea coupling in such a way that the boundary-forced predictability outweighs the predictability factor due to internal dynamics.

While active and break spells quantify synoptic-scale rainfall variability and are defined based on average rainfall across central India, this measure does not fully capture the spatial characteristics of rainfall extremes or the more extreme tails of the rainfall distribution. Recent studies have quantified the occurrence of more intense and widespread rainfall extremes that have the potential to cause extensive flooding across a large region (Roxy et al., 2017; Sagar et al., 2017). Large rainstorms over central India with heavy rainfall over at least 50,000 km^2 lasting at least 2 days have doubled in the last 6 decades (Sagar et al., 2017). Further, relatively smaller (>6,250 km^2) but more intense events have tripled over this time (Roxy et al., 2017). These changes have been linked to an increase in weaker LPS (i.e., lows) despite a decrease in the frequency of the stronger LPS (i.e., monsoon depressions) in the Bay of Bengal (Ajayamohan et al., 2010; Dash et al., 2009; Pai et al., 2016). Roxy et al., 2017 argue that such events are associated with moisture advection from the Arabian Sea by monsoon westerlies and their increase is associated with episodic enhancement of westerlies over a period of 2–3 days. While these appear contradictory, these processes act in concert—the Bay of Bengal LPS likely cause convergence of the enhanced moisture supply over the Arabian Sea, subsequently leading to widespread extreme rainfall events.

TABLE 1 Summary of studies on extreme rainfall characteristics during the Indian summer monsoon

Reference	Extreme metric	Time period and data	Key findings	Causes
Bisht, Chatterjee, Raghuwanshi, and Sridhar (2018)	95th and 99th percentile, and daily maxima	IMD (0.25° × 0.25°; 1901–2015)	Increase in magnitude of 95th and 99th percentile events and daily maxima across all *river basins except the Ganges and Brahmaputra river basins* since 1970s and spatially heterogenous changes in intensity	Effect of urbanization based on reversal of trends in daily maxima post-1970s towards mainly positive trends
Mukherjee, Aadhar, Stone, and Mishra (2018)	Annual maxima, 90th–99th percentile, multiday rainfall events	IMD (0.25° × 0.25°; 1951–2015)	Increases except over parts of *northern-central and northeastern India*	Enhancement of heavy precipitation events in central and southern India associated with enhanced dew point temperature, and attributable to anthropogenic forcings
Roxy et al., 2017	Large-scale events exceeding 150 mm/day over at least 10 grid cells	IMD (0.25° × 0.25°; 1950–2015)	Threefold increase in widespread heavy rain events over *Central India*	Increased variability in zonal moisture transport from Arabian Sea
Karmakar, Chakraborty, and Nanjundiah (2017)	99.5th percentile events during active and break spells	IMD (1° × 1°; 1951–2013)	Increase in extremes during low-frequency break spells and lesser rain during active spells over *Central India*	Enhanced atmospheric stability and reduction in vertical wind shear
Sagar, Rajeevan, and Rao (2017)	Rain storms with 125 mm/day at center and >25 mm/day over >50,000 km^2 and >2 days	IMD (0.25° × 0.25°; 1951–2015)	Near doubling of large rainstorms over *Central India*	
Deshpande, Kothawale, and Kulkarni (2016)	>100 mm/day	IMD (0.25° × 0.25°; 1951–2014)	Increase in area of extremes or intensity over Ganga, Narmada–Tapi, and Godavari river basins, which lie in *northern and central, western-central and northern-peninsular India*	
Pai, Sridhar, and Ramesh Kumar (2016)	Active and break spells (±1σ rainfall anomalies for >3 days)	IMD (0.25° × 0.25°; 1901–2012)	Increase in break days and increases in short duration active spells over *Central India* in second half of the 20th century	Increase in monsoon low pressure days despite fewer monsoon depressions
Vinnarasi and Dhanya (2016)	Extreme wet (>90th percentile) and dry events (<2.5 mm/day)	IMD (0.25° × 0.25°; 1901–2012)	Reduction in wet spell duration and increase in dry spell duration in *wet regions*; increase in frequency of wet spells in dry regions; variable changes in other characteristics, particularly over *dry regions*	
Sushama, Ben Said, Khaliq, Nagesh Kumar, and Laprise (2014)	Dry spell events (1 mm/day, 3 mm/day)	IMD (1° × 1°; 1951–2007), APHRODITE (0.25° × 0.25°; 1951–2007)	Reduction in duration dry spells over *northwestern India* and increase in number of dry days over parts of *central and peninsular India*	
D. Singh, Tsiang, et al. (2014)	Wet and dry spells (±1σ rainfall anomalies for ≥3 days)	IMD (1° × 1°; 1951–2011), APHRODITE (0.25° × 0.25°; 1951–2007)	Increase in daily variance; increase in the frequency of dry spells and intensity of wet spells; decrease in intensity of dry spells over *central India*	Enhanced moisture convergence and CAPE during wet spells; increase in CAPE during dry spells, and reduced vertical wind shear
Sabeerali et al. (2014)	Intraseasonal variability on 20–100 day filter daily data	CMAP (2.5° × 2.5°), IMD (1° × 1°), GPCP (2.5° × 2.5°) 1979–2010	Enhanced variance across *western and northeastern India*	Increased amplitude intraseasonal oscillations and enhanced moisture convergence driven by Indian Ocean warming
Vittal, Karmakar, and Ghosh (2013)	Peak over threshold, 95th and 99th percentile events	IMD (1° × 1°), 1901–2004	Reversal of trends post-1950 across some regions; decrease in frequency over *Central* and *northern India* and increases elsewhere; increase in intensity over ~66% of area	Change points in urban areas in the mid-1970s suggest impacts of urbanization
C. Singh (2013b)	Active and break spells (±1σ rainfall anomalies for ≥3 days)	IMD (1° × 1°), 1951–2003	Increase in short duration break spells and moderate duration active spells over *central India*	Slower propagation of the 20–60-day intraseasonal oscillation mode

(Continues)

TABLE 1 (Continued)

Reference	Extreme metric	Time period and data	Key findings	Causes
Ghosh et al. (2012)	30- and 100-year return levels for annual maxima using GEV	IMD (1° × 1°), 1951–2003	Lack of uniform increasing or decreasing trends but enhanced spatial variance of extremes	
Dash, Nair, Kulkarni, and Mohanty (2011)	Low, moderate, and heavy events (<40th, 40th–99th, and >99th percentile events), short (≤4 days) and long spells (≥4 days)	IMD (1° × 1°), 1951–2003	Increase in short, heavy-intensity spells across peninsular, western-central, northwestern, and central north east India, and most agro-meteorological regions except in the rain-shadow regions of central India and northern hilly regions; decrease in long, moderate-intensity spells and long and short, low-rain spells across all homogenous regions and some agro-meteorological regions	
N. Singh and Ranade (2010)	Wet and dry events (continuous periods of rainfall above and below daily climatology)	IMD (1° × 1°), 1951–2007	Increase in intensity but shorter duration wet spells and weakening intensity but longer duration dry spells across most Indian subregions	
Ajayamohan, Merryfield, and Kharin (2010)	Extreme rainfall days ~>95th or 99th percentile	IMD (1° × 1°), 1951–2003	Robust rising trends over *eastern-central India*	Increase in synoptic activity index associated with more weak-LPS systems
Rajeevan et al. (2010)	Active and break spells (±1σ rainfall anomalies for ≥3 days)	IMD (1° × 1°), 1951–2007	No significant trends in active or break spells over *central India*	
C. K. B. Krishnamurthy, Lall, and Kwon (2009)	90th and 99th percentile event	IMD (1° × 1°), 1951–2003	Increase in intensity across much of *central and peninsular India* but heterogeneity in frequency trends; ~3 times more grids show decreasing 90th percentile frequency trends than increasing but opposite for 99th percentile	
Dash, Jenamani, Kalsi, and Panda (2007); Dash, Kulkarni, Mohanty, and Prasad (2009)	Moderate and heavy events (40th–99th, and >99th percentile events), short (≤4 days) and long spells (≥4 days); dry events (<2.5 mm/day)	IMD (1° × 1°), 1951–2004	Increases in heavy rain events in *northeast* and decreases in moderate rain events across all regions; increase in short and prolonged dry spells across *all regions but the northeast*	Increase in low pressure systems but decrease in depressions and increase in severe cyclonic storms
Rajeevan, Bhate, and Jaswal (2008)	Moderate (5–100 mm/day), heavy (100–150 mm/day) and very heavy (>150 mm/day)	IMD (1° × 1°), 1901–2004	Increase in frequency of very heavy rain events since 1950s and decrease in frequency of moderate rain events over *central India*	Indian Ocean warming results in enhanced evaporative flux and moisture availability
Goswami, Venugopal, et al. (2006)	Moderate (5–100 mm/day), heavy (≥100 mm/day)	IMD (1° × 1°), 1951–2004	Increasing trend and intensity of extreme rain events, and opposite trends in moderate events over *central India*	Warming of the tropical Indian Ocean
Sen Roy and Balling (2004)	90th, 95th and 97.5th percentile	129 stations (1910–2000)	Increase in *northwestern India*, *western central and peninsular India*, and decrease over *eastern-central*	
Rakhecha and Soman (1994)	1–3-day maxima rainfall	316 stations (1901–1980)	Increase in western coastal and *western-central India* but decreases in *southern peninsular India* and *lower Ganges Basin*	

The table includes papers that focused on India.

Studies have also investigated finer-scale extremes across the subcontinent using more generalized metrics based on fixed rainfall amounts or relative thresholds (e.g., percentiles or daily maxima) at the grid point-scale or after aggregating to subregional scales (Table 1). Figure 11 summarizes the trends across different percentiles of the rainfall distribution in each of the six homogenous rainfall zones in India (Parthasarathy, Munot, & Kothawale, 1994). It is noteworthy that trends can vary in direction and magnitude across different quantiles (Figure 11) due to the changing mean and variability of rainfall (C. K. B. Krishnamurthy et al., 2009; Sabeerali et al., 2014; D. Singh, Tsiang, et al., 2014). All regions except peninsular India have experienced a significant declining trend in low rainfall events (<30th percentile; Malik, Bookhagen, & Mucha, 2016), which,

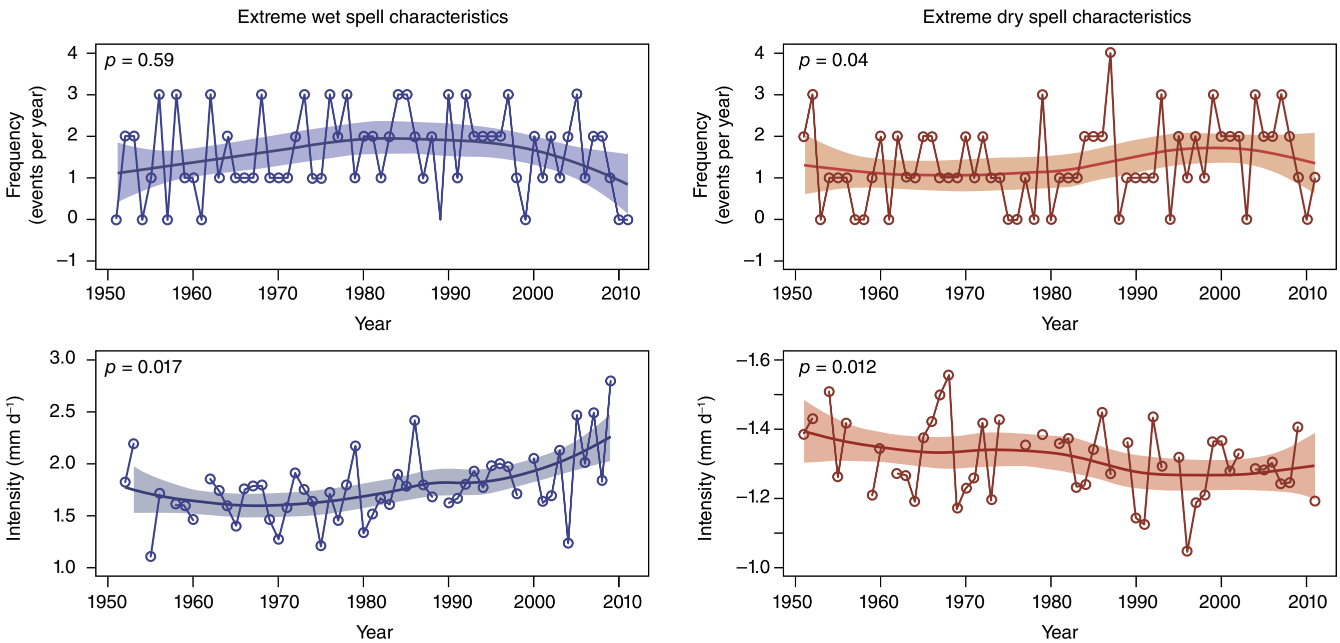

FIGURE 10 Time series of wet (blue) and dry (red) spell frequency and intensity over the core-monsoon domain. Missing links in the time series are years with no wet or dry spells. Trend lines are estimated using the nonparametric locally estimated scatterplot smoothing (LOESS) regression technique; shading represents the 90% confidence intervals of the estimated trends. *p*-values are obtained from testing the difference in means of the distributions of each variable between 1951–1980 and 1981–2011 using the nonparametric moving block bootstrap test. Colors indicate the significance level of the *p*-values (Reprinted with permission from D. Singh, Tsiang et al., (2014). Copyright Springer Nature; Nature Climate Change)

particularly in the northwest and northcentral regions, has adversely affected groundwater recharge (Asoka et al., 2018). In addition, wetter regions including central India have experienced an increase in dry spell (<2.5 mm/day) duration while drier regions of the north and northwest have experienced a decrease in dry spell duration (Sushama et al., 2014; Vinnarasi & Dhanya, 2016).

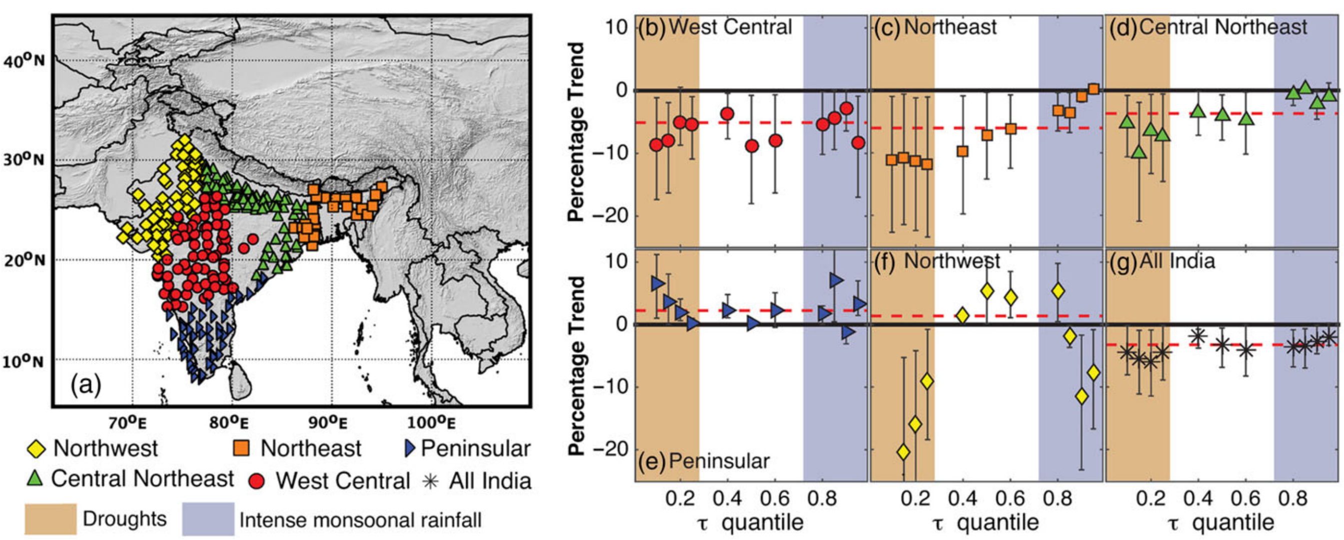

FIGURE 11 (a) Station locations used in the constructing of area-averaged time series of the IITM-HIMR dataset (1871–2012), for different homogeneous rainfall regions. Each color represents one particular region, whereas "All India data" includes all stations. IITM-HIMR data consist of area-averaged monthly rainfall amounts from 1871 to 2012. We have built the time series of annual ISM rainfall from these data by taking the average over JJAS months for each year. (b–g) Markers are the percentage trend in each quantile over the 142-year period; marker colors and shape correspond to different geographic regions and the error bars represent the 95% confidence intervals obtained using method of bootstrapping on residuals. Red dotted lines indicate the linear trend in the mean of the respective time series over the 142 years, independent of quantiles. Black heavy lines act as a reference for no change/no trend. Quantile values are indicated by τ (horizontal axes). Brown-shaded vertical bands highlight the lower quantiles, that is, trends for $\tau \in [0.1,0.3]$. Blue-shaded vertical bands highlight the higher quantiles, that is, trends for $\tau \in [0.75,0.95]$. Observe the low values of the quantile trends for $\tau \in [0.1,0.3]$ for west central, central northeast, northeast, northwest, and All India indicating intensification of droughts in these regions (Reprinted with permission from Malik et al. (2016). Copyright American Geophysical Union)

Contrastingly, changes in wetter rainfall events are relatively less widespread and the main significant changes include an increase in the magnitude of moderate–heavy rainfall events (75th–95th percentile) over peninsular India and a decline over the northwest and west central regions (Malik et al., 2016). These results are consistent with earlier work identifying declining trends in moderate–heavy rainfall events (<95th percentile) across most regions. However, there is strong agreement that extreme heavy events (>95th percentile) are increasing in intensity and/or frequency across much of northwestern, western-central, northeastern, and peninsular India but decreasing over eastern-central and northern India (Bisht et al., 2018; Dash et al., 2009, 2011; Goswami, Venugopal, et al., 2006; C. K. B. Krishnamurthy et al., 2009; Malik et al., 2016; Mukherjee et al., 2018; Rajeevan et al., 2008; Sen Roy & Balling, 2004; Vittal et al., 2013). These increasing extremes are dominated by an increase in short duration (≤4 days) but intense (>99th percentile) rainfall spells (Dash et al., 2011; Vinnarasi & Dhanya, 2016) since longer duration events are decreasing.

Over all major river basins except the Ganges and the Brahmaputra, these changes correspond to an increase in the magnitude of intense rainfall (>95th percentile and daily maxima) in the latter part of the 20th century (Bisht et al., 2018; Deshpande et al., 2016). Although there are no significant changes in the magnitude or frequency of extreme rainfall in the Ganges basin, the area under extremes of this basin has increased along with increases in the Narmada–Tapi, and Godavari river basins in central and peninsular India (Deshpande et al., 2016). At finer spatial scales, trends are undoubtedly noisy and can differ from these regional and basin-scale trends due to the inherent spatial heterogeneity of rainfall across the geographically complex region. Further, Ghosh et al. (2012, 2016) have found contrasting trends in the spatial variability of mean and extremes (Figure 12). The spatial variability of extreme rainfall shows statistically significant increasing trends over All India and central India highlighting the potential influence of the rapidly changing landscape. Therefore, caution must be taken at deriving information from regional-scale analyses for planning and management at these finer spatial scales.

Several changes in the associated processes have been identified to explain changes in the characteristics of extreme precipitation. First, changes in MISO characteristics have been related to changes in active and break spell activity over central India (Sabeerali et al., 2014; C. Singh, 2013b). However, their influence on extreme rainfall trends in other parts has yet to be examined. Second, a number of studies using the IMD database of monsoon LPS have found a significant increase in the number of lows and decreases in the number of monsoon depressions and related these changes to increasing frequency and intensity of extremes over central India (Ajayamohan et al., 2010; Dash et al., 2007, 2009; Pai et al., 2016). Their contribution to extreme events in other subregions remains unknown. Further, while most of these studies depend on the Sikka (2006) archive, a recent investigation using other sources of data have questioned the existence of monsoon depressions trends

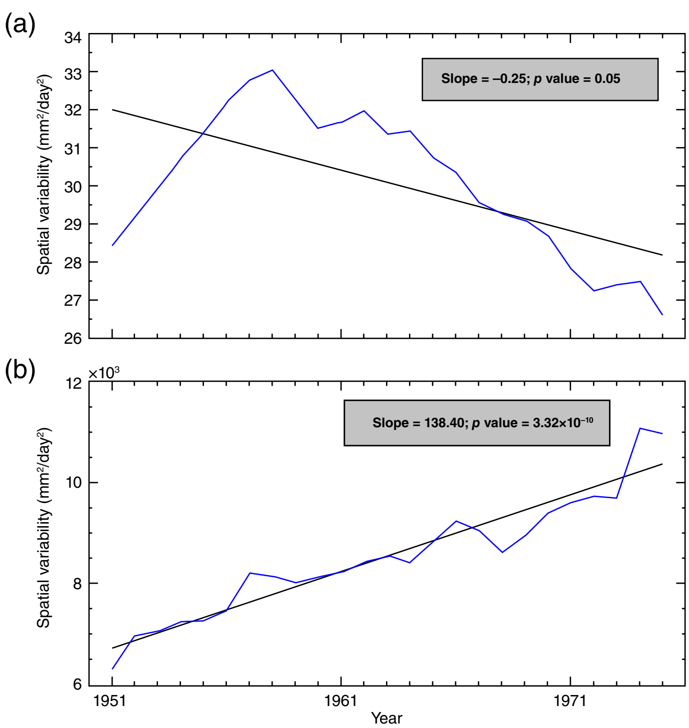

FIGURE 12 (a) Trend in the spatial variability of the mean monsoonal rainfall over the Indian region with a 30-year overlapping moving window. The blue line indicates the spatial variability of the mean rainfall, whereas the black solid line shows the fitted trend (linear) line. The mentioned trend value was computed with the modified Mann–Kendall approach. (b) Trend in the spatial variability of the extreme rainfall (corresponding to a 50-year return period) with the blue and black lines representing analyses similar to those shown in panel (a). The trends in both panels are significant at the 5% significance level (Reprinted with permission from Ghosh et al. (2016). Copyright Creative Commons Attribution License)

(Cohen & Boos, 2014), suggesting a fragile link to changing extremes. Third, increases in extreme precipitation in northern India have been linked to an increase in northward moisture convergence from the Arabian Sea via strengthened southerly winds and occurrence of transient westerly troughs (Priya et al., 2017). Fourth, increases in extreme precipitation in peninsular India have been partly related to rising dew point temperatures, a measure of humidity, in accordance with their positive (super Clausius–Clapeyron) scaling relationship (Mukherjee et al., 2018).

3.2.1 | Attribution of extreme events to historical forcings

Studies attributing the trends in extremes to anthropogenic activities are rather limited. A few recent studies have attributed the changes in extremes in certain regions to urbanization effects based on the reversal of long-term trends in the 1970s when urbanization intensified in India (Bisht et al., 2018; Vittal et al., 2013). Recently, Mukherjee et al. (2018) demonstrated the role of anthropogenic forcings in increasing the frequency of heavy precipitation events across parts of western-central and peninsular India relative to natural forcings using the CMIP5 suite of experiments, corroborating the results of Krishnan et al. (2016) using a single high-resolution model. Further, the dominant role of anthropogenic aerosol forcings has also been identified in several metrics of low and heavy precipitation extremes (Lin et al., 2018; D. Singh, Bollasina, et al., 2018; D. Singh, McDermid, et al., 2018).

However, these results contradict the findings of Mondal and Mujumdar (2015) who found no detectable fingerprint of anthropogenic activities. Such differences result from the use of different attribution techniques and inadequacies in the representation of precipitation and cloud microphysical processes in climate models, highlighting the existing uncertainties in attributing historical changes in extremes over India to anthropogenic activities. Changes in related processes such as increases in the number of monsoon lows but decreases in the number of depressions, slower propagation of MISO, and increasing mid-latitude/tropical interactions have yet to be related to anthropogenic forcings.

4 | OBSERVATIONAL UNCERTAINTIES

Simulations of South Asian monsoon by state-of-the-art General Circulation Models (GCM) are often criticized for having a large dry bias in monsoonal precipitation (Z. Wang, Li, & Yang, 2017), incorrect representation of trends (A. Saha, Ghosh, Sahana, & Rao, 2014) and very high intermodel uncertainty (Shashikanth et al., 2014). While there are several causes for these biases (refer Section 5), the most challenging task in the evaluation of the models is the handling of uncertainties in the observational data itself. Zhou, Yu, et al. (2008) and Zhou, Zhang, and Li (2008) demonstrate little difference between trends in hemispheric-scale monsoon characteristics derived from multiple datasets over the second half of the 20th century. However, uncertainties between various datasets are amplified at the regional scale, with substantial differences in the magnitude and significance of trends in precipitation over some monsoon regions (see fig. 3 and table 3 in L. Zhang & Zhou, 2011). Such dataset uncertainties have received little attention, and a majority of the studies of observed changes rely on the station-based IMD datasets (Table 1). However, several other long-term datasets have recently become available, including those that incorporate satellite data. Collins et al. (2013) evaluated the uncertainty between commonly used observational datasets, viz., APHRODITE (Yatagai et al., 2012), CMAP (Xie & Arkin, 1997), CRU (Harris, Jones, Osborn, & Lister, 2014), GPCP (Adler et al., 2003), IMD at different resolution (Rajeevan et al., 2008; Rajeevan, Bhate, Kale, & Lal, 2006), and TRMM (Huffman et al., 2007). They demonstrate that a majority of the CMIP5 models simulate climatological precipitation over South Asia within the bounds of this uncertainty among multiple observational datasets and hence, suggest that the models might be over-criticized.

The uncertainty in trends computed using multiple datasets is similarly large (Table 2). We illustrate these uncertainties by estimating trends over the Indian Institute of Tropical Meteorology (IITM) homogenous rainfall zones (refer Figure 11 for map of regions) during the overlapping period of data availability between different datasets that provide daily rainfall (Table 2). Even datasets based on rain-gauge networks alone and those developed from the same organization, IMD, at different spatial resolution show different trends for All India and the meteorological subdivisions based on homogenous rainfall zones (Parthasarathy et al., 1995). The uncertainty lies not only in the trend magnitudes but also in their signs. For instance, the IMD dataset at 1° spatial resolution shows a negative trend of ~1 mm/year for the All-India spatial average, while the IMD dataset at 0.25° spatial resolution shows no statistically significant trend. Similarly, the magnitude of the trend over the northeast Hilly region in the higher-resolution dataset is 50% larger than the magnitude in the coarser-resolution IMD dataset relative to the higher-resolution IMD dataset (Table 2). Consistent direction of trends (agreement between at least three datasets) is found over only four of the eight regions/subregions—All India, Central, Western, and Northeast regions. However, these long-term trends are uncertain over the other regions. Hence, grading the models based on simulating the negative trends (Sabeerali, Rao, Dhakate, Salunke, & Goswami, 2015; A. Saha et al., 2014) might not be appropriate without the considerations of such uncertainties. This uncertainty arises from the use of different numbers of station data in multiple products,

TABLE 2 Long-term trends (mm day^{-1} year^{-1}) in monsoon season rainfall (JJAS) for 1951–2004 from multiple observational datasets with data availability since the 1950s

Subregions	IMD (1° × 1°)	IMD (0.25° × 0.25°)	APHRODITE (0.25° × 0.25°)	IITM regional averages
All India	**−0.89**	0	**−1.11**	**−0.91**
West central	**−1.38**	**−1.68**	**−1.71**	**−2.30**
Peninsular	0.00	0.00	**−2.67**	0.00
Northwest	**−1.19**	**−1.14**	**−0.88**	**−0.98**
Central northeast	**1.12**	0.00	0.00	0.00
Northeast	**3.45**	**4.59**	0.00	**1.05**
Northeast hilly	**−11.90**	**−7.01**	0.00	**Not available**
Jammu and Kashmir	**0.00**	**1.83**	**−0.72**	**Not available**

Trends that are statistically significant at 0.05 level are denoted in bold. Insignificant trends are noted as zero; trends are computed for a generated time series with 11 years moving window to avoid interannual fluctuations. Subregions (shown in Figure 11) are based on the Indian Institute of Tropical Meteorology (IITM) homogenous zones (Parthasarathy, Munot, & Kothawale, 1995). Gray shading indicates agreement in sign between at least three datasets.

inconsistencies in the records across time, and different interpolation methodologies, and must be considered for model evaluation and evaluation of historical climate change across the subcontinent.

Physical processes associated with monsoon and its changing patterns are characterized using variables from reanalysis datasets, which also tend to substantially differ from each other (e.g., Annamalai, Slingo, Sperber, & Hodges, 1999; Misra, Pantina, Chan, & DiNapoli, 2012; Shah & Mishra, 2014). The climatological patterns of temperature, precipitable water, circulation, surface fluxes, and evaporation associated with intraseasonal and interannual monsoon activity show substantial differences over the Indian landmass between datasets (Annamalai et al., 1999; Misra et al., 2012; Shah & Mishra, 2014). As an example of their effects, the uncertainties in downscaled precipitation over India arising from the use of environmental variables from different reanalysis datasets are found to be of similar magnitudes to the uncertainties arising from the use of multiple GCMs in climate change impacts assessment (Kannan, Ghosh, Mishra, & Salvi, 2014). These uncertainties gets magnified at a regional scale (Sebastian, Pathak, & Ghosh, 2016) for the estimated precipitation and evapotranspiration from reanalyses as compared to the divergence of atmospheric moisture flux computed over South Asian region. This is because of the differences in closure terms (error) of the atmospheric water budget as computed for different reanalysis. Explanation of changing patterns of monsoon characteristics, therefore, needs the description of processes from multiple reanalyses.

4.1 | Comparison of climatological precipitation patterns across datasets

To further highlight this observational uncertainty, we compare commonly used precipitation characteristics across five datasets that cover the South Asian domain and have data availability for at least 25 years—IMD (1° and 0.25°), APHRODITE (0.25°), Climate Prediction Centre (CPC) data (0.5°) and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data (0.05°). We examine the climatology and trends of 7 metrics that capture the mean and extremes of the distribution (Figures 13 and 14)—seasonal total, dry day (DD) frequency, 95th percentile rainfall magnitude, total (TOT) extreme precipitation quantified as the precipitation amount greater than the 95th percentile (TOT > 95), 5th percentile, and total low rainfall quantified as the total rainfall amount less than the 5th percentile (TOT < 5). The spatial patterns of seasonal rainfall are more or less consistent across all the data products; although APHRODITE and CPC show slight underestimation over the Himalayan foothills and central India compared to other datasets. This is probably associated with lower values of extreme rainfall in these datasets. Similar discrepancies between APHRODITE and CHIRPS monsoon season precipitation are also discussed in Aadhar and Mishra (2017). The DD frequency is also similar across all the datasets, with a relatively dry northwestern and peninsular India. However, their frequency along the Western Ghats is overestimated in CHIRPS. Although the overall spatial pattern remains consistent same across all datasets, the 95th percentile values of rainfall showing average extreme conditions are lower for APHRODITE, particularly over central India, whereas the other datasets show similar magnitude. In addition, the 5th percentile magnitude and total amount of low rainfall in APHRODITE is higher than that of other datasets over the Western Ghats and northeast India.

4.2 | Comparison of historical trends across datasets

Changing patterns of the Indian monsoon have been a major research area of tropical meteorology in recent years and there exists large disagreement among different studies. The Indian monsoon underwent oscillating changes at multidecadal scales since 1871, which has been reported in the literature (Goswami, Madhusoodanan, Neema, & Sengupta, 2006; Kodra, Ghosh, & Ganguly, 2012). The overall declining trend of summer monsoon rainfall concurrent with an increasing trend of extremes over central India, the core region of maximum convergence, is one of the most widely studied changes (e.g., Ajayamohan et al.,

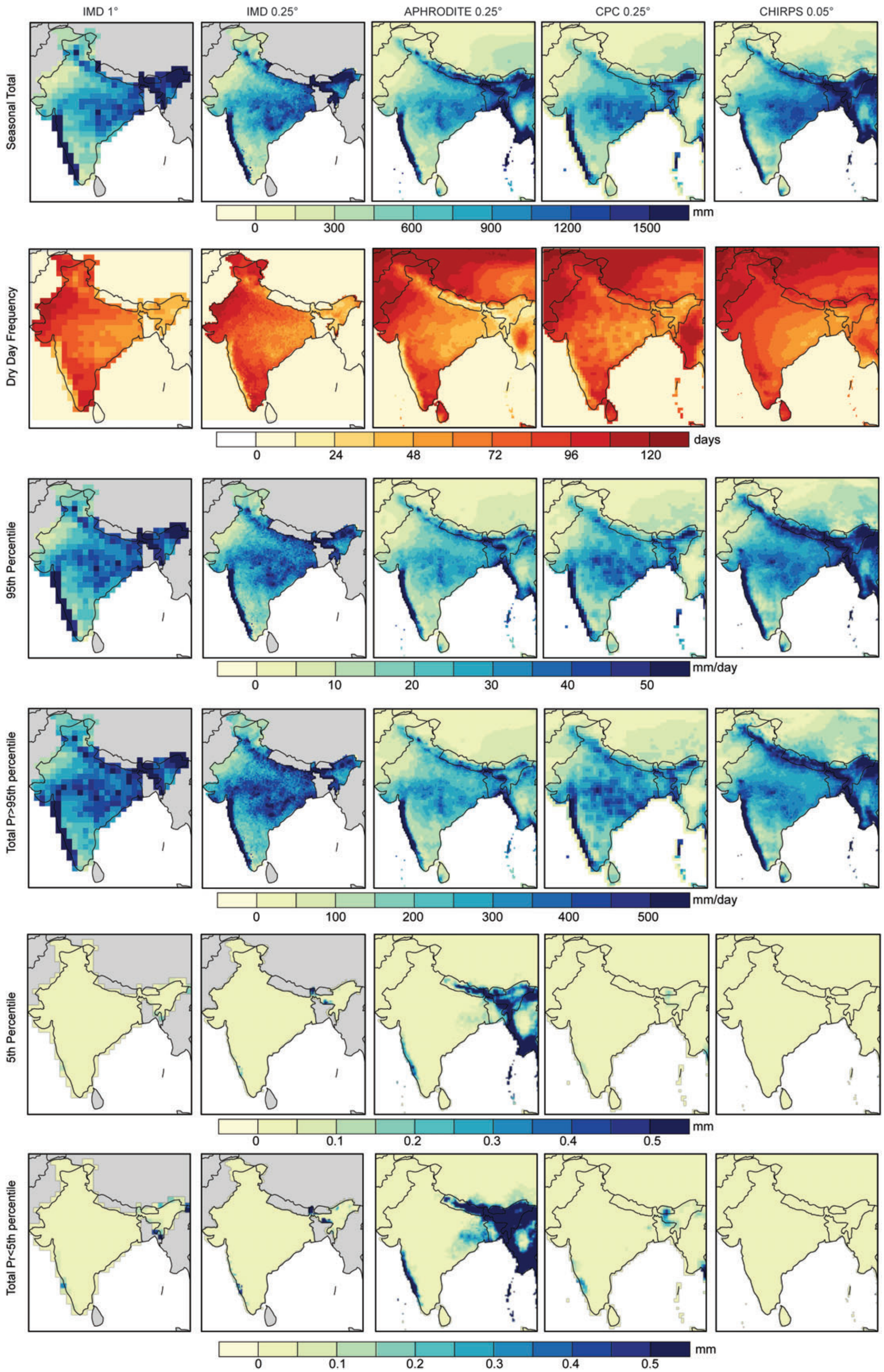

FIGURE 13 Comparison of the climatological patterns of different rainfall characteristics from five datasets (IMD: 1° (1951–2013), IMD: 0.25° (1901–2015), APHRODITE: −0.25° (1951–2015), CPC: −0.5° (1979–present), CHIRPS: 0.05° (1981–present)). The climatology is calculated over 1981–2007
Note: Depiction of political boundaries in these maps may not be authoritative/accurate.

2010; Goswami, Venugopal, et al., 2006; Karmakar et al., 2017; C. K. B. Krishnamurthy et al., 2009; Pai et al., 2016; Rajeevan et al., 2006, 2010; Roxy et al., 2017; Sagar et al., 2017; C. Singh, 2013a; D. Singh, Tsiang, et al., 2014). However; there exist inconsistencies across different dataset in computing the trends during the last few decades, particularly on sub-regional scales.

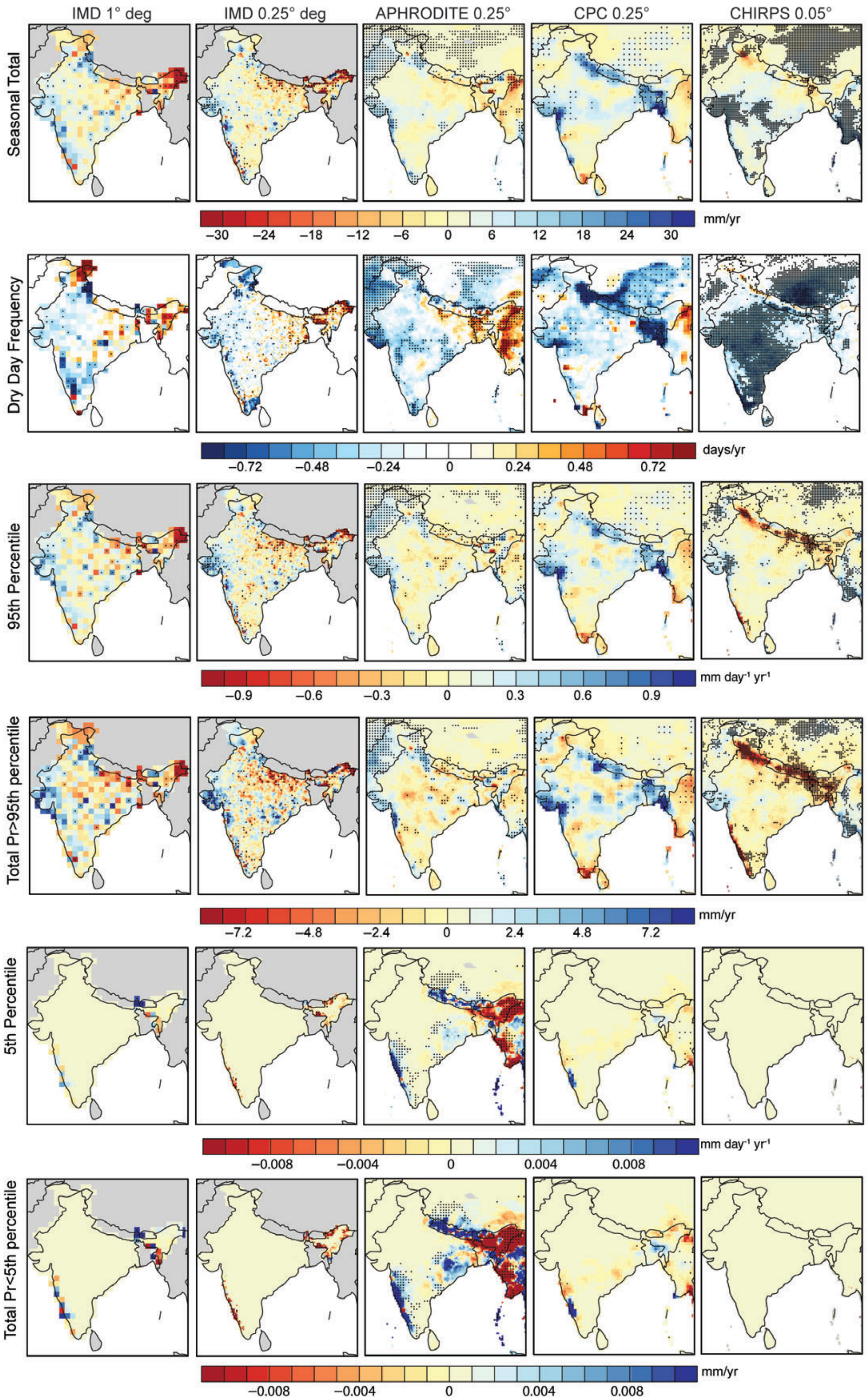

FIGURE 14 Same as in Figure 13 but for linear trends from 1981 to 2013. Gray dots indicate significance of trends at the 5% level
Note: Depiction of political boundaries in these maps may not be authoritative/accurate.

Figure 14 presents the spatial patterns of trends over 1981–2013 for seven precipitation metrics. This period corresponds to the common period of data availability from all five datasets. For seasonal total, there is consistency across datasets in the declining trend over central and eastern-central India and the increasing trend over the northern parts of western-peninsular

India. However, there are inconsistent trends over northeast India, where the IMD 1° dataset shows a strong drying trend that is not visible in other products; over northern India, where CHIRPS shows a strong drying trend while other datasets show opposite or no trends; western-coastal India, where IMD datasets show diverging trends on the windward and leeward side of the Western Ghats that are not captured in other datasets; and peninsular India, where only the IMD 1° and CHIRPS show widespread wetting trends. Further, the cause of uncertainties in the ALL-India rainfall can be understood from the discrepancies in subregional trends. For instance, the declining trend over the densely populated and heavily irrigated Ganges and Brahmaputra Basins, the main contributors to the negative trend in the IMD 1° dataset, has mixed trends in other datasets and significant spatial variability. This spatial variability also points to the importance of assessing subregional changing patterns of the monsoon that might be associated with heterogenous forcings.

For the trends in DD frequency, large uncertainty is observed across the different datasets. IMD and APHRODITE, both at a spatial resolution of 0.25°, have contrasting trends over central India. High inconsistency exists between the two IMD datasets at different resolutions. The IMD 1° shows a trend toward fewer DD, consistent with CHIRPS and CPC, whereas the IMD 0.25° largely shows a trend toward more DD. Another interesting feature is the decreasing trends in 95th percentile that generally follow the patterns of seasonal total but are more consistent across different data products, with the exception of more widespread declines over northern India in CHIRPS. Over parts of central India, opposite trends are observed in the trend of TOT >95 relative to the 95th percentile magnitude in the IMD and CPC datasets. These different trends in the 95th percentile magnitude and TOT >95 are likely associated with the contrasting trend of rainfall quantiles and occurrences and needs careful attention, especially in the design of hydrologic systems that depends on the characteristics of extreme rainfall, such as intensity, duration, and frequency. Hence, contrasting changes in different characteristics, if they exist, need to be addressed toward flood adaptation and management. Low rainfall characteristics remain almost similar across all datasets with negligible trends except in APHRODITE, which also shows substantially different climatologies (Figure 13). Addressing such uncertainties across different datasets is a challenging task, specifically when the station level data are not available, but has major implications for societal systems and evaluation of climate models.

5 | CHALLENGES IN ATTRIBUTING CHANGES IN THE SOUTH ASIAN SUMMER MONSOON

Attributing observed changes to anthropogenic activities and studying the influence of external forcings or internal variability requires the use of climate models. However, accurate simulations of the South Asia summer monsoon have been a persistent challenge. The lack of ability of the major global climate models included in CMIP5 (Taylor, Stouffer, & Meehl, 2012) to simulate the South Asian monsoon, along with their coarse resolutions, make them unsuitable for studies on impacts assessment in the region. We discuss the main biases in seasonal drivers and subseasonal processes in global climate models, and factors contributing to these biases in the following sections. Recent efforts to reduce these biases have included various approaches to high-resolution modeling. We also discuss the improvements from such high-resolution modeling efforts.

5.1 | Representation of precipitation processes in global climate models

Only a small fraction of the CMIP5 multimodel ensemble can simulate the spatial and temporal features of summer monsoon precipitation, LPS activity and subseasonal processes and dynamics of the summer monsoon (e.g., Ashfaq et al., 2017; Menon, Levermann, & Schewe, 2013; Mishra et al., 2014; Praveen, Sandeep, & Ajayamohan, 2015; Ramesh & Goswami, 2014; Sabeerali et al., 2014; Sperber et al., 2013). Ashfaq et al. (2017) provide a comprehensive analysis of the various biases in monsoon season onset, temperature, precipitation maxima, and circulation characteristics in the CMIP5 models. Their analysis shows that only about one-third of the models are able to simulate the correct timing of the precipitation maxima and the seasonal precipitation magnitude to within 25% of the observed values. Even fewer are able to represent the patterns of subseasonal variability (Sharmila, Joseph, Sahai, Abhilash, & Chattopadhyay, 2015).

One contributing factor is the challenge of representing the region's complex topography, which is crucial in shaping the monsoon characteristics (e.g., Boos & Kuang, 2010; Wu et al., 2012). Previous global climate assessments such as the CMIP5 include models at coarse resolutions that do not fully represent the region's topographic features, the associated atmospheric heating over the Himalayas, and the meridional thermal gradients, contributing to their inability to accurately represent the monsoon circulation (Ashfaq et al., 2017). Inaccuracies in representing the tropospheric thermal gradients reflect in the location of the monsoon trough, and the strength of the upper- and lower-level winds and, therefore, the wind shear. These biases consequently affect the location of the precipitation maxima and the strength, propagation and genesis of the monsoon low-pressure systems (Ashfaq et al., 2017; Praveen et al., 2015).

In addition to orography, several other biases and unrepresented processes contribute to the overall biases in seasonal and subseasonal precipitation characteristics. Biases in SSTs, potentially related to biases in the large-scale circulation (Sandeep &

Ajayamohan, 2014), can also influence the tropospheric thermal gradients that shape the monsoon. A recent analysis by B. Wang, Lee, et al. (2015) and B. Wang, Xiang, et al. (2015) demonstrates that the state-of-the-art numerical models fail to accurately represent the warming trend in the Indo-Pacific region, a major reason for the monsoon seasonal prediction skills to lessen in the recent decades and for the failure of these models in simulating the post-1950 decreasing trend of monsoon rainfall (A. Saha et al., 2014). Moisture from oceanic sources, mainly the Indian Ocean, that substantially contribute to early season precipitation is also affected by these biases (Ashfaq et al., 2017; Mei et al., 2015). Reduced precipitable water availability due to early season cold SST biases in models, reduces the convergence of moisture over land and therefore, results in a weaker monsoon (Levine, Turner, Marathayil, & Martin, 2013). Such early-season biases can propagate through the remaining season because of its effects on temperature, which in turn influence monsoon onset and strength (Ashfaq et al., 2017).

Since the monsoon is a land–atmosphere–ocean coupled system, lack of representation of the coupling processes or biases in the strength of the coupling also influence the monsoon. The accurate representation of convection over the equatorial Indian Ocean in models, particularly in the pre-monsoon season, is closely related to the timing and magnitude of monsoon precipitation through its influence on early season SST (Hagos, Leung, Ashfaq, & Balaguru, 2018). Weaker atmosphere–ocean interactions over the Indian Ocean, Arabian Sea, and Bay of Bengal in the models affect moisture availability, the structure of LPS and their contribution to total precipitation (Praveen et al., 2015). Poor atmosphere–ocean interactions over the equatorial Indian Ocean also influence the characteristics of the northward and northwestward propagating modes of variability. Only ~5 of 32 models that were evaluated by Sabeerali et al. (2013) were able to reasonably represent the characteristics of observed precipitation variance, which were also the few to capture the evolution of these propagating modes due to an accurate representation of the relationship of intraseasonal SST variability and convection.

Another important coupling in the monsoon system is that of the land–atmosphere that defines the sensitivity of precipitation to soil moisture conditions (e.g., Dirmeyer, 2011; Douville, Chauvin, & Broqua, 2001; Koster et al., 2004). The strength of these feedbacks affects local moisture recycling, which is a major source (>30%) of mid- to late-season precipitation (Mei et al., 2015; Pathak et al., 2014). These feedbacks are underrepresented in most global climate models, contributing to precipitation biases (Ashfaq et al., 2017). Biases in these land–atmosphere feedbacks can also influence the propagation of subseasonal variability modes that are associated with active and break spells (Sabeerali et al., 2013). Due to the strong land–atmosphere coupling in the region, soil moisture biases, particularly in the monsoon trough, also have an influence on the formation and propagation of monsoon LPS (Hunt & Turner, 2017; Kishtawal et al., 2013). Wet soil moisture conditions in the region substantially increase the likelihood of formation of LPS relative to dry soil conditions (Kishtawal et al., 2013), and favor greater inland penetration by enhancing lower-tropospheric moisture that enhances convective activity (Hunt & Turner, 2017; Kishtawal et al., 2013).

Biases in soil moisture conditions can, therefore, influence the spatial and temporal features of simulated precipitation. Land-surface modifications such as agricultural expansion, irrigation, and urbanization, influence local soil moisture, and their incomplete representation in models will contribute to the biases in simulating precipitation. While land-surface representations of agriculture are included in most models, irrigation, which is increasingly being recognized as a global climate forcing, is not (e.g., Cook et al., 2015; Puma & Cook, 2010; Sacks et al., 2009; Shukla et al., 2014). There is also much variation among climate models in their inclusion and representation of irrigation as part of the suite of historical global climate forcings (Cook, Shukla, Puma, & Nazarenko, 2014; McDermid et al., 2017), and most modeling groups participating in the CMIP6 do not include irrigation as part of the historical forcing set. Of the groups that do include irrigation, several approaches exist to determine regional irrigation water requirements and abstraction from available resources (Nazemi & Wheater, 2015a; Pokhrel et al., 2015). Some use a "soil moisture deficit" approach that maintains soil moisture at or near field capacity by adding surface water (e.g., from an infinite source) (Nazemi & Wheater, 2015b; Pokhrel, Hanasaki, Wada, & Kim, 2016; Saeed, Hagemann, & Jacob, 2009; Tuinenburg, Hutjes, Stacke, Wiltshire, & Lucas-Picher, 2014). Other approaches combine maps of irrigated areas in conjunction with offline hydrological modeling to create monthly irrigation time series for the historical record (Döll & Siebert, 2002; Freydank & Siebert, 2008; Wada, Wisser, & Bierkens, 2014). Still other representations consider the impact of CO_2 changes on crop conductance and evapotranspiration, which can substantially alter latent heat fluxes (Bondeau et al., 2007), or more crop-specific approaches due to the wide variation of irrigation demand (Ozdogan, Rodell, Kato Beaudoing, & Toll, 2010).

Therefore, simplified representation of the region's complex topography and land-surface conditions due to the coarse model resolution, incomplete representation of regional forcings, and biases in the coupling between various earth system components, are among the factors contributing to the lack of model ability to represent monsoon characteristics. Given these biases in factors that influence subseasonal processes of variability, it is no surprise that less than half of the CMIP5 models have overall (area-averaged) biases lower than 20% in representing summer monsoon precipitation extremes over India (Mishra et al., 2014).

5.2 | Potential for bias reduction from high-resolution coupled modeling

Evaluation of the effects of model resolution on the accuracy of representation of monsoon processes is not feasible with the CMIP5 suite for reasons including their limited range of resolutions and varying complexities. A comparison of the same model at different resolutions suggests that higher resolution modeling offers some potential for improvements in simulating monsoon processes along with improvements in land–atmosphere interactions (e.g., Ashfaq et al., 2017; Johnson et al., 2016). Efforts to improve the representation of fine-scale processes include nested dynamical downscaling (e.g., Ashfaq et al., 2009; Giorgi & Gutowski, 2015; Stowasser, Annamalai, & Hafner, 2009), statistical downscaling (Shashikanth et al., 2014), variable resolution modeling (Sabin et al., 2013), and high-resolution global climate modeling (e.g., Johnson et al., 2016; Rajendran & Kitoh, 2008; Sabin et al., 2013; Sandeep, Ajayamohan, Boos, Sabin, & Praveen, 2018). The major limitation of most of these studies is the lack of model intercomparison for assessing uncertainties. To overcome this limitation, the multimodel dynamical downscaling initiative known as Coordinated Regional Downscaling Experiments (CORDEX) included simulations with several regional models with boundary conditions from CMIP5 models. The CORDEX suite provides the opportunity to evaluate the robustness of improvements across multiple models. After their release, the CORDEX simulations were used extensively for impact assessment studies, specifically in the hydrologic sector, sometimes without a proper assessment on the added value by the regional models.

S. Singh, Ghosh, Sahana, Vittal, and Karmakar (2017) provide a comprehensive evaluation of the CORDEX simulations for Indian monsoon characteristics, including, northward and eastward propagation, onset, seasonal rainfall patterns, intraseasonal oscillations, spatial variability, and patterns of extremes. These simulations generally improve the representation of the mean and variability of precipitation over elevated topography (Himalayas and the Western Ghats) relative to the coarser resolution models (Mishra et al., 2014; Varikoden et al., 2018). However, there is no systematic improvement relative to the parent global climate models, and in some cases, a deterioration of the representation of the climatological spatial and temporal features of monsoonal precipitation including active/break spells and extremes, or the related subseasonal processes over the rest of South Asia relative to the global climate models (e.g., Choudhary, Dimri, & Maharana, 2017; Mishra et al., 2014; S. Singh et al., 2017). In the Himalayan regions, the CORDEX simulations also have a cold, dry bias along the Himalayan foothills, and wet bias at high elevations, overestimate warming by threefold, and fail to represent historical precipitation trends (Ghimire, Choudhary, & Dimri, 2018; Mishra, 2015).

These studies suggest that factors other than the improved spatial resolution such as parameterizations and boundary conditions are relevant (Giorgi & Gutowski, 2015; Mishra et al., 2014). S. Singh et al. (2017) attributes the poor performance of the CORDEX simulations to poor boundary conditions from GCMs and the lack of ocean–atmosphere coupling in the nested regional modeling. Biases in the land–atmosphere processes might play a significant role. The Climate Forecast System 2 (CFSv2) recently adopted by the Government of India as their operational monsoon model shows very large dry biases over the Indian region, particularly over the agriculture intensive and populated Indo-Gangetic basin. Sahana, Pathak, Roxy, and Ghosh (2018) attribute this dry bias to the misrepresentation of moisture transport guided by energy cycle and land–ocean thermal contrast and low recycled precipitation during the end of monsoon, which is a common issue across global climate models. Devanand, Roxy, and Ghosh (2018) demonstrated reductions in biases over northern and central India with the inclusion of high-resolution land-surface models (at a horizontal resolution 36 km instead of the original 100 km) coupled to the regional simulations nested within CFSv2, due to two main improvements. First, a better representation of the Himalayan orography prevented cold air intrusion from the midlatitudes over the Indian land mass, reducing cold biases and improving the representation of the land–sea thermal contrast. Second, the coupling improved the accuracy of local recycling over the Ganges Basin and, therefore, late-season precipitation. These further confirm the importance of topography and land–atmosphere coupling in simulating the monsoon.

However, nested regional climate simulations from CORDEX have several other limitations such as sensitivity to boundary conditions, resolution, and domain, limited representation of sources of uncertainty, and lack of interaction between processes across scales (Giorgi & Gutowski, 2015; Hawkins & Sutton, 2011), that reduce their suitability for attribution and projections. Although computationally more expensive, the variable resolution or global high-resolution simulations provide a more suitable platform by overcoming some of the limitations of nested modeling. These studies show several improvements in the representation of processes associated with precipitation and its overall spatial characteristics, relative to the coarser resolution models (e.g., Karmacharya, New, Jones, & Levine, 2017; Kitoh, 2017; Krishnan et al., 2016; Rajendran & Kitoh, 2008; Sabin et al., 2013). While these simulations still do not explicitly resolve convection, they are able to reproduce observed large-scale and synoptic monsoon circulation features; orographic effects of the Himalayas, Western Ghats, and the East African Highlands; fine-scale temperature and moisture gradients; and other moist processes (Johnson et al., 2016; Sabin et al., 2013). Improvements in these features are effective in facilitating improvements in the seasonal cycle and spatial distribution of precipitation, active and break spell characteristics, and propagation, density and location of monsoon LPS (Johnson et al., 2016; Sabin et al., 2013).

6 | PROJECTIONS OF MONSOON MEAN, VARIABILITY, AND EXTREMES

Projections of the mean South Asian summer monsoon in response to enhanced GHG emissions from the recent Model Intercomparison Projects (MIPs) have been reviewed in Kitoh et al. (2013) and Kitoh (2017). We provide a brief summary of these projections here. There is widespread agreement among global climate models from both generations of MIPs that the South Asia monsoon will intensify by the end of the 21st century due to an increase in moisture convergence despite a weakening of the monsoon circulation (e.g., Chaturvedi, Joshi, Jayaraman, Bala, & Ravindranath, 2012; Mei et al., 2015; Ogata et al., 2014; Sooraj, Terray, & Mujumdar, 2015; Stowasser et al., 2009; Turner & Annamalai, 2012; Ueda, Iwai, Kuwako, & Hori, 2006; Lee & Wang, 2014). The increase in moisture convergence is primarily associated with enhanced atmospheric moisture content in response to projected warming of the remote Indian Ocean, the largest source of precipitation over India (Mei et al., 2015; Ueda et al., 2006). While these changes were believed to be monotonic, recent work has highlighted the potential for near-term weakening of monsoonal rains depending on the evolution of aerosol emissions (mainly sulfur dioxide) over Asia (Bartlett et al., 2018). This highlights the need for consideration of external drivers other than GHG in better quantifying the (un)certainty in near-term climate change over the region.

While the seasonal response of the monsoon to GHG enhancement in the 21st century has been extensively investigated, projections of extreme events are rather limited (Table 3). Consistent with observations (D. Singh, Tsiang, et al., 2014), a majority of models project an increase in daily variability during the monsoon season throughout the 21st century under the strongest emissions scenario—Representative Concentration Pathways 8.5 (Menon et al., 2013). Sharmila et al. (2015) suggest that this increase results from an increase in the intensity of heavy rainfall events (>40 mm/day), a decrease in low rainfall events (<10 mm/day), and fewer wet days (>0.1 mm/day) across much of India, which are broadly consistent with observations over certain subregions. The projected fewer wet days in a warmer climate are consistent with an earlier study that examined subseasonal extremes under doubled CO_2 concentrations (Turner & Slingo, 2009). In addition, increase in MISO variance in regions of strongest MISO activity, particularly over Bay of Bengal, central equatorial Indian Ocean, central India, and the northwest Pacific (Sabeerali et al., 2014) could contribute to the increase in rainfall variability in a warmer climate. However, the spatial pattern of increase in MISO variability varies considerably between models (Sharmila et al., 2015). Therefore, the factors contributing to enhancement in future daily variance still need to be investigated.

TABLE 3 Key findings from studies of projections of subseasonal extremes and their related processes

Reference	Scenario/model	Key findings
	Global climatic models	
W. Zhang, Zhou, Zou, Zhang, and Chen (2018)	CMIP5, RCP 4.5 and 8.5	Highest rates of increase in 5-day accumulated precipitation over South Asia relative to other monsoon regions (~7–10%/K) although differences between 1.5 and 2°C levels of warming are spatially variable
Mukherjee et al. (2018)	CMIP5, RCP8.5	Robust increases in exceedance of historical maxima in near, mid- and late-21st century, particularly over southern India
Sharmila et al. (2015)	CMIP5 subset (MIROC5, BNU-ESM, MPI-ESM-LR, and NorESM1-M)	Increase in intraseasonal variability, intensification of active and break spells, higher frequency of short duration active spells and short and extended breaks, amplification in magnitude of low-frequency mode
Sabeerali et al. (2014)	MPI_ESM-LR, RCP4.5	Increase in MISO variance over Bay of Bengal, western coastal, equatorial Indian Ocean, and to a lesser extent central India, decrease speed of northward propagation but increased amplitude
Menon et al. (2013)	CMIP5, RCP 8.5	Enhanced daily variability of All-India rainfall
Turner and Slingo (2009)	HadCM2, 2xCO_2	Fewer wet days and intensification of heavy rainfall, intensification of active and break spells without changes in duration or frequency
Mandke, Sahai, Shinde, Joseph, and Chattopadhyay (2007)	CMIP3	Increased duration, strengthening and expansion of break spells
	Regional/high resolution	
Sandeep et al. (2018)	HiRAM	Reduced synoptic activity, weakening and poleward LPS genesis, more genesis over land, increase in 95th percentile extremes in Indo-Gangetic Plains and southern India and decrease in central India
Shashikanth, Ghosh, Vittal, and Karmakar (2017)	Statistical downscaling of a few CMIP5 models (RCP 8.5)	Enhanced spatial variability, increase in average annual maxima over central India and fewer extremes in parts of the northeast
Krishnan et al. (2016)	LMDZ	Increase in frequency of heavy rainfall events (>100 mm/day) over central India
Ashfaq et al. (2009)	RegCM	Increased frequency of break spells, suppression of the dominant oscillatory mode of variability
Stowasser et al. (2009)	RegCM	Increase in number of monsoon depressions with speeds >15–20 m/s
K. K. Kumar et al. (2006)	PRECIS with HadCM3 and HadAM3 global models	Increase in 1–5-day precipitation maxima over western coastal and central India

Studies with a few global climate models suggest an intensification of active and break spells with enhanced GHG (Mandke et al., 2007; Sharmila et al., 2015; Turner & Slingo, 2009). However, changes in the frequency, duration, and extent are still uncertain. Some studies suggest an increase in occurrence of short duration active spells and break spells (Ashfaq et al., 2009; Sharmila et al., 2015) and increase in duration and spatial extent of break spells (Mandke et al., 2007). Other studies find no change in duration and frequency of active and/or break spells (Ashfaq et al., 2009; Turner & Slingo, 2009), possibly due to different approaches for defining these events but also due to lack of model agreement. These changes could be related to the amplification of the northward propagating mode of variability with warming (Sabeerali et al., 2014; Sharmila et al., 2015). However, using a regional climate model, Ashfaq et al. (2009) find a suppression of the dominant mode of variability. Therefore, the projections of the amplitude and propagation characteristics of the propagating modes are still uncertain.

Similarly, there are substantial discrepancies in the projections of extreme precipitation events between models. Statistically downscaled CMIP5 models project an increase in the intensity of precipitation maxima robustly over central India (Shashikanth et al., 2017), consistent with early studies (Rupa Kumar et al., 2006). Mukherjee et al. (2018) also find an increased frequency of exceedance of the historical maxima, mainly over Southern India among the "best" CMIP5 models with smaller changes over central India. In addition, accumulated 5-day precipitation increases robustly (low intermodel uncertainty) across India in the CMIP5 ensemble under future warming of 1.5–2°C (W. Zhang et al., 2018). Using a variable resolution model, Krishnan et al. (2016) find an increase in the frequency of heavy precipitation events (>100 m/day) over central India. Further, a recent investigation with a global high-resolution model (HiRAM) projects a weakening of the 95th percentile intensity over central India but increases over the Indo-Gangetic Plains and southern India related to reduced synoptic activity and genesis over the Bay of Bengal (Sandeep et al., 2018). Although these studies suggest consistent results for southern India, the findings for central India are inconsistent among studies. Therefore, while there are consistencies in multimodel ensembles for certain extreme precipitation characteristics such as accumulated 5-day precipitation, there are remaining uncertainties in understanding the response of other extreme precipitation characteristics, particularly over the core-monsoon region. At least some of these uncertainties are associated with different subsets of the CMIP ensembles or different climate models used in these analyses (Table 3).

Although there is substantial spatial variability in extremes in most subregions, some of the variations in projections are a result of the precise metric used (i.e., peak over threshold vs. block maxima or percentiles) (Shashikanth et al., 2017). Studies investigating the entire spectrum of the rainfall distribution are limited but could resolve some of these discrepancies. It is also noteworthy that the lack of agreement between simulated and observed trends, and large biases several processes make projections for this region highly uncertain (Sabeerali et al., 2015; Sharmila et al., 2015). Sharmila et al. (2015) demonstrate that only a small subset (=4) of models are able to capture the observed spatial and temporal features of subseasonal rainfall characteristics, severely limiting the scope for multimodel-based assessments.

7 | ROBUST FINDINGS, KEY ISSUES, AND OPPORTUNITIES

Reliable, consistent and timely rainfall during the summer monsoon season is critical for agricultural activities and water availability for the billions of people living in the Indian subcontinent. Therefore, rainfall variability during the monsoon season over various spatial scales can have enormous societal impacts. Since industrialization and agricultural activities intensified globally and locally, the summer monsoon has experienced several detectable changes in seasonal and subseasonal rainfall characteristics. Four main robust changes have emerged from recent studies. First, a long-term weakening of the large-scale monsoon circulation, decline in seasonal rainfall over the monsoon-core region and an increase in parts of western and peninsular India. Second, changes in the frequency, intensity, and duration of large-scale, low-frequency extremes known as active and break spells over central India. These include an increase in dry-spell frequency, increase in short duration wet-spell frequency, and increase in wet-spell intensity. Third, an increase in widespread extremely heavy precipitation events (>100–150 mm/day) across central India and increases in the intensity of intense (>95th percentile) precipitation events at finer scales across much of India except eastern-central India. Fourth, a reduction in duration of dry spells and intensification of wet spells over the western-northwestern parts of India. Understanding the drivers of these historical changes is imperative to better predicting the response of monsoonal rainfall to increasing anthropogenic activities and their impacts in the future.

Anthropogenic activities that result in aerosol emissions and land-cover/land-use change are particularly acute in this region to meet the growing needs of the region's population. The seasonal-scale monsoon weakening over the core region in the late 20th century has been attributed to anthropogenic forcing with a number of hypotheses about the individual drivers. A majority of studies using the CMIP5 suite of models agree on the role of anthropogenic aerosols in weakening the monsoonal rains (Bollasina et al., 2011; Guo et al., 2015; Ramanathan et al., 2005; Salzmann et al., 2014). However, recent studies highlight the potential for land-cover/land-use changes to have similar effects (Cook et al., 2015; Douglas et al., 2009; Niyogi et al., 2010; Paul et al., 2016). Other studies have also raised the idea that the Indian Ocean warming, largely associated with rising GHG, has contributed to the weakening of the circulation (Roxy et al., 2014, 2015). Historical changes have likely resulted from the interactions between these various forcings. Since these individual factors have changed simultaneously and have distinct technological controls, there is a need to distinguish their roles on these historical changes. To date, no study has considered the interactive effects of all forcings in driving the seasonal-scale rainfall changes. The existing attribution studies have three main issues: (a) they rely on models that do not accurately simulate the monsoon processes, teleconnections, and historical trends (Ashfaq et al., 2017), (b) they do not include all the major external forcings for this region, and (c) they do not consider the spatial footprint of these forcings.

Attributing historical changes to anthropogenic activities and making reliable projections require a consistent testbed of multimodel, multi-ensemble simulations that incorporates the extent of external atmospheric and land-surface forcings relevant for this region and simulates internal variability in seasonal and subseasonal processes. There is undoubtedly a need to prioritize the improvement of representation of monsoon processes in the global models, which will in part be addressed using the experiments planned within the GMMIP (Zhou et al., 2016) and the High-Resolution Model Intercomparison Project (HighResMIP; Haarsma et al., 2016). One major aim of GMMIP is to better understand the role of orography and resolution in simulating monsoon processes, toward which the HighResMIP would also provide valuable insights. Given the importance of fine-scale processes in the region, improvements in resolution of the global climate models for CMIP6 (Eyring et al., 2015) have the potential to improve the simulations of the monsoon. However, higher-resolution modeling studies suggest that these relatively coarse global climate models still might not provide a sufficient advance in the model representations of the monsoon. In addition, irrigation, a potentially substantial regional forcing (Cook et al., 2015; Shukla et al., 2014), was not part of the historical forcings for CMIP5 and are still not part of the main historical forcings that will be used in the Detection and Attribution MIP (DAMIP; Gillett et al., 2016), which might contribute to persistent biases in the region. For these reasons, there is still limited potential for fully attributing historical climatic changes over South Asia.

While seasonal-scale changes have been the subject of several attribution studies, the attribution of subseasonal rainfall characteristics remains largely unexplored. Subseasonal rainfall extremes result from various processes acting on a range of spatial and temporal scales (Figure 15). Understanding and attributing historical changes on various timescales in this region will benefit from a holistic approach of examining the various physical processes that shape the spatiotemporal distribution of rainfall including the large- and fine-scale circulation features, thermal and moisture gradients, propagating modes of intraseasonal variability, LPS, and tropical–midlatitude interactions that we discuss in Section 2. Figure 15 summarizes some of the pathways by which various forcings might influence these processes, some of which have been identified in the literature or inferred from the ingredients of the driving physical processes. Systematically testing these linkages and studying the role of anthropogenic forcings in their historical evolution will provide a process-based, physically grounded understanding of the region's complex climate changes.

Another dimension that needs urgent consideration is the spatial scale of attribution. While most attribution research focuses on the overall regional-scale average rainfall, the spatial variation in monsoon rainfall characteristics and trends highlights the importance of understanding the drivers of spatial variability. Investigating the spatial patterns of rainfall changes

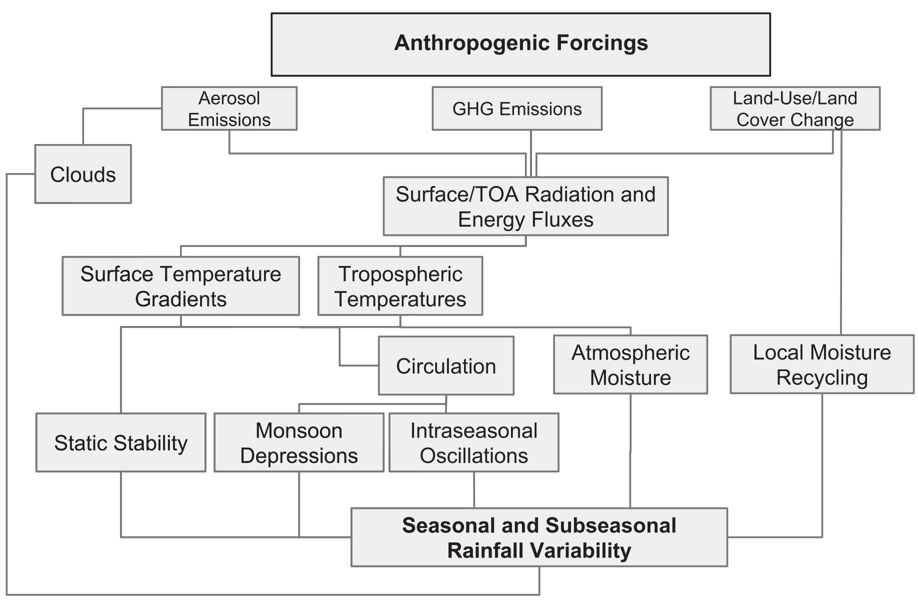

FIGURE 15 Summary of established and potential pathways by which anthropogenic forcings can influence seasonal and subseasonal rainfall characteristics

could yield insights into the relative roles of different forcings at subregional scales. Although larger internal variability at finer scales could influence the detectability of changes, local drivers such as urbanization and LULCCs and their interactions with local orography (Paul et al., 2018; Shastri, Paul, Ghosh, & Karmakar, 2015) could be more important than other external drivers at these scales.

Finally, it is imperative to take into account observational uncertainties in evaluating models and quantifying historical changes (Collins et al., 2013; Lin & Huybers, 2018). While multiple observational datasets agree on the direction of changes in some characteristics, there are still considerable uncertainties between datasets in the characteristics of low and heavy rainfall events and these discrepancies are larger in some subregions such as northern India and parts of peninsular India. Resolving such discrepancies requires the availability of the underlying, raw IMD rain-gauge data from which these datasets are derived and a comparison of the interpolation approaches with identical underlying data. Although satellite data is spatially uniform and not affected by changes in the observing system, they are calibrated based on rain-gauge data. Therefore, improvements in the rain-gauge network, particularly enhanced density of the observational network in areas with high spatial variability and complex topography (such as the Himalayas and Western Ghats), will improve the accuracy of satellite-derived data and facilitate better records for studying long-term climate change. There are also uncertainties in the changes in governing processes such as in the trends in monsoon lows and depressions (Cohen & Boos, 2014). Reducing such uncertainties requires refining algorithms for detection and tracking such systems and comparing their derived characteristics between multiple existing data products. The quantification and resolution of such uncertainties in various physical processes from multiple data sources is therefore required and should be prioritized. Further, surface-based measurements, particularly at the interface of the climate system elements, and upper-air observations, will provide valuable data for studying important monsoonal processes. Together, an improved network of land, ocean, and air measurements will facilitate modeling efforts to improve the simulation of these processes and examine the influence of various forcings.

A better understanding of the causes of historical changes will be critical for informing strategies for adaptation and climate risk mitigation. Recent national initiatives to interlink the rivers of India are being considered; however, these changing rainfall patterns highlight the need for detailed hydrometeorological investigations for planning for such water transfer schemes and examining their potentially severe ecological implications and climatic feedbacks. Historically, drivers other than GHG have had a dominant influence on rainfall characteristics in the region and might continue to have an influence in the near-term. Planning for future changes in a GHG-dominated world based on historical changes, therefore, might inevitably result in less than optimal strategies and potentially unintended consequences. The severe impacts of rainfall extremes on billions of lives and large uncertainties that make climate risk assessment challenging, highlight the urgency for efforts toward better understanding and predicting the monsoons.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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