6 Droughts and Floods

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Key Messages

- The frequency and spatial extent of droughts over India have increased significantly during 1951–2015. An increase in drought severity is observed mainly over the central parts of India, including parts of Indo-Gangetic Plains (*high confidence*). These changes are consistent with the observed decline in the mean summer monsoon rainfall.
- Increased frequency of localized heavy rainfall on sub-daily and daily timescales has enhanced flood risk over India (*high confidence*). Increased frequency and impacts of floods are also on the rise in urban areas.
- Climate model projections indicate an increase in frequency, spatial extent and severity of droughts over India during the twenty-first century (*medium confidence*), while flood propensity is projected to increase over the major Himalayan river basins (e.g. Indus, Ganga and Brahmaputra) (*high confidence*).

6.1 Introduction

Hydroclimatic extremes such as droughts and floods are inherent aspects of the monsoonal landscape. Droughts over India are typically associated with prolonged periods of abnormally low monsoon rainfall that can last over a season or longer and extend over large spatial scales across the country (Sikka 1999). The slow evolutionary nature of monsoon droughts and enhanced surface dryness exert significant impacts on water availability, agriculture and socio-economic activities over India (Bhalme and Mooley 1980; Swaminathan 1987; Sikka 1999; Gadgil and Gadgil 2006; Asoka et al. 2017; Pai et al. 2017). Compared to droughts, floods typically occur over smaller locales in association with heavy precipitation and stream flows on shorter timescales (Dhar and Nandargi 2003; Kale 2003, 2012; Mishra et al. 2012a; Sharma et al. 2018). Every year, nearly 8 million hectares of the land area is affected by floods over India (Ray et al. 2019). Droughts and floods across India are known to have complex linkages with the space-time distribution of monsoon rainfall and socio-economic demand (Sikka 1999; see Chap. 3 for details).

Observations for the recent decades, from post-1950, clearly show a significant rising trend in frequency and intensity of both heavy rain events as well as consecutive dry days (CDD). These trends are particularly notable over central parts of the Indian subcontinent during the south-west (SW) monsoon and southern peninsular India during the north-east (NE) monsoon (see Chap. 3 for details). The observed rainfall data indicates that there have been 22 monsoon droughts since 1901 (Fig. 6.1a). Interestingly, studies have shown that drought, as well as flood frequency, have increased since the 1950s. India experienced an increase in intensity and percentage of area affected by moderate droughts along with frequent occurrence of multi-year droughts during recent decades (Niranjan Kumar et al. 2013; Mallya et al. 2016). In this chapter, an assessment based on observational evidences from instrumental, palaeoclimatic records and likely future changes from climate model projections on droughts and floods across India is presented.

6.2 Observed Variability of Droughts

Droughts are broadly categorized into four major classes: (1) meteorological drought, as a deficit in precipitation; (2) hydrological drought, as a deficit in streamflow, groundwater level or water storage; (3) agricultural drought, as a deficit in soil moisture; and (4) socio-economic drought, incorporating water supply and demand (Wilhite and Glantz 1985; Anderson et al. 2011). All these four categories of droughts usually initiate with a deficiency in precipitation. Some of the prominent drought indices for the categorization of meteorological droughts in India are summarized in Table 6.1. Out of these indices, standardized precipitation evapotranspiration index (SPEI) has been used for analysing drought trends and variability over India (Mallya et al. 2016). The SPEI has also been used for evaluating reanalysis products during drought monsoon years (Shah and Mishra 2014); for drought monitoring (Aadhar and Mishra 2017), and adopted by the India Meteorology Department (IMD) for the operational purpose (http://imdpune.gov.in/hydrology/hydrg_index.html). As SPEI index is considered better suited to explore the effects of warming temperatures on droughts (Table 6.1; also Box 6.1), the present chapter uses SPEI for assessing the variability of droughts over India.

Box 6.1: Details of SPEI drought indicator

SPEI was computed at horizontal grid spacing of 0.5° longitude x 0.5° latitude, using monthly rainfall (0.25° x 0.25°) from IMD and potential evapotranspiration (PET; 0.5° x 0.5°) from the Climate Research Unit (CRU) for the period 1901-2016, with respect to the base period 1951–2000. PET was calculated from a variant of the Penman–Monteith formula (Sheffield et al. 2012) recommended by the United Nations Food

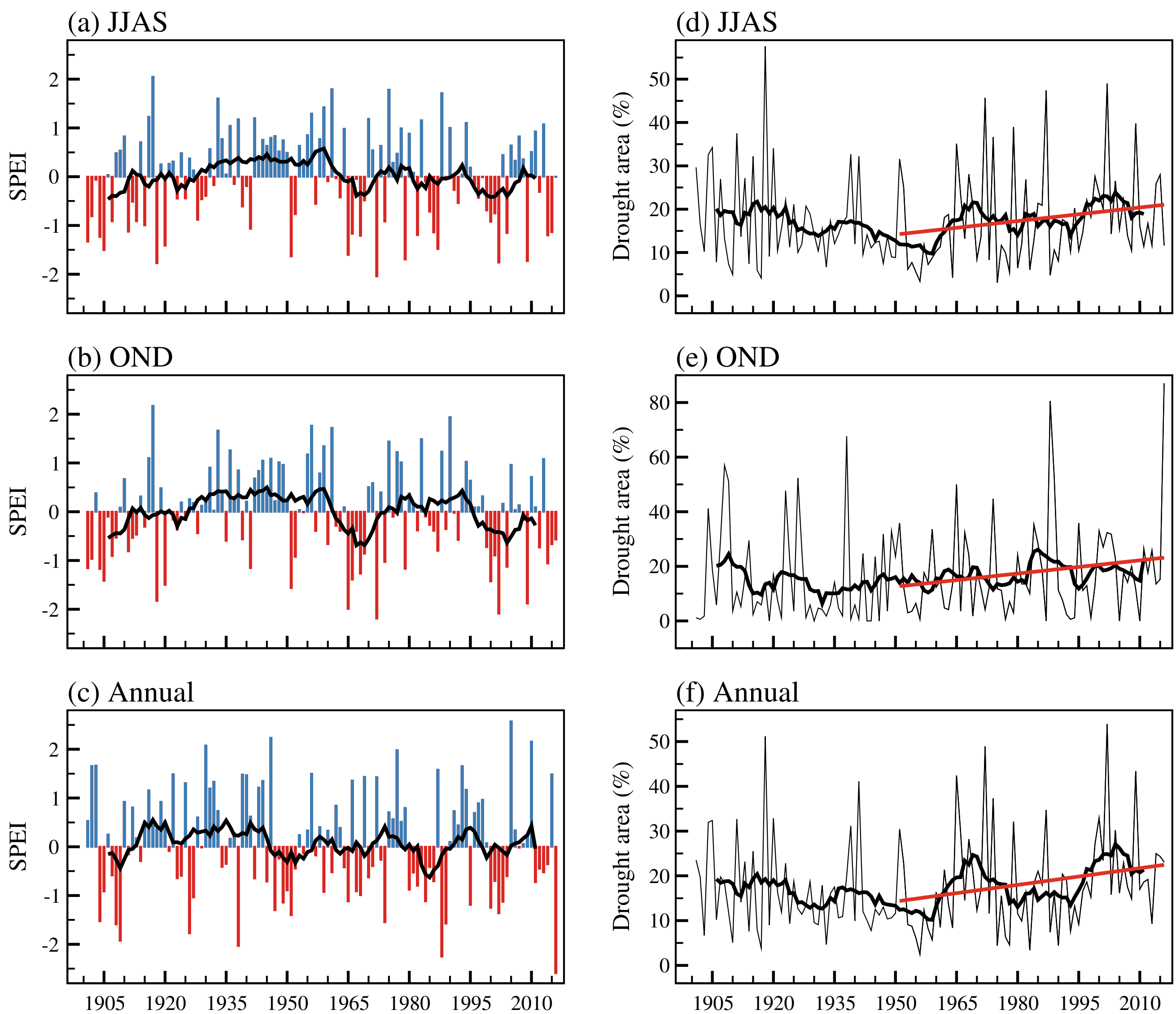

Fig. 6.1 Time series of **a**–**c** SPEI and **d**–**f** percentage area affected by drought (SPEI < −1) for **a**, **d** SW monsoon, **b**, **e** NE monsoon and **c**, **f** annual scale, during 1901–2016. SPEI in **a**–**c** is computed for **a** all India during JJAS, **b** NE monsoon region for OND, and **c** all India for the entire year, with respect to the base period 1951–2000. Black lines indicate 11-year smoothed time series. Blue (red) bars in **a**–**c** denote wet (dry) years. Red lines in (**d**–**f**) indicate a linear trend for the period 1951–2016

and Agriculture Organization (FAO; http://www.fao.org/docrep/x0490e/x0490e06.htm). The Penman-Monteith formulation is based on physical principles of energy balance over a wet surface and is considered superior to empirically based formulations, which usually consider the effects of temperature and/or radiation only (see Ramarao et al. 2019 and references therein). The SPEI is a normalized index and can be used to infer both wet (positive SPEI) and dry (negative SPEI) conditions over the region of interest. Although the theoretical limits are (-∞, +∞), SPEI value normally ranges from -2.5 to +2.5. An index of +2 and above indicates extremely wet; (1.5 to 1.99) very wet; (1.0 to 1.49) moderately wet; (0.99 to -0.99) near normal; (-1.0 to -1.49) moderately dry; (-1.5 to -1.99) severely dry; (-2.0 or less) extremely dry. For the analysis presented in this chapter, SPEI is computed for 4 month, 3 month and 12 month timescales spanning the JJAS (SPEI-SW), OND (SPEI-NE) and Annual from January to December (SPEI-ANN) to represent SW, NE monsoons, and annual scale respectively. The SPEI-SW and SPEI-ANN are computed for the Indian subcontinent, whereas SPEI-NE is computed for the southern peninsular India, the region under the

Table 6.1 Various meteorological drought indices

Index	Computation	Strength and weakness
Percent of normal precipitation (PNP)	Actual precipitation divided by normal precipitation—typically a 30 year mean and multiplied by 100 (%)	**Strength**: Simple measurement, very effective in a single region or a single season, can be calculated for a variety of timescales **Weakness**: Biased by the aridity of the region, cannot compare with different locations, cannot identify the specific impact of drought
Palmer drought severity index (PDSI)	Computed from precipitation and temperature (Palmer 1965; Dai et al. 2004)	**Strength**: Widely used for drought characterization **Weakness**: Lags the detection of drought over several months due to its dependency on soil moisture, which is simplified to one value in each climate zone
Standardized precipitation index (SPI)	SPI is defined based on the cumulative probability of a given rainfall event. It is derived from the transformation of fitted gamma distribution of historical rainfall to a standard normal distribution (Mckee et al. 1993)	**Strength**: Not biased by aridity, better than PNP and PDSI. It can be computed for different timescales. Considers multi-scalar nature of droughts. Allows comparison of drought severity at two or more locations, regardless of climatic conditions **Weakness**: Only precipitation is used and does not consider other crucial variables, e.g. temperature
Standardized precipitation evapotranspiration index (SPEI)	SPEI uses accumulations of precipitation minus potential evapotranspiration (PET) and thereby accounts for changes in both supply and demand in moisture variability over the region of interest (Vicente-Serrano et al. 2010)	**Strength**: Similar to SPI. Includes the effect of temperature via evaporative demand. More suited to explore impacts of warming temperatures on the occurrence of droughts. A more extensive range of applications than SPI **Weakness**: Sensitive to PET computation

Several other drought indices have been developed based on different indicator variables such as soil moisture, run-off and evapotranspiration (Karl and Karl 1983; Mo 2008; Shukla and Wood 2008; Hao and AghaKouchak 2013)

Table 6.2 List of SW monsoon droughts from 1901 to 2015. Years in bold letters represent severe droughts

Period	Drought years	Total number of droughts (per decade)
1901–1930	1901, 1904, **1905**, 1911, **1918**, 1920	6 (2)
1931–1960	1941, **1951**	2 (0.7)
1961–1990	**1965**, 1966, 1968, **1972**, **1979**, 1982, 1986, 1987	8 (2.7)
1991–2015	**2002**, 2004, **2009**, 2014, 2015	5 (1.9)

influence of NE monsoon. The NE monsoon region comprises of 5 meteorological sub-divisions over the southern peninsular India, namely, coastal Andhra Pradesh, Rayalaseema, South interior Karnataka, Kerala and Tamil Nadu.

For both SW and NE monsoons, the time series of SPEI shows considerable interannual and multidecadal variations with a slight negative trend (Fig. 6.1a, b), corresponding to the respective monsoon rainfall variations. The declining trend in SPEI time series is indicative of an increase in the intensity of droughts. The annual scale SPEI time series is shown in Fig. 6.1c. The variability in the frequency of SW monsoon droughts during different epochs can be noted in Table 6.2. The drought frequency for the period 1901–2016 revealed 21, 19 and 18 cases of moderate to extreme droughts (SPEI ≤ -1) for the SW, NE monsoons and annual timescale, respectively, with almost 2 droughts per decade on an average. The number of wet monsoon years (SPEI $\geq$ 1) is found to be 16, 14 and 19 for the SW, NE

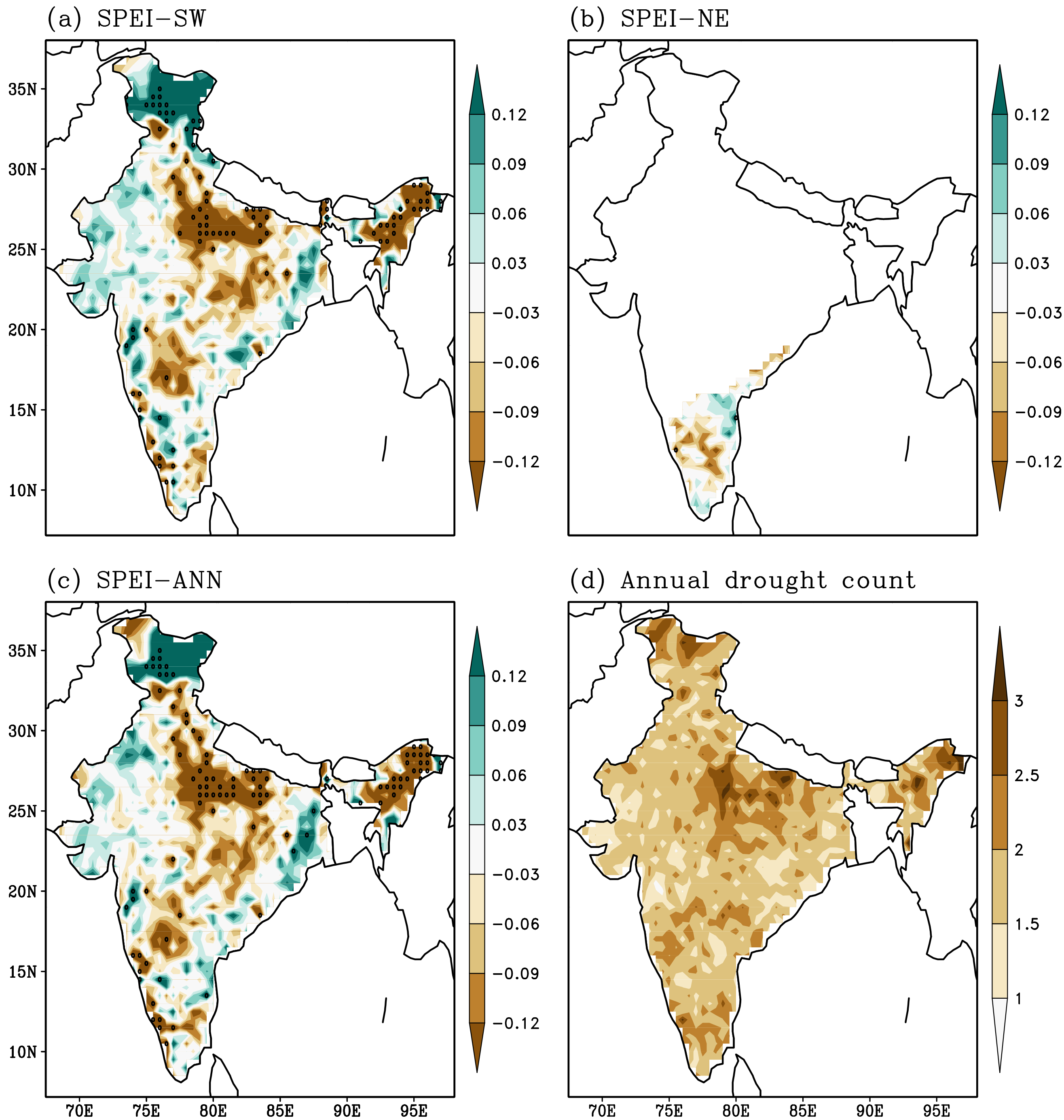

Fig. 6.2 Spatial pattern of trends (decade^{-1}) in **a** SPEI-SW for JJAS, **b** SPEI-NE for OND and **c** SPEI-ANN for annual, during 1951–2016. Regions with statistically significant (at 95% confidence level) trends are hatched. **d** Frequency of annual droughts (SPEI-ANN $\leq$ −1.0) per decade, from 1951 to 2016

monsoon seasons and annual timescale, respectively, with about 1–2 wet monsoon years per decade. The second half of data period (1951–2016) has witnessed frequent droughts with 14, 11 and 12 cases, compared to the previous period 1901–1950 (7, 8 and 6), for the SW, NE monsoon seasons and annual timescale, respectively.

The number of severe to extreme drought cases (SPEI $\leq$ −1.5) for 1951–2016 period is 6, 4 and 5 for the SW, NE monsoon seasons, and annual timescales respectively, compared to 2, 5 and 1 during 1901–1950 (Fig. 6.1a–c). Additionally, an increasing trend in drought area is observed for the entire period of analysis (1901–2016), with a statistically significant trend (at 95% confidence level) for JJAS season and annual timescale for 1951–2016 (Fig. 6.1 d–f). The period 1951–2016 also witnessed 1.2%, 1.2% and 1.3% increase in dry area per decade for SW, NE monsoon seasons and annual timescale, respectively. It is interesting to note that the drying trends are slightly higher for annual scale droughts. The analysis thus shows that the period 1951–2016 witnessed an increase in frequency and areal extent of droughts. Consistent with this, previous studies also reported an increase in frequency, duration as well as the intensity of the monsoon droughts for the post-1960 period compared to the pre-1960 period (Mallya et al. 2016; Mishra et al. 2016). Further, a relative enhancement of moderate to severe drought frequency has occurred during the recent epoch of 1977–2010 compared to 1945–1977 (Niranjan Kumar et al. 2013). Interestingly, an increase in the episodes of two consecutive years with deficient monsoon has also occurred during the post-1960 period (Fig. 6.1a; Niranjan Kumar et al. 2013). Studies highlight an increasing trend in dry areas (Niranjan Kumar et al. 2013; Mallya et al. 2016). The similar conclusions reached by different studies using different datasets and approaches provides a "high confidence" finding that frequency, as well as percentage area under drought, have increased over the Indian subcontinent during the second half of the twentieth century when compared to the first half of the century.

Significant drying trend (negative values in SPEI), during the SW monsoon season, was observed over the humid regions of Central India, and over some regions of north-east as well as west coast of India during 1951–2016 (Fig. 6.2a). A wetting trend is noticed over north-west and few parts of southern peninsular India (Fig. 6.2a). This indicates that the humid regions exhibit a tendency towards drying and more intense droughts during 1951–2016. This drying tendency is seen prominently during recent decades (Yang et al. 2019). Long-term (1901–2002) multiple data sources and methods also revealed that droughts are becoming much more regional in recent decades and depict a general migration from west to east and over the Indo-Gangetic plain (Mallya et al. 2016). This study also identified an increase in the duration, severity and spatial extent of droughts during the recent decades, highlighting the Indo-Gangetic plain, parts of coastal south India and central Maharashtra as regions that are becoming increasingly vulnerable to droughts. Strong drying over the central and the north Indian regions (Fig. 6.2a) has also been revealed from other observational studies using rainfall observations (Krishnan et al. 2013; Preethi et al. 2017a) and various drought indices (Pai et al. 2011; Niranjan Kumar et al. 2013; Damberg and Agha-Kouchak 2014; Yang et al. 2019). It is to be noted that these regions are also accompanied by an increase in aridity (Ramarao et al. 2019; Yang et al. 2019). As a result, the conclusion regarding, the drying and potential for increasing drought propensity over central and northern India, is a high confidence finding.

During the NE monsoon season, the spatial trends in SPEI depict an increase in drought intensity over the majority of region (Fig. 6.2b). A similar pattern as that of SPEI-SW is seen for the entire year (Fig. 6.2c) probably due to the dominance of rainfall contribution from SW monsoon compared to that of NE monsoon. It is worth noting that the regions which witnessed significant drying trend, e.g. Central India, Kerala, some regions of the south peninsula, and north-eastern parts of India, also experience higher annual frequency of droughts, with more than two droughts per decade on average for the 1951–2016 period (Fig. 6.2d), thus confirming that these regions are becoming more vulnerable to droughts during recent decades (high confidence). The frequent and intense droughts will likely pose significant challenges for food and water security in India by depleting soil moisture and groundwater storages (Asoka et al. 2017). Soil moisture droughts hamper crop production in India, where the majority of the population depends on agriculture and leads to famines over the region (Mishra et al. 2019). Past studies have reported that the frequency and areal extent of soil moisture-based droughts have increased substantially during 1980–2008 (Mishra et al. 2014), and hence, efforts are being made to provide forecasts of standardized soil moisture index over India (Mishra et al. 2018; https://sites.google.com/iitgn.ac.in/expforecastlandsurfaceproducts/erf-forecasted-sri-and-ssi).

Apart from the aforementioned observational studies, a limited number of investigations using climate models are available that provide additional insight into the drought occurrence and variability. Among the various climate models participated in the Coupled Model Intercomparison Project 5 (CMIP5), very few could capture the observed monsoon rainfall variability, particularly the frequent occurrence of droughts and spatial variability of rainfall during drought years in the recent historical period (Preethi et al. 2019). Further, a marked increase in the propensity of monsoon droughts similar to the observations during the post-1950s is reasonably well simulated by the high resolution (horizontal grid size $\sim$35 km) Laboratoire de Météorologie Dynamique (LMDZ4) global model with telescopic zooming over the South Asia region (Krishnan et al. 2016). It is reported that the SPEI index at 12-month and 24-month timescales in historical simulation (with both natural and anthropogenic forcings) exhibits an increase in the frequency and intensity of droughts during 1951–2005, which is possibly attributed to the influence of anthropogenic forcing on the weakening monsoon circulation and rainfall over the India subcontinent (Krishnan et al. 2016). It is important to note that the climate models have a large bias in simulating monsoon rainfall and its variability on different timescales (Turner and Annamalai 2012; Chaturvedi et al. 2012;

Rajeevan et al. 2012; Jayasankar et al. 2015; Preethi et al. 2010, 2017b). Large uncertainties are also found in reconstructing agricultural drought events for the period 1951–2015 based on simulated soil moisture from three different land surface models (Mishra et al. 2018). These uncertainties are mainly due to differences in model parameterizations and hence the study highlighted the importance of considering the multi-model ensemble for real-time monitoring and prediction of soil moisture drought over India.

6.2.1 Drought Mechanism

General features associated with SW monsoon droughts are weaker meridional pressure gradient, a larger northward seasonal shift of the monsoon trough, more break days, reduction in the frequency of depressions and shorter westward extent of depression tracks (Mooley 1976; Parthasarathy et al. 1987; Raman and Rao 1981; Sikka 1999). Droughts during the SW monsoon are, in general, significantly related to external forcings such as sea surface temperature (SST) variations in the tropical oceans, particularly with the warm phase of El Niño–Southern Oscillation (ENSO; Sikka 1980, 1999; Pant and Parthasarathy 1981; Pai et al. 2011, 2017; Mishra et al. 2012b; Preethi et al. 2017a and the references therein) events in the eastern equatorial Pacific, central Pacific El Niño (Kumar et al. 2006) or El Niño Modoki events (Ashok et al. 2007) and also the negative Indian Ocean Dipole (IOD) events (Saji et al. 1999; Ashok et al. 2001). Apart from the tropical teleconnections, impacts on SW monsoon droughts from extra-tropics are evident from negative phase of the North Atlantic Oscillation (NAO; Goswami et al. 2006) on interannual timescale, negative phase of Atlantic Multidecadal Oscillation (AMO; Goswami et al. 2006) and positive phase of Pacific Decadal Oscillation (PDO; Krishnan and Sugi 2003) on multidecadal timescales. On the other hand, NE monsoon droughts are associated with a negative phase of ENSO (La Niña) and negative phase of IOD (Kripalani and Kumar 2004). In addition to the tropical influence, extratropical influence is evident as a relationship between the positive phase of the NAO and NE monsoon drought (Balachandran et al. 2006). Further details can be obtained from Box 3.2 in Chap. 3. It is to be noted that these teleconnections exhibit a secular variation, with epochs of strong and weak relationship with SW as well as NE monsoon rainfall (Kripalani and Kulkarni 1997; Kumar et al. 1999; Pankaj Kumar et al. 2007; Yadav 2012; Rajeevan et al. 2012).

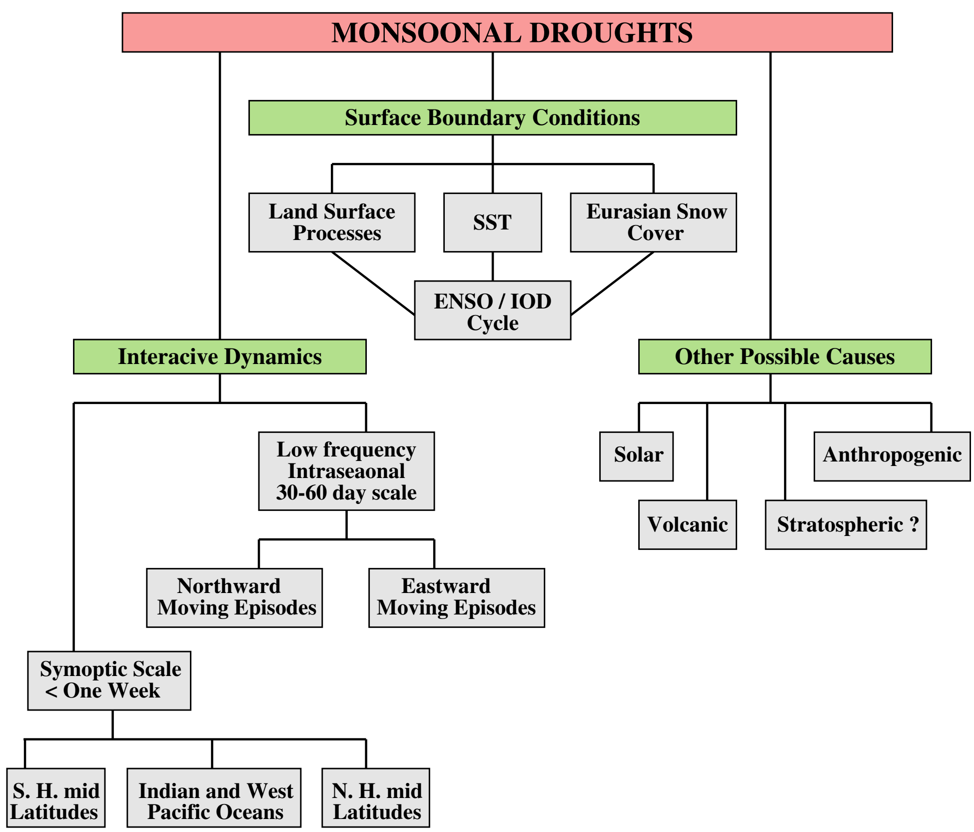

Fig. 6.3 Schematic diagram representing the interactive mechanisms leading to droughts (This Schematic is an adaptation of Fig. 4.4 in Joint COLA/CARE Technical Report No.2, July 1999 Monsoon Drought in India by D. R. Sikka, and is used with permission of the Center for Ocean-Land-Atmosphere Studies.)

Table 6.3 List of recent major droughts over India

Year	Region affected	Cause
1987	Central and North India	Warmer SSTs over equatorial Indian and Pacific oceans related to ENSO and IOD phases were unfavourable and lead to suppressed rainfall over India (Krishnamurti et al. 1989)
2000	North-west and Central India	Enhanced convective activity associated with the warmer equatorial and southern tropical Indian Ocean SSTs induced anomalous subsidence over the Indian subcontinent and thereby weakened the monsoon Hadley cell which ultimately decreased the rainfall. The warmer SSTs also led to a higher probability of occurrence of dry spells and prolonged break monsoon conditions over the subcontinent (Krishnan et al. 2003)
2002	North-west parts of India	The anomalous atmospheric convective activity over north-west and north-central Pacific associated with moderate El Niño conditions induced subsidence and rainfall deficiency over the Indian landmass (Mujumdar et al. 2007). A slower 30–60 days mode dominated the season and led to deficit monsoon rainfall (Kripalani et al. 2004). Prevailing circulation features over mid-latitudes of Eurasia and the south Indian ocean, the negative phase of SOI, warmer SST over South china sea and El Niño conditions have favoured the monsoon drought (Sikka 2003)
2008	Central India	The abnormal SST warming in southern tropical Indian Ocean due to the combined influence of a warming trend in the tropical Indian Ocean and warming associated with the IOD, resulted in enhancement of convection in the south-west tropical Indian Ocean and forced anticyclonic circulation anomalies over the Bay of Bengal and Central India, leading to suppressed rainfall over this region (Rao et al. 2010)
2009	Most of the country except north and south interior Karnataka	The unfavourable phases of the two important modes, viz., El Niño and the equatorial Indian Ocean Oscillation (EQUINOO) along with the reversal of the SST gradient between the Bay of Bengal and eastern equatorial Indian Ocean, played a critical role in the rainfall deficit over the Bay of Bengal and the Indian region (Francis and Gadgil 2010). Also, monsoon break conditions extended by the incursion of western Asian desert dry air towards Central India (Krishnamurti et al. 2010) and by the westward propagating convectively coupled planetary-scale equatorial Rossby waves (Neena et al. 2011) leading to a seasonal deficit in rainfall. Thus, weak cross-equatorial flow, monsoon systems not moving in land, penetration of mid-latitude upper tropospheric westerlies and the circulation associated with the Walker and Hadley circulation, with descending motion over the Indian landmass, collectively resulted in less moisture supply, leading to a drought (Preethi et al. 2011)
2015	Indo-Gangetic plains and western peninsular India	Enhanced convective activity associated with the pronounced meridional sea surface temperature (SST) gradient across the central-eastern Pacific ocean induce large-scale subsidence over the monsoon region (Mujumdar et al. 2017a)

Also, internal variability induced by the intraseasonal oscillations of monsoon could lead to seasonal droughts that are not connected to the known external forcing (Goswami 1998; Kripalani et al. 2004). Monsoon droughts are generally associated with at least one very long break with a duration of more than ten days (Joseph et al. 2010). The ocean-atmosphere dynamical coupling, between the monsoon flow and thermocline depth on intraseasonal timescales, in the equatorial Indian Ocean, plays an important role in forcing extended monsoon breaks and causes droughts over the Indian subcontinent (Krishnan et al. 2006). Complex thermodynamical interactions among equatorial Indo-Pacific and off-equatorial northern Indian Ocean (between 10° N—25° N) convective systems on intraseasonal timescale as well as the ocean-atmosphere coupling on interannual timescale can also trigger the occurrence of very long breaks (Joseph et al. 2010). Moreover, the initiation of extended breaks resulting in drought conditions could be influenced by the extratropical systems as well (Krishnan et al. 2009). A schematic diagram representing the interactive mechanisms leading to large-scale droughts is provided in Fig. 6.3. Major SW monsoon droughts along with their possible causes are also listed, in Table 6.3.

In recent decades, warming of the Indian Ocean, at a faster rate than the global oceans (Roxy et al. 2014) could have implications on the variability of rainfall over India, contributing to the declining trend of SW monsoon rainfall (Roxy et al. 2014; Preethi et al. 2017a) and aiding occurrence of frequent droughts (Niranjan Kumar et al. 2013). Niyogi et al. (2010) have shown using observational analysis that landscape changes due to agricultural intensification and irrigation could also contribute to declining monsoon rains and aid drought occurrences particularly in northern India. Also, the increase in anthropogenic aerosol emissions might have contributed to the observed decline in monsoon rainfall (see Chap. 3 and Box 5.3 of Chap. 5). In this context, it is important to have an estimation of likely future changes in rainfall, particularly droughts, under warming scenario. Additionally, quantitative information on rainfall and related atmospheric and oceanic parameters prior to the period of recorded meteorological data is also essential for understanding and possibly mitigating the effects of projected climate change. Hence, a look into the palaeoclimatic records has also been made, in the following section, for understanding the variability of monsoon droughts in the past.

6.2.2 Palaeoclimatic Evidences

Evidences from proxy records indicate that past monsoonal variations were dominated by decadal- to millennial-scale variability and long-term trends (Kelkar 2006; Sinha et al. 2018; Band et al. 2018 and references therein). Reconstruction of SW monsoon variability based on stalagmite oxygen isotope ratios from Central India indicates a gradual decrease in monsoon during the beginning of the mid-Holocene from 8.5 to 7.3 ka BP (Before Present: 1950 AD), followed by a steady increase in monsoon intensity between 6.3 and 5.6 ka BP. This overall trend of monsoon during the mid-Holocene is punctuated by abrupt mega-drought events spanning 70–100 years. During the past 1500 years, centennial-scale climate oscillations include the Medieval Warm Period (MWP) during 900–1300 AD—with relatively stronger monsoon, and the Little Ice Age (LIA) during 1400–1850 AD—with the relatively weaker monsoon (e.g. Sinha et al. 2007, 2011a, b; Goswami et al. 2015; Kathayat et al. 2017 and references therein). Severe drought, in India, lasting decades occurred during fourteenth and mid-fifteenth centuries in LIA. Nearly every major famine, including the devastating Durga Devi famine during 1396–1409 AD, coincides with a period of reduced monsoon rainfall, reconstructed from $\delta^{18}O$ of speleothems collected from Central India (Sinha et al. 2007). A possible influence of ENSO is suggested for the Indian monsoon variability during the mid-Holocene, MWP and LIA (Mann et al. 2009; Band et al. 2018; Tejavath et al. 2019).

Indian monsoon drought history for past 500 years and its association with El Nino was derived by Borgaonkar et al. (2010) from 523-year (1481–2003 AD) tree-ring chronology from Kerala, south India (Fig. 6.4a). This chronology exhibits a significant positive relationship with the observed SW monsoon rainfall for the instrumental period (1871–2003 AD; Fig. 6.4b, c). LIA with weaker monsoon is also evident (Fig. 6.4a: 1600–1700 AD). Higher frequency of low tree growth occurrences (Fig. 6.4b) was observed in years of monsoon droughts (Fig. 6.4c), these events are associated with El Niño since the late eighteenth century. Prior to that, many low tree growth years were detected during known El Niño events, probably related to deficient Indian monsoon rainfall (Fig. 6.4a; Borgaonkar et al. 2010). It is noteworthy, however, that the mid-eighteenth century is a time where drought is indicated in northern Thailand (Buckley et al. 2007) and northern Vietnam (Sano et al. 2009), suggestive of a weakened monsoon in the late eighteenth century. Most of these periods, including those prior to the mid-eighteenth century, have also been reported to have widespread droughts in India (Pant et al. 1993). Aforementioned studies thus indicate a strong influence of Indo-Pacific SSTs on past monsoon droughts at decadal to millennial timescales.

6.3 Observed Variability of Floods

Floods, as compared to droughts, have regional characteristics and are typically confined to shorter timescales ranging from several hours to days. Floods are classified into different types such as riverine (extreme rainfall for longer periods), flash (heavy rainfall in cities or steep slopes), urban (lack of drainage), coastal (storm surge) and pluvial (rainfall over a flat surface) flooding. Regions prone to frequent floods mainly include river basins, hilly, coastal areas and in some instances, cities. In India, different types of floods frequently occur primarily during the SW monsoon season, the major rainy season. In addition, south peninsular India experiences floods during the NE monsoon season (Dhar and Nandargi 2000, 2003). The majority of floods in India are closely associated with heavy rainfall events, and not all of these heavy rain events translate into floods. Apart from the rainfall extremes, flood occurrences are linked to other factors such as antecedent soil moisture, storm duration, snowmelt, drainage basin conditions, urbanization, dams and reservoirs, and also proximity to the coast (Rosenzweig et al. 2010; Mishra et al. 2012a; Sharma et al. 2018). In addition, several other factors, such as infrastructure, siltation of rivers, deforestation, and backwater effect, can accelerate the impacts of floods.

In India, the spatial variation of floods mostly follows the monsoon intraseasonal oscillations. For example, Central India experiences the majority of flood events during the active monsoon phase, primarily due to heavy rainfall received from monsoon disturbances (Dhar and Nandargi 2003; Kale 2003, 2012; Ranade et al. 2007; Sontakke et al. 2008). On the contrary, regions near the foothills of the Himalayas typically experience floods during the break monsoon condition, due to heavy rainfall associated with the movement of monsoon trough towards the foothills, orographic uplift of moist monsoon flows and also due to tropical and mid-latitude interactions (Dhar and Nandargi 2000; Krishnan et al. 2000, 2009; Vellore et al. 2014). Occasionally, low pressure systems and western disturbances interact to give rise to heavy rains and floods (Sikka

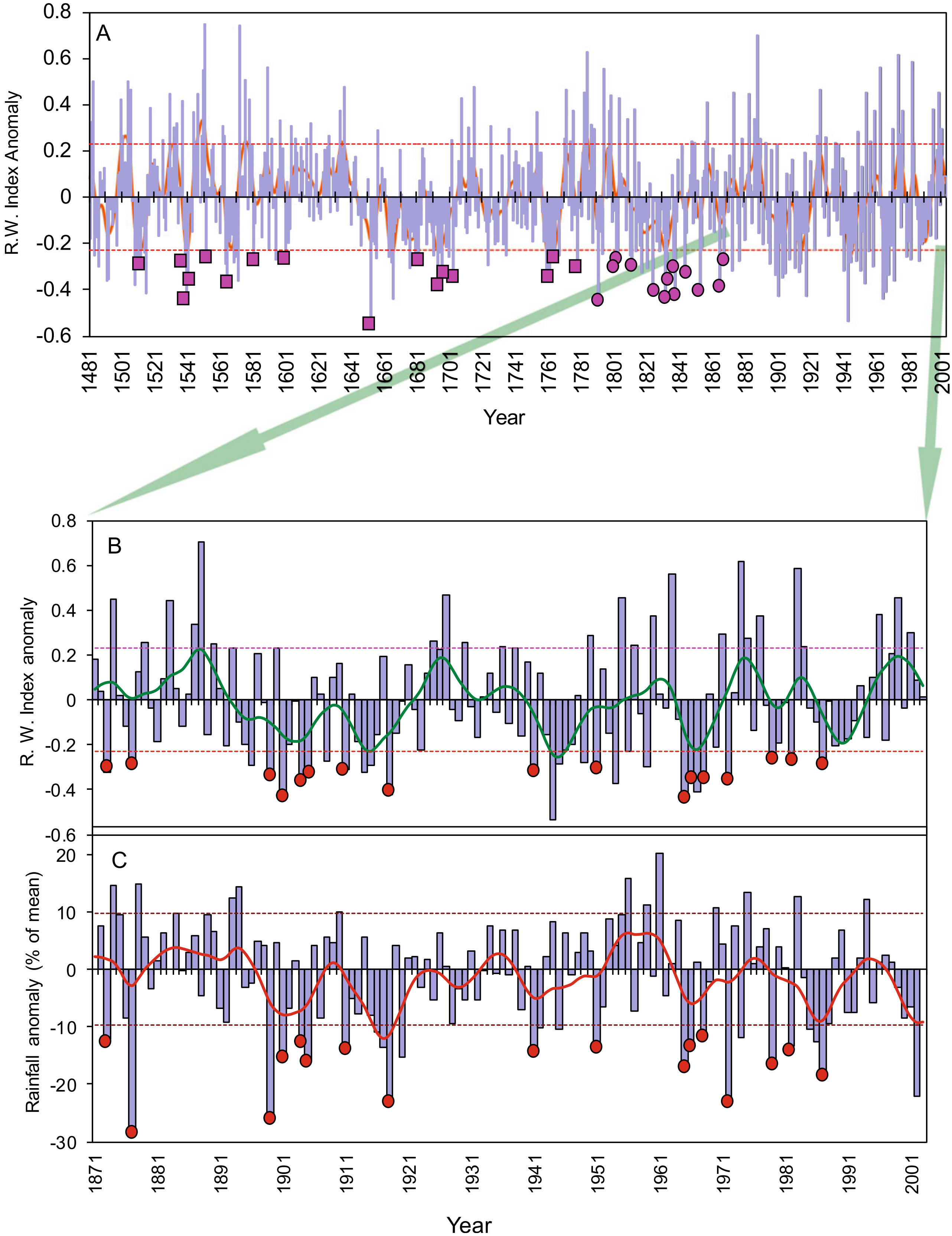

Fig. 6.4 Correspondence between tree-ring width index anomaly of Kerala tree-ring chronology (KTRC) and SW monsoon rainfall. **a** KTRC anomaly for the period 1481–2003. Anomalies in (**b**) KTRC and (**c**) SW monsoon rainfall for the instrumental period of 1871–2003. Smooth line denotes 10-year cubic spline fit. Dashed lines in the figures indicate "mean ± std.dev." limits. In Figure (**a**), circles indicate low growth events during the years of deficient rainfall (droughts) associated with El Niño and Squares are low growth associated with El Niño years. Circles in Figure (**b**) are low growth years and have one to one correspondence with deficient ISM rainfall (drought) years associated with El Niño, shown as circle in Figure (**c**)

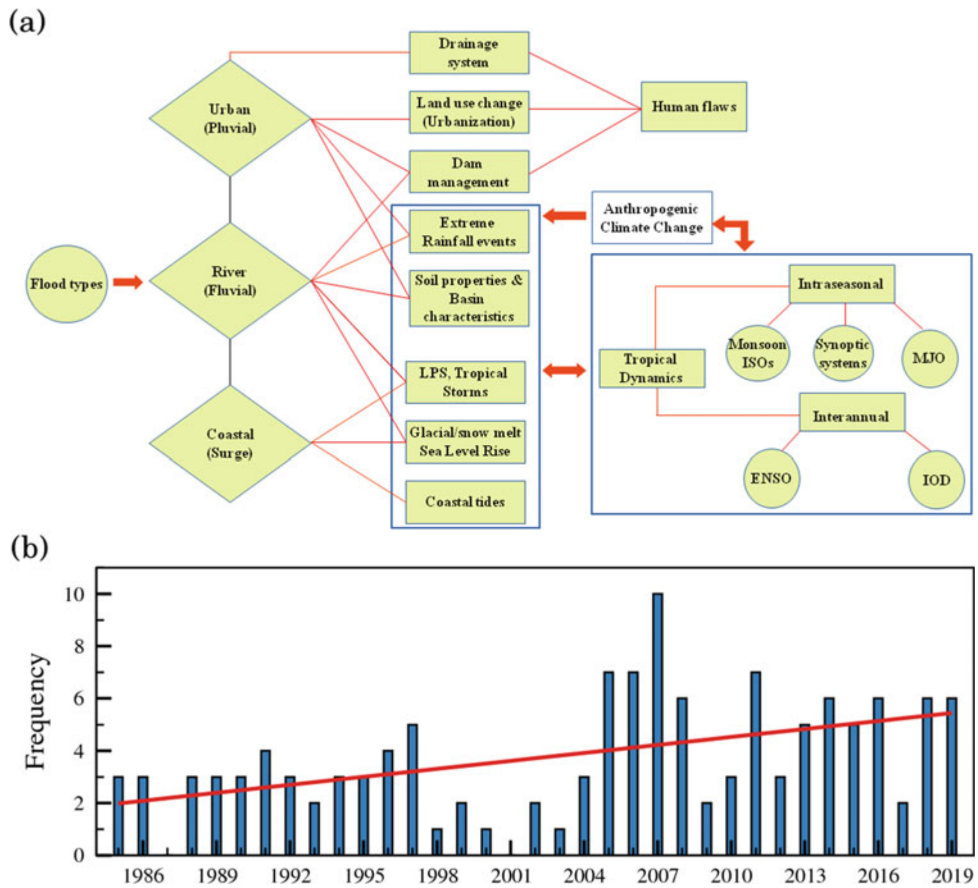

Fig. 6.5 **a** Schematic diagram representing various types of floods and causative interactive mechanisms. **b** Time series of the frequency of severe flood events over India, during 1985–2019 based on flood database of the Dartmouth Flood Observatory (http://www.dartmouth.edu/~floods/Archives/index.html). The red line in (**b**) indicates linear trend

et al. 2015). Low pressure systems during the monsoon season or active monsoon conditions or monsoon breaks are the root cause of extreme floods in the South Asian rivers (Ramaswamy 1962; Dhar and Nandargi 2003). Further details on heavy rainfall occurrences and monsoon disturbances are given in Chaps. 3 and 7, respectively. In addition to the intraseasonal variability, floods exhibit variations on interannual to multidecadal timescales, in association with the flood producing extreme rainfall events. The variations in floods are reported to be also linked to the large-scale climatic drivers such as ENSO, NAO, AMO, PDO (Chowdhury 2003; Mirza 2003; Ward et al. 2016; Najibi and Devineni 2018). In particular, flood duration appears to be more sensitive to ENSO conditions in current climate. Long duration floods mainly occur during El Niño and La Niña years, compared to neutral years (Ward et al. 2016), while the influence of ENSO on flood frequency is not so strong as that on the flood duration. A schematic diagram representing the various types of floods and causative interactive mechanisms is provided in Fig. 6.5a.

Under changing climate, an intensification of the global water cycle could accelerate the risk of floods and exposure to flooding on a global scale (Milly et al. 2002; Dentener et al. 2006; Trenberth 2011; Schiermeier 2011; Hirabayashi et al. 2013). Observations for the period 1985–2015 reported an increase in frequency as well as long duration floods over the globe with a fourfold increase in frequency of floods in tropics after 2000 (Najibi and Devineni 2018). The increasing trend in extreme rainfall over the Indian subcontinent, in spite of the weakening of monsoon circulation observed during the post-1950s, also hints towards an increase in flood risk in a warming environment (Rajeevan et al. 2008; Guhathakurta et al. 2011; Roxy et al. 2017). A noticeable increase in the flood events has also occurred over the Indian subcontinent. In particular, urban and river floods (discussed in detail in the following subsections) have increased considerably along with the increasing trend in heavy rainfall events. A brief description of the major flood events that occurred over the Indian subcontinent since 2000 can be found in Table 6.4. The analysis of severe flood events using the flood database of Dartmouth Flood Observatory indicates a statistically significant increasing trend (1 flood event per decade) in the frequency of severe flood events over India during the period 1985–2019 (Fig. 6.5b). The severity of the flood events is calculated following the formulation used by the Dartmouth Flood Observatory. Studies have shown that extreme floods over South Asia cluster during excess monsoons and these extremes are rising post-1950s in the river basins across India

Table 6.4 List of recent major flood events over India

Year	Region	Cause
2005 (July)	Mumbai flood	Heavy downpour resulted in a huge rainfall as much as 994 mm of rain fell in just 24 h and 684 mm in only 12 h. Resulted in massive flooding of the Mithi river. The impact was further amplified by the inadequate drainage and sewage resulting in massive flooding (Gupta and Nikam 2013)
2007 (August)	Bihar flood	Extremely heavy and long-term rainfall flooded various rivers in Bihar and Uttar Pradesh
2008 (August)	Bihar flood	The flooding of the Kosi river valley in the northern Bihar due to breaking of Kosi embankment
2012 (June)	Brahmaputra floods	Extremely heavy monsoon rainfall resulted in over-flowing of Brahmaputra river and its tributaries
2013 (June)	North India floods (Uttarakhand)	Notable natural disaster in Uttarakhand. Continuous heavy monsoon rainfall followed by landslides in the hills led to flash flooding (Vellore et al. 2016). This region has recently experienced frequent flooding and landslides (e.g. flash floods in 2010; floods and landslides in 2011; and Himalayan flash floods in 2012)
2013 (July)	Brahmaputra floods	Similar to the 2012 event, extremely heavy monsoon rainfall resulted in over-flowing of Brahmaputra river and its tributaries
2014 (September)	Kashmir floods	Continuous rainfall for more than three days resulted in floods and landslides in Jammu and Kashmir after the Jhelum river reached above the dangerous level
2015 (June and August)	Assam floods	Extremely heavy monsoon rainfall resulted in the bursting of Brahmaputra river and its tributaries causing landslides in the region
2015 (July)	Gujarat flood	Monsoon deep depression over the Arabian Sea caused intense rainfall and flooding across the coast of Gujarat
2015 (November)	Chennai floods	The transition of low pressure into a deep depression after crossing the coast resulted in very rainfall. It is likely due to blocking of clouds by the Eastern Ghats which led continuous rainfall and produced massive urban flooding. (Assessment AR 2016; Van Oldenborgh et al. 2016). Also, rampant urban development could have played a vital role
2016 (July)	Assam floods	Extremely heavy monsoon rainfall mostly during monsoon breaks resulted in the bursting of Brahmaputra river and its tributaries
2017 (June and July)	North-east India floods	Extremely heavy monsoon rainfall mostly during monsoon breaks resulted in the bursting of Brahmaputra river and its tributaries
2017 (July)	Bihar flood	The torrential rain in the Nepal region resulted in a sudden increase in the discharge in all the eight rivers in Bihar, which led to massive flooding
2017 (July)	West Bengal floods	Week-long continuous rainfall due to cyclone Komen during monsoon resulted in dangerous floods in West Bengal and Jharkhand
2017 (July)	Gujarat flood	Simultaneous occurrence of rainfall due to low pressure systems from Arabian sea as well as Bay of Bengal. It is also likely that the heavy inflow into dams Dharoj and Dantiwada resulted in the massive flooding
2017 (August)	Mumbai flood	Massive Mumbai flood after 2005. The high tide and the extreme rainfall (468 mm in 12 h) along with inadequate drainage and sewage resulted in massive flooding
2018 (August)	Kerala floods	The unusual rainfall during the monsoon season has resulted in massive flooding. Other reasons are a sudden discharge of water from the reservoir, land-use changes and landslides (Mishra and Shah 2018)
2019 (July, August and September)	Widespread over Indian regions	A series of devastating floods over areas of several states (such as Maharashtra, Karnataka, Kerala, Gujarat, Rajasthan, Andhra Pradesh, Orissa, Uttarakhand, Madhya-Pradesh, Bihar, Uttar Pradesh, West Bengal, Assam and Punjab) due to persisting monsoonal deluges with excessive rain rates, stream flow and run-off during peak monsoon months extending into September (Global Disaster Alert and Coordination System, GDACS www.gdacs.org, https://erccportal.jrc.ec.europa.eu/ and http://floodlist.com/tag/india)

(Kale 2012; Nandargi and Shelar 2018; Mirza 2011; Ali et al. 2019). Increase in extreme rainfall events (Goswami et al. 2006; Rajeevan et al. 2008; Guhathakurta et al. 2011), rate of intensification of cyclones into severe cyclones (Niyas et al. 2009; Kishtawal et al. 2012; Chap. 8 on Extreme storms) and prolonged breaks (Ramesh Kumar et al. 2009; Chap. 3 on

Precipitation changes in India) are suggested to be the possible reasons for the intensification of river floods during post-1950 period, in addition to the anthropogenic induced changes in the catchment and river hydrology (Kale 2012). The increasing trend in floods is also possibly attributed to long-term climate variability (Ward et al. 2016; Najibi and Devineni 2018).

6.3.1 Urban/Coastal Floods

In general, urban areas are prone to river or flash flooding. Additionally, the major factors for urban floods include the effect of anthropogenic geographical alterations, inadequate drainage and storm water management system as well as high structural inhomogeneity due to intense land-use changes in proportion to increased urban population, and also the increasing population (Carvalho et al. 2002; Shepherd 2005; Goswami et al. 2010; Yang et al. 2015; Liu and Niyogi 2019). Under global warming, the observed increasing trend in heavy rainfall events has resulted in more frequent and intense flash floods over urban areas (Kishtawal et al. 2010; Guhathakurta et al. 2011; Mishra and Lilhare 2016). It is also reported that the regions which are not traditionally prone to floods experience severe inundation due to downpour and cloud burst during recent decades.

The major urban flood events of India have occurred in Mumbai (2005, 2014, 2017), Bangalore (2005, 2007, 2015), Chennai (2002, 2004, 2005, 2006, 2007, 2015), Ahmadabad (2017) and Kolkata (2007, 2017). It is to be noticed that three major metropolitan Indian cities experienced severe flooding in the same year 2005, i.e. Mumbai in July 2005, Bangalore and Chennai in October and December 2005, respectively (Guhathakurta et al. 2011). In the case of Mumbai flood of 2005, apart from about 944 mm rainfall recorded in 24-h, the intrusion of sea water into the city resulted in mass inundation due to the complex drainage system (Gupta and Nikam 2013). Studies also suggest that Mumbai region is highly vulnerable to climate change due to sea-level rise, storm surge and extreme precipitation (Hallegatte et al. 2010). The coastal city of Kolkata is also prone to flooding due to extreme rainfall activities associated with tropical cyclones. The subsidence of land in this region combined with high-tide results in heavy flooding and is a major problem for the river-side dwellers of the city which could be exacerbated in this era of climate change (Dasgupta et al. 2013). The Chennai city is more prone to tropical disturbances, and cyclones, which often leads to flooding of major rivers and clogging of drainage systems (Boyaj et al. 2018). A major flood event occurred in December 2015 was reported as one of the most disastrous floods in the history of the region (Assessment AR 2016, vandenborgh et al. 2016). In spite of numerous flood occurrences, there is a knowledge gap in assessing the impact of climate change on flooding over urban areas. However, floods in Mumbai and Kolkata are attributed to the impact of climate shifts, urbanization, sea-level rise and other regional factors.

6.3.2 River Floods

The major river basins of South Asia such as the Brahmaputra, Ganga, Meghna, Narmada, Godavari and Mahanadi are mainly driven by the SW and NE monsoons apart from snow and glacier melt for Himalayan rivers (Mirza 2011). River basin scale flooding is generally due to the occurrence of extreme rainfall as well as variations in the factors associated with the basin catchment characteristics (e.g. Mishra and Lilhare 2016). Several intense floods were recorded in all the large river basins in South Asia during the second half of the twentieth century, such as the 1968 flood in the Tapi river, the 1970 flooding of the Narmada, the 1978 and 1987 floods on the Ganga, the 1956 and 1986 floods in the Indus river, the 1979 flood of the Luni river, the 1982 flooding of the Mahanadi river, the 1986 flooding of the Godavari river, the 1988 and 1998 floods of the Brahmaputra and the catastrophic flood of 2010 along the Indus basin (Kale 2012). River basins located in Central India, i.e. Ganga, Narmada-Tapi and Godavari, exhibit a significant increasing trend in the area covered by heavy rainfall episodes, during the monsoon season for the period 1951–2014 (Deshpande et al. 2016), which has lead to increased flooding over these basins. The increase in flood events over the Ganga-Brahmaputra basin is compounded by subsidence of land (Higgins et al. 2014) as well as glacier and water from snowmelt feeding into these rivers (Lutz et al. 2014). Hence, in a global warming scenario, melting of glaciers and snow could get accelerated and could lead to larger flood risks in the Himalayan rivers.

River floods are found to have a close association with ENSO events. A strong connection between rainfall over the Ganga-Brahmaputra-Meghna basin and the Southern Oscillation Index (SOI) was identified (Chowdhury 2003), with less than normal rainfall during the negative phase of the SOI (El Niño) whereas severe flooding due to significant increase in rainfall during positive SOI (La Niña). Moreover, major floods over the basin have occurred during La Niña years and also La Niña years co-occurring with negative IOD events (Pervez and Henebry 2015). The extreme floods across the Brahmaputra river in 1988 (Bhattacharyya and Bora 1997), 1998 (Dhar and Nandargi 2000), 2012, 2016, 2017; over the Narmada river in 1970, 2012, 2016 and over the Indus river in 1956, 1973, 1976, 2010 (Houze et al. 2011;

Webster et al. 2011; Mujumdar et al. 2012; Priya et al. 2015) have also occurred during La Niña years. Thus indicating that, in addition to the regional factors, remote forcing also has a strong influence on the flood occurrences in the Indian river basins.

In general, the increasing trend in the heavy rainfall events is found to be the major factor for the rising trend in flood occurrences in India. However, with the limited observational flood records, it is difficult to ascertain whether the increasing trend in floods is attributed to natural climate variability or to anthropogenically driven climate change. In this context, an assessment of palaeoclimatic records from the Indian subcontinent can provide crucial information on the natural variations in floods during the pre-instrumental era and the same is provided in the next section.

6.3.3 Palaeoclimatic Evidences

Palaeoclimate records from Indian peninsular rivers have indicated the occurrence of floods in the ancient period as well (Kale and Baker 2006; Kale 2012). Moreover, considerable variations in the frequency and magnitude of large floods during the last two millennia are observed in some of the western, central and south Indian rivers such as Luni, Narmada, Tapi, Godavari, Krishna, Pennar and Kaveri. The Late Holocene period witnessed clustering of large floods whereas extreme floods were absent during the late MWP and LIA (Kale and Baker, 2006; Kale 2012). This suggests a close association of century-scale variations in river floods with the variations in monsoon rainfall across the Indian subcontinent. However, a comparison of the Late Holocene floods with the post-1950 floods over palaeoflood sites in the Indian peninsular rivers indicates that the recent flood events are more intense than those during the past (Kale and Baker 2006; Kale 2012).

6.4 Future Projections

India has witnessed an increase in the frequency of droughts and floods during the past few decades. Notably, the humid regions of the central parts of India have become drought-prone regions. Also, the flood risk has increased over the east coast, West Bengal, eastern Uttar Pradesh, Gujarat and Konkan region, as well as a majority of urban areas such as Mumbai, Kolkata and Chennai (Guhathakurta et al. 2011). Given the adverse impacts of droughts and floods on food and water security in India, it is imperative to understand the future changes in drought and flood characteristics projected to develop suitable adaptation and mitigation policies.

6.4.1 Droughts

Climate model projections indicate an increase in monsoon rainfall, however, the models also show a large inter-model spread leading to uncertainty (Turner and Annamalai 2012; Chaturvedi et al. 2012; Jayasankar et al. 2015). Apart from this, a probable increase in the severity and frequency of both strong and weak monsoon as indicated by strong interannual variability in future climate is suggested by a reliable set of CMIP5 models, identified based on their ability to simulate monsoon variability in the current climate (Menon et al. 2013; Sharmila et al. 2015; Jayasankar et al. 2015). Along with this, an increase in consecutive dry days has also been projected for the future (see Chap. 3 for details). However, drought severity and frequency in the future warming climate remain largely unexplored over India and are considered in a limited number of studies. Hence, to bring out characteristics of future droughts, additional analysis is undertaken using six dynamically downscaled simulations using the regional climate model RegCM4 for historical, RCP 4.5 and RCP 8.5 scenarios till the end of the twenty-first century. These simulations are available from CORDEX South Asia experiments, and details are provided in Box 2.3, Table 2.6 (see list of IITM-RegCM4).

Similar to the observations, discussed in Sect. 6.2 (see Box 6.1), the SPEI drought index is computed for 4-month, 3-month and 12-month timescales spanning the JJAS (SPEI-SW), OND (SPEI-NE) seasons and annual from January to December (SPEI-ANN), for 1951–2099 with respect to the base period 1976–2005. Monthly rainfall and PET computed using the Penman-Monteith formula, from the six downscaled historical, RCP 4.5 and RCP 8.5 experiments, are used to derive SPEI. Consistent with the observation (Fig. 6.1a–c), the ensemble mean of CORDEX simulations (Fig. 6.6a–c) depicts a weak negative trend in SPEI for both the monsoon seasons and annual timescale. The large spread among the different members indicates low skill in simulating the rainfall variability over the Indian subcontinent, as mentioned earlier. The future projections, however, depict a spread larger than the historical period for both the scenarios RCP 4.5 and RCP 8.5, for all the seasons (Fig. 6.6a–c). The spread is seen more notably, especially for the SW monsoon season (Fig. 6.6a) and for RCP 8.5 scenario (Fig. 6.6a–c). In spite of the large spread, the ensemble mean projected a weak declining trend till 2070 for all the time series in both the scenarios. A stronger decreasing trend is projected for the post-2070 period by the high emission RCP 8.5 scenario compared to the medium emission scenario of RCP 4.5. Also, a weak increasing trend in drought area is simulated for the historical period, compared to that of observations (Fig. 6.1d–f). Similar to drought intensity (Fig. 6.6a–c), large spread among the

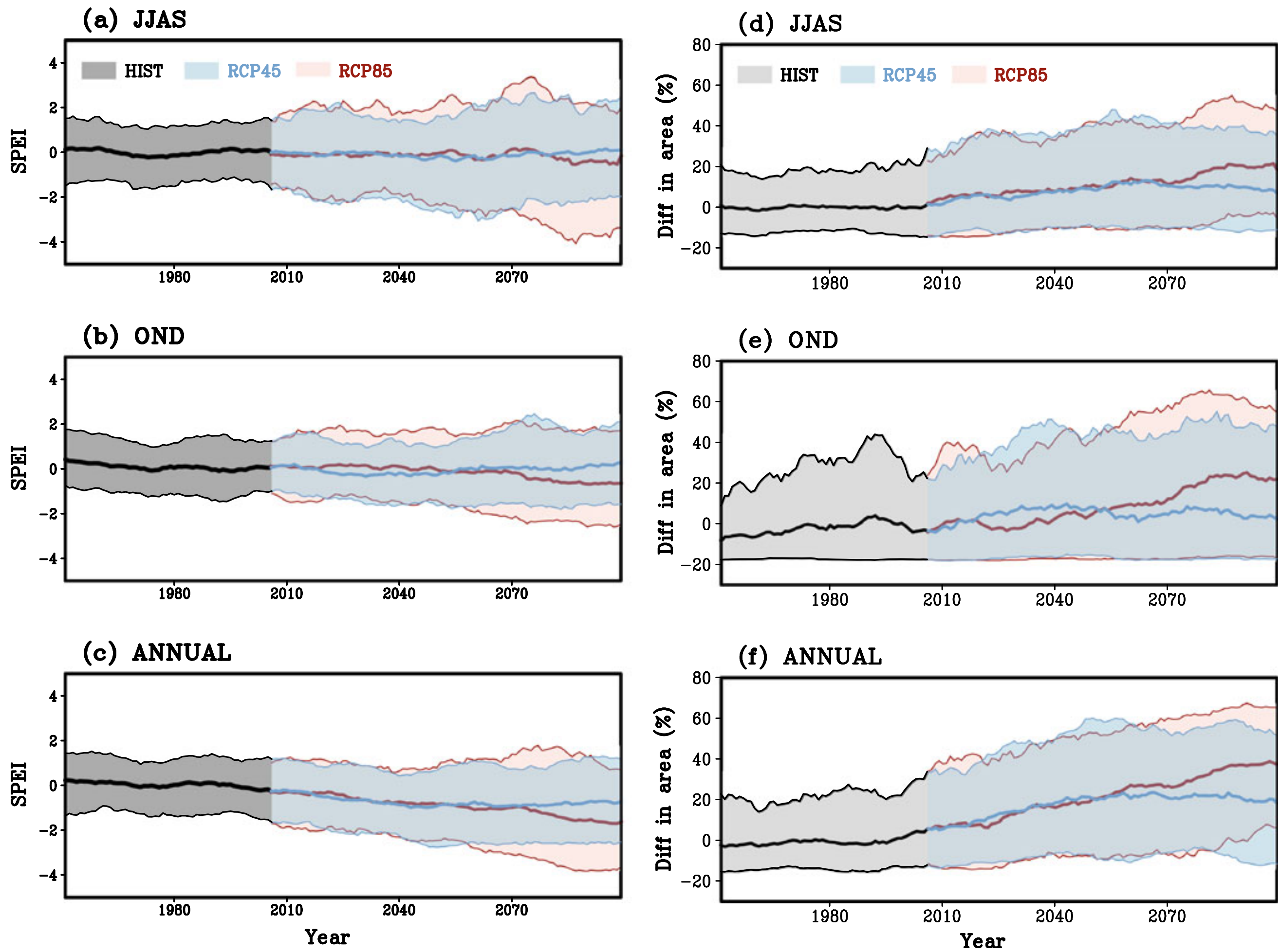

Fig. 6.6 Time series of **a**–**c** SPEI and **d**–**f** difference in percent area affected by drought during 1951–2099 (relative to 1976–2005), from six CORDEX South Asia downscaled regional climate simulations for **a**, **d** SW monsoon **b**, **e** NE monsoon and **c**, **f** annual scale. The historical simulations (grey) and the downscaled projections are shown for RCP4.5 (blue) and RCP8.5 (red) scenarios for the multi-RCM ensemble mean (solid lines) and the minimum to the maximum range of the individual RCMs (shading)

ensemble members is noted in all the timescales (Fig. 6.6d–f). Compared to the historical period, the spread is larger in the future projections, indicating the difficulty in estimating the drought characteristics for the future. For 2006–2099, the dry area is projected to increase by 0.84%, 0.35% and 1.64% per decade under RCP 4.5 scenario for SW, NE monsoons and annual timescale, respectively. A significant (95% confidence level) increase of 1.87, 3.22 and 3.81% per decade are projected for the respective seasons under RCP 8.5 scenario. It is interesting to note that the projected trends in dry areas are slightly higher for annual scale droughts. Under the RCP 4.5 scenario, the drought area is projected to reduce slightly after the 2070s until the end of the century.

Under RCP 4.5 scenario, the ensemble mean frequency of SW monsoon droughts is projected to increase by 1–2 events per decade over central and northern parts of India with more than two droughts over eastern parts of India in both near (2040–2069) and far (2070–2099) future, against the reference period of 1976–2005. On the other hand, a decrease of 1–2 drought events per decade is projected over southern peninsular India under RCP 4.5 scenario (Fig. 6.7a, d). Under RCP 8.5, more frequent occurrence of moderate and severe SW monsoon droughts (>2 events per decade) is projected over Gangetic plains, north-west and central parts of India while a reduction in drought frequency is projected over south peninsular India (Fig. 6.7g, j). For NE monsoon, the drought frequency is projected to increase by 1–2 events under RCP 4.5 scenario (Fig. 6.7b, e), whereas an increase by more than two events per decade in the far future is indicated under RCP 8.5 scenario (Fig. 6.7h, k). An increase of more than three annual scale drought events per decade is suggested for north-west India during the twenty-first century under RCP 4.5 scenario (Fig. 6.7c, f). The increase in drought frequency (>3 events per decade) for the near future (Fig. 6.7i) is larger under RCP 8.5 scenario in comparison with RCP 4.5. Moreover, the area with more than three

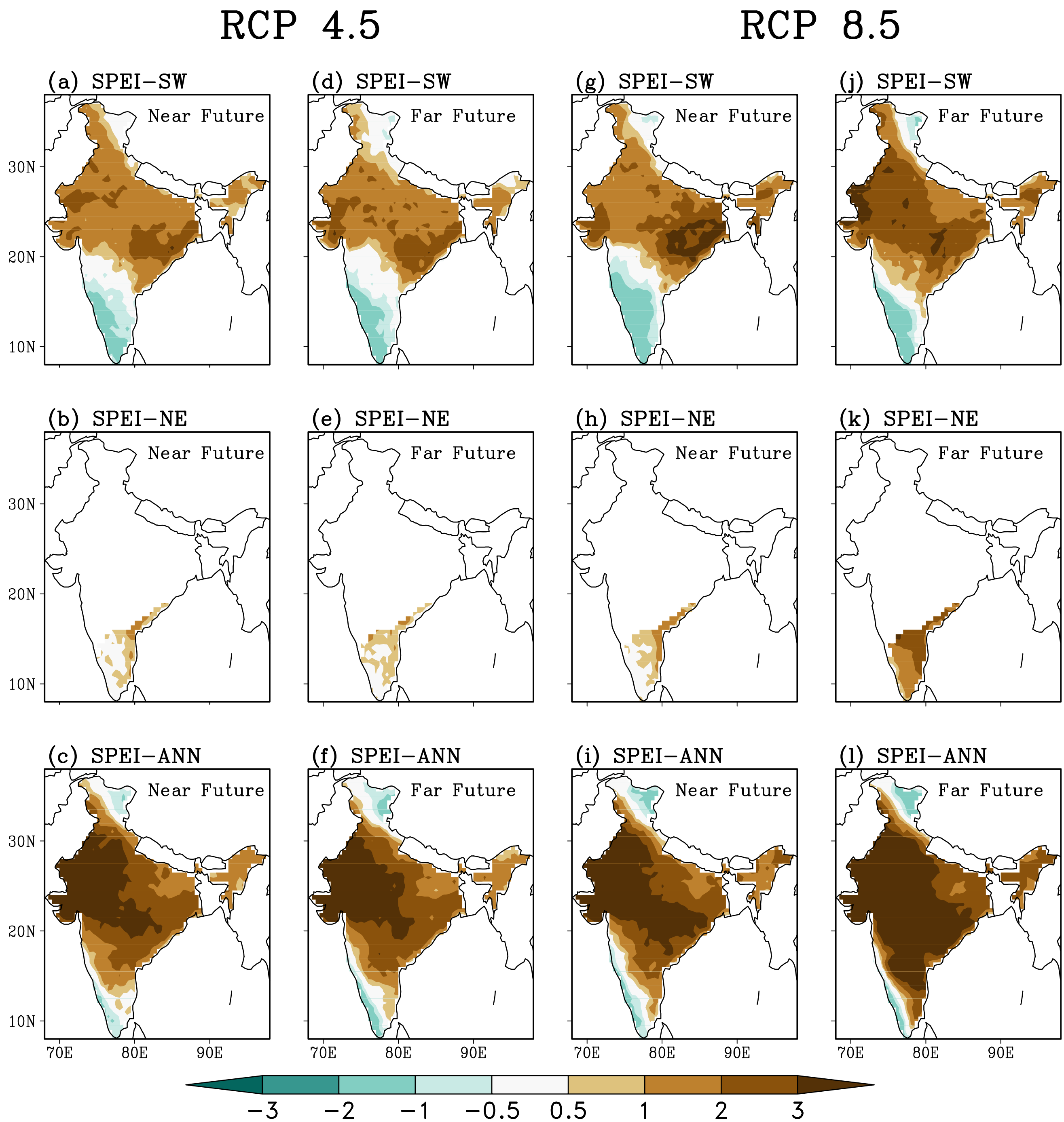

Fig. 6.7 Changes in frequency (per decade) of moderate and severe droughts (SPEI ≤ −1) for **a**, **d**, **g**, **j** JJAS, **b**, **e**, **h**, **k** OND and **c**, **f**, **i**, **l** annual timescale, projected by multi-model ensemble of six CORDEX simulations for **a–c**, **g–i** near future (2040–2069) and **d–f**, **j–l** far future (2070–2099) from **a–f** RCP4.5 and **g–l** RCP8.5 scenarios, with respect to the historical period (1976–2005)

drought events per decade is projected to expand across most of the regions in India by the end of the twenty-first century under RCP 8.5 scenario (Fig. 6.7l). Thus, more frequent droughts are projected under RCP 8.5 in comparison with RCP 4.5 for all the timescales.

Similar results are obtained from various climate model studies. A probable increase in drought intensity over the Indian region towards the end of the twenty-first century is suggested under the RCP 4.5 scenario (Krishnan et al. 2016). SPEI index derived from 5 CMIP5 climate models indicates a possibility of more frequent occurrences of severe droughts by the end of the twenty-first century under both RCP 4.5 and RCP 8.5 scenarios. The similar results are reproduced using CORDEX South Asia experiments (Spinoni et al.

2020). The area affected by severe drought is also projected to increase by 150% with warming under RCP 8.5 scenario (Aadhar and Mishra 2018). Another study using a subset of 9 CMIP5 model simulations also suggests a high likelihood of above moderate drought conditions along with a significant rising trend in a drought area and an increase in the average drought length in a warming climate under RCP 4.5 and RCP 8.5 scenarios (Bisht et al. 2019). Using multiple drought indices like PNP, SPI and percentage area of droughts, two CMIP5 models, which adequately simulate frequent droughts during recent decades, have projected frequent occurrence of droughts during near and mid future, with a pronounced intensification over Central India, dynamically consistent with the modulation of the monsoon trough under RCP 4.5 scenario (Preethi et al. 2019).

On the other hand, few studies have revealed contradicting drought projections. For example, a study using drought projections based on SPI shows a decrease in the drought frequency in the twenty-first century (Aadhar and Mishra 2018). A global analysis of the CMIP5 projections of a drought hazard index based on precipitation in a warming climate (Carrão et al. 2018) evaluated that although drought has been reported in the agriculture dominated parts of India at least once in every 3 years during the past five decades, the CMIP5 ensemble mean for the present time period is found to be less consistent with the observed drought hazard index over subtropical western India. Further, this study concluded that although the clear signals of wetting are found in the CMIP5 simulations for the core monsoon zone in South Asia-east India, the projected future changes in drought hazard are neither robust nor significant for this region. Also the SPEI analysis, based on CORDEX simulations, suggests that the projected future change in drought frequency is not robust over India (Spinoni et al. 2020).

It is interesting to note that recent climate modelling studies suggest a possible frequent occurrence of El Niño events in the future (Cai et al. 2014; Azad and Rajeevan 2016) with a stable inverse relationship between El Niño and monsoon rainfall (Azad and Rajeevan 2016). This is in turn indicative of the persistent influence of El Niño events on the Indian monsoon droughts in the future. Moreover, in a warming climate, the rise in atmospheric water demand (or PET) can lead to depletion of soil moisture and prolonged drought conditions (Scheff and Frierson 2014; Ramarao et al. 2015; Krishnan et al. 2016). In summary, the above studies using regional as well as global models indicate that there is a high likelihood of an increase in the frequency, intensity and area under drought conditions even in a wetter and warmer future climate scenario. However, the large spread in the model simulations and implementation of different drought indices introduces uncertainties in analysis which eventually brings down confidence in future projections of droughts. In spite of that, an increase in droughts in the future can pose a severe threat to the availability of regional water resources in India and highlight the need for better adaptation and water management strategies.

6.4.2 Floods

Many studies have projected a possible increase in extreme precipitation events in a warming environment (see Chaps. 3, 7, and 8 for further details), which could likely increase the flood risk over the Indian subcontinent. Analysis of precipitation extremes under 1.5 and 2.0 °C global warming levels (GWL), committed under the "Paris Agreement", suggested a rise in the short duration rainfall extremes and associated flood risk over urban areas of India (Ali and Mishra 2018). The increase in temperature over Indus-Ganga-Brahmaputra river basins, which are highly sensitive to climate change, is projected to be in the range of 1.4–2.6 °C (2.0–3.4 °C) under 1.5 °C (2 °C) GWL. A further amplified warming is projected under RCP 4.5 and RCP 8.5 scenarios, possibly leading to severe impacts on streamflow and water availability over these river basins (Lutz et al. 2019). Due to the proximity of Indus-Ganga-Brahmaputra river basins to the foothills of the Himalayas, the run-off is projected to increase primarily by an increase in precipitation and accelerated meltwater in a warming environment, at least until 2050 (Lutz et al. 2014). Other major river basins of India also suggest an increase in run-off in the future, with the most significant change over the Meghna basin, indicating a high probability for flood occurrences (Mirza et al. 2003; Mirza 2011; Masood et al. 2015).

The projected changes in the frequency of extreme flooding events of 1-day, 3-day and 5-day duration for the periods 2020–2059 and 2060–2099 estimated based on the 20-year return period streamflow values with respect to the historical base period (1966–2005) are provided in Fig. 6.8 (modified from Ali et al. 2019). A higher increase in 1-day flood events is projected for the far future than that of the near future under RCP 8.5 scenario (Fig. 6.8a). The highest increase is located over the Brahmaputra basin as well as the river basins in the central parts of the Indian subcontinent, while the least increase is seen over the Indus basin. It can also be noticed that the projected increase in multi-day (3 and 5 days) flood events is more compared to one-day events across all the river basins under both RCP 2.6 and RCP 8.5 scenarios (Fig. 6.8). The increase in the frequency of all the flood events of different duration is more in the high emission scenario of RCP 8.5 compared to low emission scenarios of RCP 2.6. In another study, a rise in flood frequency, with respect to the magnitude of floods of 100-year return periods in the historical simulation, is projected over the majority of the Indian subcontinent in the twenty-first century under the RCP8.5 scenario by CMIP5

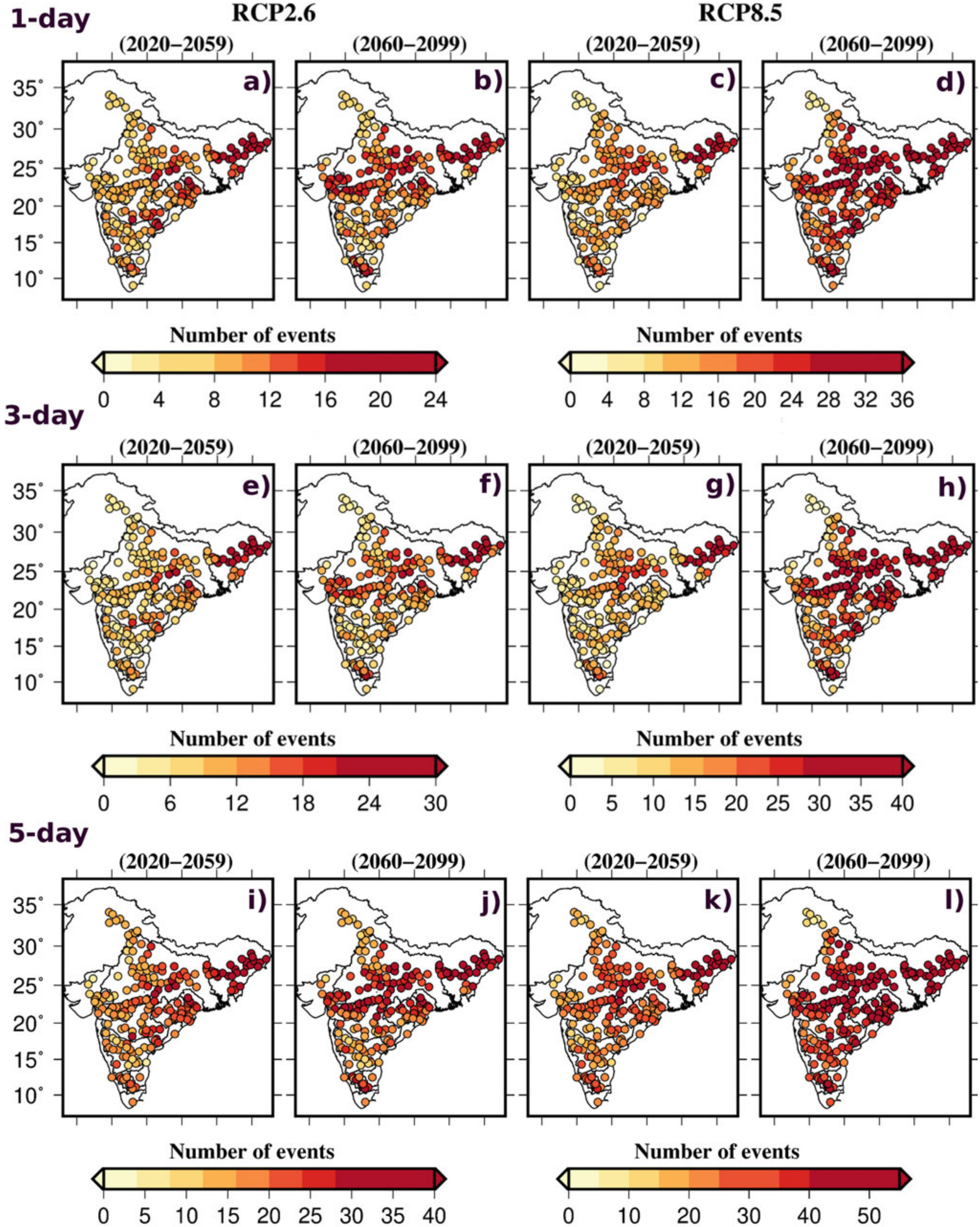

Fig. 6.8 Changes in frequency of **a**–**d** 1-day, **e**–**h** 3-day and **i**–**l** 5-day duration extreme flood events, projected for **a**, **e**, **i**; **c**, **g**, **k** near future 2020–2059 and **b**, **f**, **j**; **d**, **h**, **l** far future 2060–2099, exceeding 20-year return level based on the historic period 1966–2005, as derived from the ensemble mean of five GCMs for **a**, **b**; **e**, **f**; **i**, **j** RCP2.6 and **c**, **d**; **g**, **h**; **k**, **l**) RCP8.5 scenario (Modified from Ali et al. 2019)

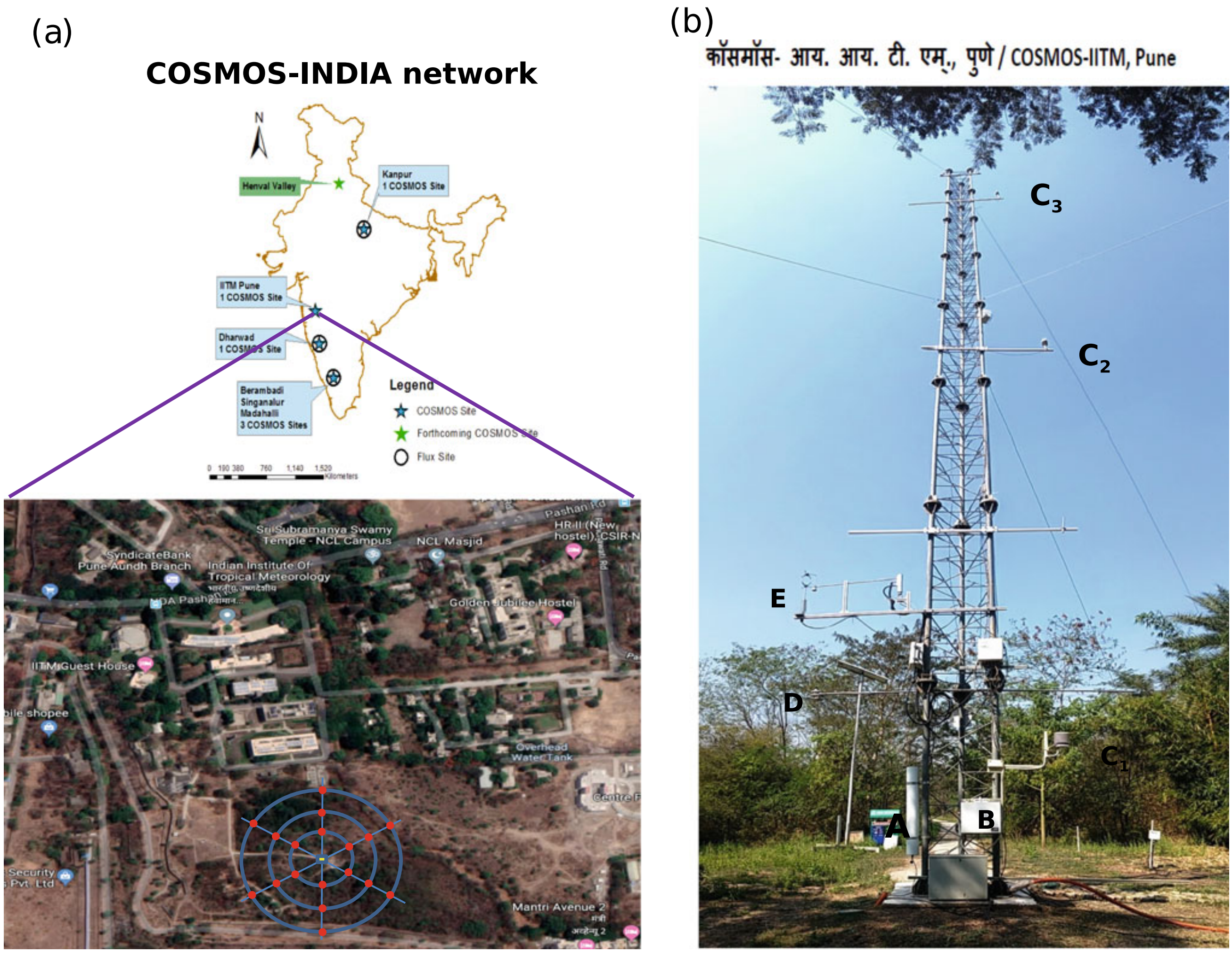

Fig. 6.9 **a** COSMOS-INDIA network, **b** COSMOS-IITM site. Notation A, B, C, D and E are used to indicate different hydro-meteorological sensor installed at COSMOS-IITM site Pune. A—COSMOS Probe; B—Data logger; $C_{1,2,3}$—Multiweather component sensor; at 2 heights 10 and 20 m; D—Net radiometer E—Eddy covariance system

models. The southern peninsular India, Ganges, and Brahmaputra basins are projected to experience floods of similar magnitude at a higher frequency (<15 years) in the twenty-first century, with high consistency among the models (Hirabayashi et al. 2013). The majority of studies projected an increasing flood risk for Indus-Ganga-Brahmaputra river basins (Higgins et al. 2014; Shrestha et al. 2015; Kay et al. 2015; Wijngaard et al. 2017; Lutz et al. 2019) and these basins are considered as hotspots in a changing climate (De Souza et al. 2015). The increased flood risk in terms of frequency and duration of flood events can exert profound impacts on food production, water resources and management. Additionally, the human-induced influences such as land-use changes, irrigation, mismanagement of dams and reservoirs can aggravate the magnitude and the frequency of flood events in the future.

6.5 Knowledge Gaps

This section highlights some of the knowledge gaps that would be of relevance for future studies on drought and flood assessments.

1. Lack of dense observational networks for essential climate variables like soil moisture, surface and sub-surface energy, water fluxes, stream flow, etc. limits our scientific understanding of the complex multiscale (spatial and temporal) interactions taking place in the climate system. To better understand the processes involved in the variations of intensity and duration of floods and droughts over India in a warming climate, novel observational datasets are highly required. For example, network of the

newly developed neutron scattering method, used in non-invasive Cosmic ray soil moisture monitoring system (COSMOS), could potentially help scale gap between the conventional point scale, remote sensing techniques and model simulations of surface soil moisture (see Fig. 6.9 and Mujumdar et al. 2017b).
2. Attribution of anthropogenically induced climate change to the variability of drought and floods in historical as well as future projections remains a challenging issue and an open problem for further scientific research.
3. Model uncertainties in reproducing the observed variability of droughts and floods, as well as the spread among the models, also hamper our confidence in assessing future changes. Thus efforts are needed for reducing the model uncertainties.
4. Assessing the impact of increasing urbanization, as well as agricultural intensification on the hydroclimatic extremes of heavy rains/floods and droughts, continues to be a challenge for the Indian monsoon region, and additional multiscale assessments are critically needed.

6.6 Summary

A detailed assessment of the long-term variability of droughts and floods in the current as well as future climate is presented in this chapter, in view to support a better framing of climate mitigation and adaptation strategies in India. Indian subcontinent witnessed a decline in monsoon rainfall along with frequent occurrences of droughts and flood events in the past few decades, in association with the changes in regional and remote forcings. Besides, many studies projected a probable increase in these hydroclimatic extreme events in a warming environment.

The analysis of SPEI over India for the period 1901–2016 identified more droughts ($\sim$2 per decade) compared to wet (1–2 per decade) monsoon years. For the post-1950 period, a high frequency of droughts along with an expansion of dry area at a rate of 1.2, 1.2 and 1.3% per decade is observed in SW, NE monsoon seasons and annual timescale, respectively. In the humid regions of the country, particularly the parts of Central India, Indo-Gangetic plains, south peninsula and north-east India experienced significant drying trend with more intense droughts during SW monsoon season. On the other hand, the east coast and southern tip of India show slight wetting trend during the NE monsoon season. In recent decades (post-1950 period), droughts have been more frequent (>2 droughts per decade on average) over Central India, Kerala, some regions of the south peninsula, and north-eastern parts of India, making these regions more vulnerable. These results are consistent among various studies (Pai et al. 2011, 2017; Niranjan Kumar et al. 2013; Damberg and AghaKouchak 2014; Mallya et al. 2016; Krishnan et al. 2016; Mishra et al. 2016; Preethi et al. 2019; Yang et al. 2019). Thus, it is assessed with high confidence that the frequency and spatial extent of droughts over the country have increased significantly along with an increase in intensity, mainly confining to the central parts including the Indo-Gangetic plains of India, during 1951–2016. These changes are observed in association with the decline in monsoon rainfall, which is likely due to an increase in anthropogenic aerosol emissions in the northern hemisphere, regional land-use changes as well as warming of the Indian Ocean. During this period, an increasing trend in floods is also reported over the majority of the Indian river basins associated with the rise in heavy rainfall episodes. In addition to the enhanced stream flow due to increase in extreme precipitation events, the floods over the Himalayan rivers are compounded by subsidence of land as well as glacier and snowmelt water feeding into these rivers. The observed increasing trend in heavy rainfall events combined with the intense land-use changes has resulted in more frequent and intense flash floods over urban areas, like Mumbai, Chennai, Bangalore, Kolkata, etc. (Guhathakurta et al. 2011). Though there is high confidence in the rising trend in extreme rainfall events and the associated flood risk over India, its attribution of climate change remains a challenging issue and an open problem for further scientific research.

Future projections of regional as well as global climate models indicate a high likelihood of an increase in frequency, intensity and area under drought conditions over India, with medium confidence due to large spread in model projections (Aadhar and Mishra 2018; Bisht et al. 2019; Preethi et al. 2019). Though the climate models project an enhanced mean monsoon rainfall, the projected increase in droughts could be due to the larger interannual variability of rainfall and the increase in atmospheric water vapour demand (potential evapotranspiration) over the country (Menon et al. 2013; Scheff and Frierson 2014; Jayasankar et al. 2015; Sharmila et al. 2015; Krishnan et al. 2016). Moreover, climate model projections also indicate frequent El Niño events in the Pacific Ocean with a stable inverse relation with the monsoon, which could also result in more number of monsoon droughts in future (Cai et al. 2014; Azad and Rajeevan 2016). The climate projections for India also indicate an increase in frequency of urban and river floods, under different levels of warming, 1.5 and 2.0 °C, as well as for different emission scenarios in association with an expected rise in heavy rainfall occurrences (Hirabayashi et al. 2013; Ali and Mishra 2018; Lutz et al. 2019). However, larger changes in flood frequency are projected in the high emission scenario of RCP 8.5. Flood frequency and associated risk are projected to increase over the major river basins of India, with a higher risk for the Indus-Ganges-Brahmaputra river basins in a warming climate (Lutz et al. 2014). The enhanced flood risk is likely due to increasing stream flow and run-off associated with the projected increase in frequency of extreme rainfall events over the major Indian river basins and is compounded by glacier and snowmelt over the Indus-Ganges-Brahmaputra. The projected enhanced droughts and flood risk over India highlight the potential need for a better adaptation and mitigation strategies.

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