Chapter 7

Impact of Climate Change on Drought Frequency over India

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Abstract

Historical observations suggest that severe drought frequency has been increasing in the recent decades over India. In the future climate, significant variability and change in monsoon rainfall and temperature would further affect the future drought conditions. Here, we analysed data from five Global Climate Models (GCMs) that participated in the coupled model intercomparison project-5 (CMIP5) to estimate the changes in drought conditions under the warming climate in India. Our analysis show more frequent droughts in the warming climate in near (2011-2040), mid (2041-2070), and end (2071-2100) period using standardized precipitation evapotranspiration index (SPEI) whereas the drought projections based on just precipitation (Standardized Precipitation Index: SPI) show a decrease in the drought frequency in the 21st century. The change in drought frequency is projected to increase by more than two-three severe droughts per decade over the majority of India using SPEI in the end period. The increased warming resulted in an increased atmospheric water demand (potential evapotranspiration: PET) in the region, which is reflected in the increased drought frequency. The change in area under severe drought is projected to increase by 150% at the end of the 21st century using SPEI against the reference period 1971-2000. Overall, we conclude that the drought frequency of severe drought is projected to increase in warmer and wetter future climate in India and the increased frequency of droughts can largely attributed to increased PET due to anthropogenic warming. This chapter highlights that despite the projected increase in the monsoon season precipitation, the risk of frequent droughts in India is higher under the warming climate, which will have implications to water management in the future.

7.1. Introduction

India is the world's second most populated country where the majority of the population depends on agriculture for livelihood. In the last few decades, increasing drought frequency (Mishra et al., 2016) and weak summer monsoon (Roxy et al., 2015) have adversely affected agriculture production, water availability, and socio-economic conditions. Moreover, the growing population and declining water availability pose further challenges to food and water security in the future in India.

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Drought hampers surface and groundwater availability and can create a disaster situation in any place. For instance, in India, more than 300 million people were affected due to the extreme drought in 2002 (Bhat, 2006). In 2014 and 2015, the Gangetic region and Maharashtra experienced more than 500 year return period drought that resulted in severe water scarcity and affected millions of people living in these regions (Mishra et al., 2016) Increased CO_2 emissions due to anthropogenic activities has triggered changes in the global climate in the past decades (Reichstein et al., 2013; Wang et al., 2015). In the changing climate, weak Indian Summer Monsoon (ISMR) has been reported in India (Roxy et al., 2015; Sinha et al., 2015). India has faced frequent and severe drought (once in every three years) in the last few decades (Aadhar and Mishra, 2017; Mishra et al., 2016; Shah and Mishra, 2015). However, drought severity and frequency in the future warming climate remains largely unexplored over India.

Here, using the observed and future simulations, we report the changes in the drought frequency in the past and future projected climate over India. Future simulations using the global climate models (GCMs) from Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012, 2007) have been widely used in hydro-climatic (Mishra et al., 2017; Mukherjee et al., 2018; Trenberth et al., 2014; Zarch et al., 2015) studies for future projection. We use Standard Precipitation Index (SPI) (Mckee et al., 1993) to measure the meteorological drought over the study region. SPI calculates the precipitation deficit for multiple time scale at the end of a particular period. However, SPI does not consider the role of temperature in drought. Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), which considers the role of temperature by estimating PET, is also used. Based on the SPI and SPEI drought indices, we assess the frequency and areal extent of severe drought (drought index < -1.2) events in observed and future climate across India. The information of drought in future warming climate can be helpful to develop the mitigation and adaptation policies in this region.

7.2. Observed and Model Data.

We obtained monthly gridded observed precipitation data from India Meteorological Department (IMD) at 0.25° spatial resolution for the period 1951-2016. The gridded dataset was developed using 6995 stations across India (Pai et al., 2015). Station data were interpolated using Inverse Distance Weighting (IDW) interpolation method as described in Shepard (1968). The gridded dataset effectively captured the features of precipitation variability and climatology over India and showed a better representation of orographic precipitation in the Western Ghats and north-eastern India (Shah and Mishra, 2015). Moreover, the dataset captured the extreme rainfall variability very well in the foothill of Himalaya region and Western Ghats (Kumar et al., 2013; Pai et al., 2014). The IMD-rainfall dataset has been widely used in drought studies over India (Mishra et al., 2016; Shah and Mishra, 2015). Detailed information about data development can be obtained from Pai et al. (2015).

Also, we used temperature data in this study to analyse the combined effect of precipitation and temperature on droughts. We obtained monthly observed minimum and maximum temperature datasets from IMD at 1° resolution from 1951-2016. Temperature data were developed using 395 quality controlled observing stations across India (Srivastava et al., 2009), and gridded using a modified angular distance weighting interpolation method (Shepard, 1968; Srivastava et al., 2009). Further, we regridded the minimum and maximum temperature data from 1° to 0.25° resolution (for consistency with precipitation data) using the lapse rate method described by Maurer et al. (2002).

For future drought projection, we obtained daily Precipitation, minimum and maximum temperature data from Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012, 2007) global climate models (GCMs) from the r1i1p1 experiment for RCP 4.5 and RCP 8.5 (https://esgf-node.llnl.gov/search/cmip5/) for the period 2006-2100. We selected five GCMs (GFDL-CM3, GFDL-ESM2M, NorESM1-M, MIROC-ESM, and MIROC-ESM-CHEM) out of about 40 CMIP5-GCMs based on their skill to simulate the monsoon rainfall over India. Our selection of the best five models was consistent with other studies (Jayasankar et al., 2015; Saha et al., 2014). Further, we downscaled (Maurer et al., 2002) the CMIP5-GCMs data at 0.25° resolution and corrected the bias in GCMs data against the observed IMD data for the historic (1951-2005) and future (2006-2100) periods. Bias correction in GCMs was performed using the trend-preserving statistical method developed within the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) as described in Hempel et al. (2013).

7.3. Drought Analysis.

We analysed the observed data from IMD from 1951-2016 for historical drought information and CMIP5 GCMs data for future projection of drought over India. Standardized Precipitation Index (SPI) (Mckee et al., 1993) and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) drought indices are used to estimate the severe drought frequency (SPI or SPEI < -1.2). R SPEI (Čadro and Uzunovi, 2013) package was used to evaluate the 4-month or 12-month SPI and SPEI drought indices in observed and future simulation using Gamma and log-logistic distribution, respectively. In SPEI, we used the Hargreaves-Samani method (Hargreaves and Samani, 1985) method to estimate the potential evapotranspiration (PET). PET estimated using the Hargreaves-Samani method showed similarity with the Penman – Montieth method (Kingston et al., 2009). We estimated the projection of drought severity for near (2011-2040), mid (2041-2070), and end (2071-2100) period in RCP 4.5 and RCP 8.5 scenarios.

7.4. Drought Frequency during the Observed Period.

Figure 7.1 illustrates the drought frequency during the observed period 1957-2016 in India. We used 4-month and 12-month SPI and SPEI drought indices to evaluate the severe drought (<-1.2) frequency and areal extent in the last few decades. The analysis shows that the large frequency (>10 events in last 60 years) of severe drought occurred in highly populated and agriculturally intense Indo-Gangetic Plain, North, South, and Eastern parts of India (Fig. 7.1). Recently, Mishra et al. (2016) reported an increase in the occurrence of drought in post-1960 compared with the pre-1960 period. We estimated the drought indices for 4-month and 12-month time-scale, which show the deficit in the monsoon season and annual cycle at the end of September and December, respectively. We also estimated area (%) under severe drought during the period 1957-2016 using SPI and SPEI for 4-month and 12-month time scales (Fig. 7.1e-f). We find that 1965, 1972, and 2002 were the most severe droughts in the last 60 years with more than 35% area under severe drought for the 12-month time-scale. Droughts estimated using SPEI show a higher drought frequency and area under drought compared to SPI, which considers only precipitation (Fig. 7.1).

7.5. Drought Frequency in the Changing Climate.

To evaluate the characteristics of drought in future climate, we estimated change in the severe drought (drought index <-1.2) frequency using SPEI and SPI (Fig. 7.2-4) in near (2011-2040), mid (2041-2070), and end (2071-2100) period against the reference period of 1971-2000 using multi-model ensemble mean of the five CMIP5-GCMs. Future drought severity was estimated for 12-month time-scale at the end of December using SPI and SPEI for the period 1971-2100 using the reference period 1971-2000. Figure 7.2 shows the change in the frequency of severe drought using 12-month SPI and SPEI drought indices for the near period. Frequency of severe drought changes from -1 to 3 severe drought events per decade in the near period (2011-2040) for RCP 4.5 and RCP 8.5 (Fig. 7.2). The ensemble mean of GCMs shows -0.5 to 1.5 drought events per decade under the RCP 4.5 scenario and decrease in severe drought events per decade under the RCP 8.5 across most of the regions in India using SPI. Change in drought frequency based on SPEI is projected to increase compared to estimates based on SPI indicating an elevated atmospheric water demand in the warming climate (RCP 4.5 and RCP 8.5). Under the RCP 4.5, the occurrence of severe drought is projected to increase by 1-1.5 events per decade in Gangetic plains, Northern, and part of southern India using SPEI. The projected increase is lower in SPI compared with SPEI. In the near period, increase in drought is more in the RCP 4.5 compared to the RCP 8.5 which shows more water scarcity under the RCP 4.5.

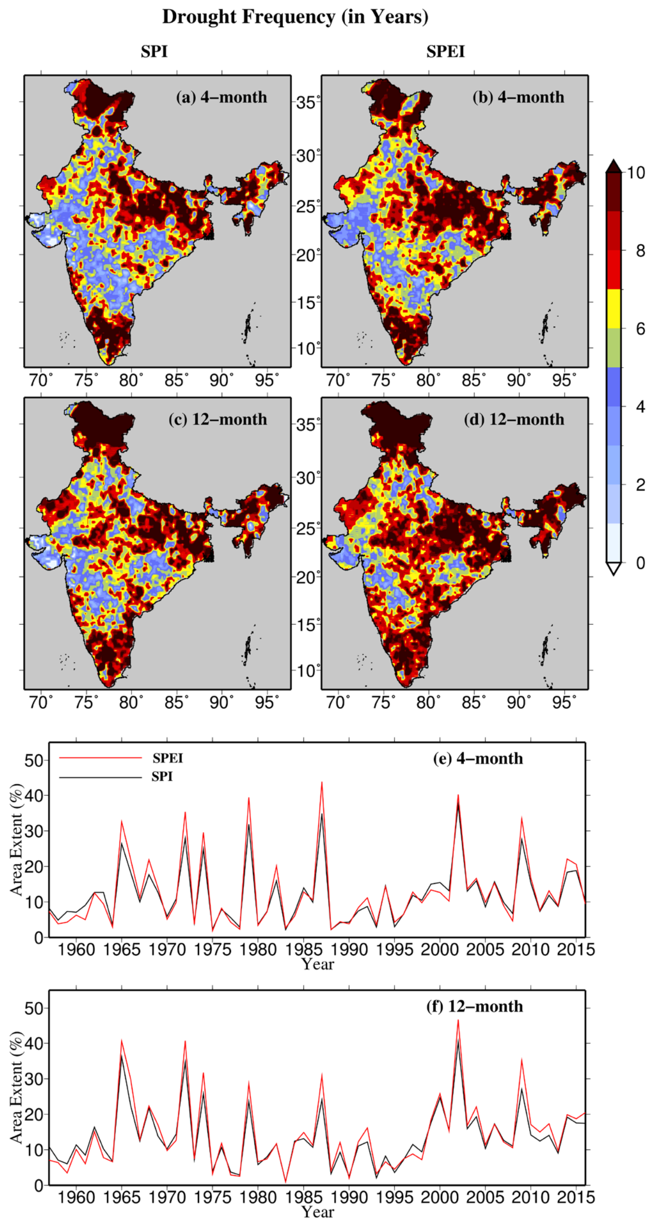

Figure 7.1 **Observed drought frequency and areal extent over India for the period 1957-2016. (a, b, c, d) Frequency of severe droughts (SPI or SPEI <-1.2) based on 4-month and 12- month SPI (Left) and SPEI (Right) at the end of September and December, respectively for the reference period 1971-2000. (e) percentage area under the severe drought using 4-month SPI and SPEI at the end of September and (f) percentage area under the severe drought using 12-month SPI and SPEI at the end of December.**

During the mid-period (2041-2070), change in severe drought frequency based on SPI is projected to decrease over the majority of India under the RCP 4.5 and RCP 8.5 while the occurrence of drought based on SPEI is projected to increase by more than 1.5 events per decade (Figure 7.3). Gangetic plain, Northern, and Southern regions show a high increase (more than two events per decade) in droughts based on SPEI under both RCP 4.5 and RCP 8.5 (Figure 7.3c-d). On the other hand, drought projection based on SPI show a decline in the frequency in the majority of India (Figure 7.3a-b). The decline in the drought frequency using SPI shows that precipitation is projected to increase in the mid-period. However, high drought frequency using SPEI shows an increase in atmospheric water demand in the mid-period compared to the reference (1971-2000) and near period (2011-2040).

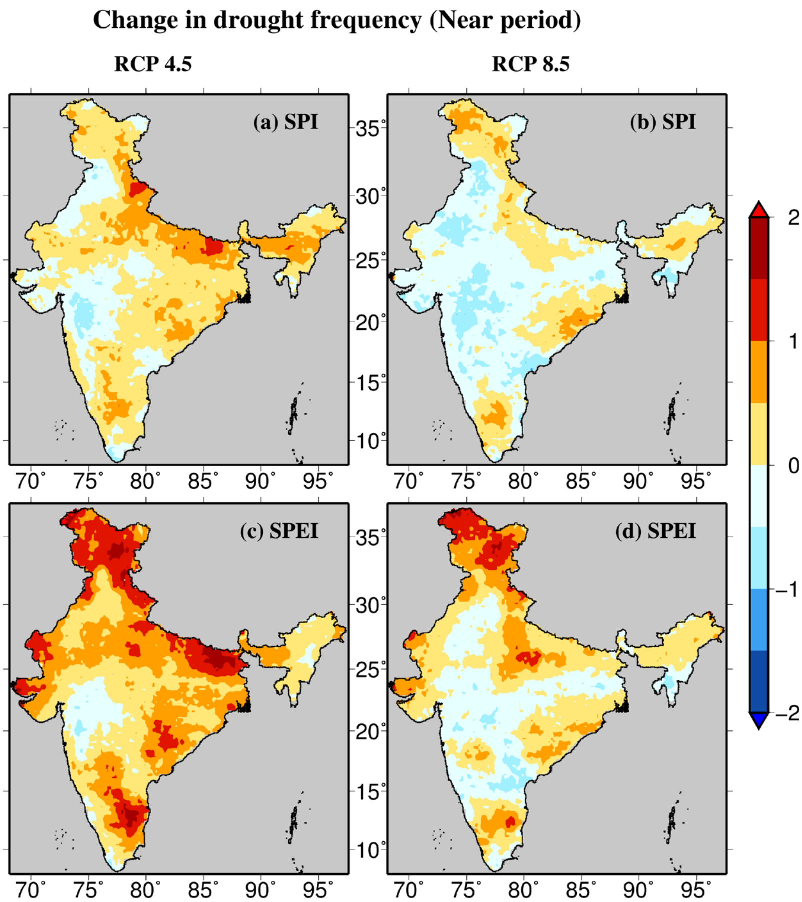

Figure 7.2 **Change in drought frequency (per decade) in near period (2011-2040). Change in the frequency of severe droughts (per decade) using five CMIP5-GCMs based on 12- month SPI (a, b) and SPEI (c, d) in the near period (2011-2040) against the reference period 1971-2000 in RCP 4.5 (left) and RCP 8.5 (right).**

Moreover, drought frequency is projected to increase more under RCP 8.5 in comparison to RCP 4.5 using SPI and SPEI. These results indicate towards more water scarcity under the RCP 8.5 in the mid-period (Fig. 7.3). In the end period, the projection of drought is significantly different using SPI and SPEI drought index (Figure 7.4). The severe drought frequency based on SPI is projected to decline during the end period. However, drought frequency based on SPEI is projected to increase by more than two events per decade in Northern and Southern India (Fig. 7.4c-d). Under RCP 8.5, drought frequency based on SPEI is projected to increase by 2-3 events per decade using SPEI showing a high risk of water availability at the end of the 21st century. Increase in the drought frequency based on SPI and SPEI is higher in the RCP 8.5 compared to the RCP 4.5. Since SPI does not consider the effect of temperature on drought estimation, it shows lesser drought frequency under the future warming climate (Figure 7.4). Therefore, drought projection using SPEI is more robust under the warming climate.

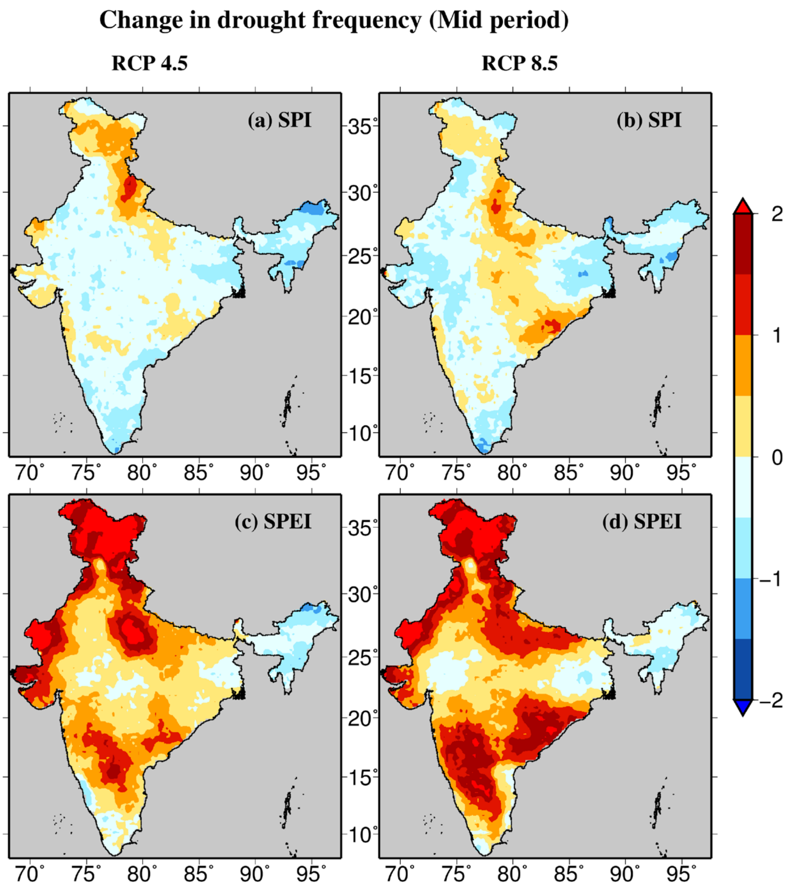

Figure 7.3 **Change in drought frequency (per decade) in mid period (2041-2070). Change in the frequency of severe droughts (per decade) using five CMIP5-GCMs based on 12- month SPI (a, b) and SPEI (c, d) in the mid period (2041-2070) against the reference period 1971-2000 in RCP 4.5 (left) and RCP 8.5 (right).**

We also estimated the changes in the area under severe droughts in India using 12-month SPEI and SPI for the period 2011-2100 against the reference period 1971-2000 under RCP 4.5 and RCP 8.5 (Figure 7.5). The change in drought area is estimated using 30-year moving mean starting from the year 2011 (2011-2040, 2012-2041, and so on) against the reference period 1971-2000. The area under severe droughts is projected to increase using SPEI in the RCP 8.5. Moreover, the change in the area is increased by 150% at the end of the 21st century against the reference period 1971-2000 using SPEI under the RCP 8.5. In the future climate, the area under severe drought based on SPI is projected to decrease under the RCP 4.5 while the area is projected to decrease constantly (about -10 %) under the RCP 8.5 (Fig 75). Similarly, based on SPEI, the area under the severe drought is projected to increase steadily (about 50-60%) under the RCP 8.5. Overall, the change in drought area and its frequency are projected to increase by the end of the 21st century using SPEI.

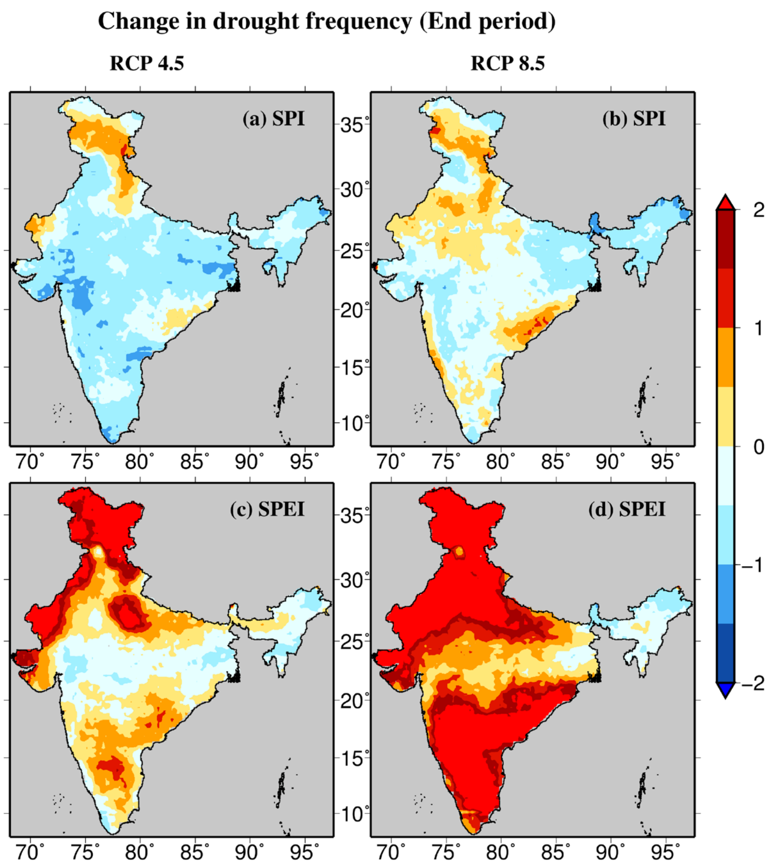

Figure 7.4 **Change in drought frequency (per decade) in end period (2071-2100). Change in the frequency of severe droughts (per decade) using five CMIP5-GCMs based on 12- month SPI (a, b) and SPEI (c, d) in the end period (2071-2100) against the reference period 1971-2000 in RCP 4.5 (left) and RCP 8.5 (right).**

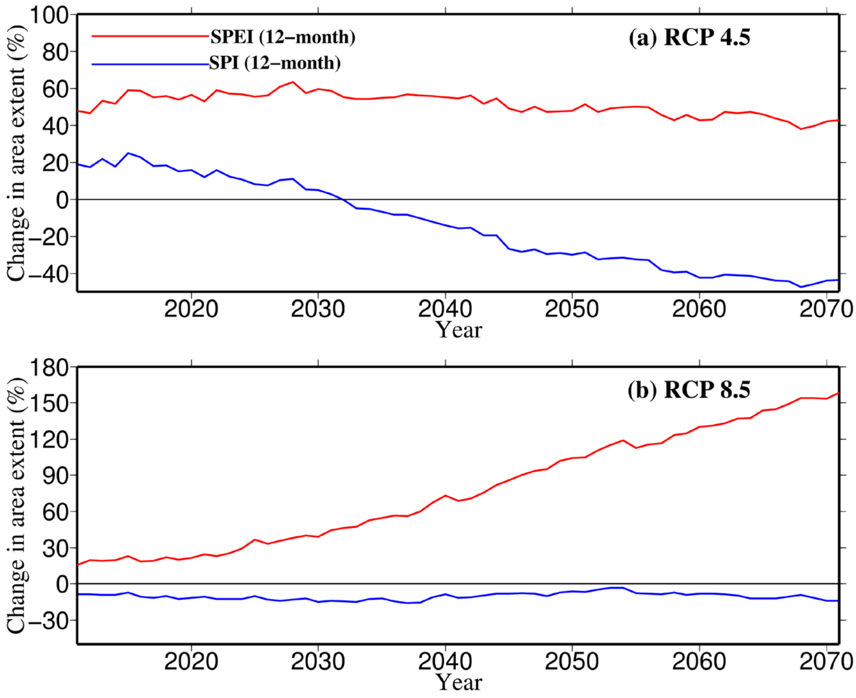

Figure 7.5 Multimodel ensemble mean changes (%) in the area under severe drought. Change (%) in area under the severe drought from 2011 using 30-year moving mean (2011-2040, 2012-2041, and so on) against the reference period 1971-2000 using 12-month SPI (blue) and SPEI (red) at the end of December in (a) RCP 4.5 and (b) RCP 8.5 scenarios.

7.6. Discussion and Conclusions

In Recent decades, drought severity has been reported to increase in the Indian region (Aadhar and Mishra, 2017; Dey et al., 2011; Mishra et al., 2016). Highly populated Indo-Gangetic plain is severely affected in recent decades with the occurrence of more than 9 severe drought events in the last 60 years (Mishra et al., 2016). Sinha et al. (2015) reported that Indian summer monsoon rain (ISMR) is currently in the decreasing phase of multi-decadal oscillation using two millennia proxy data. Assessing the drought severity information for changing climate is helpful for this region to develop adaptation and mitigation policies related to climate change. Recent studies reported strong ISMR under the future climate (Jayasankar et al., 2015; Lee and Wang, 2014). However, strong monsoon does not confirm the less drought severity in the region. Since, atmospheric water demand is projected to increase with warming in the future climate (Roderick et al., 2015; Scheff and Frierson, 2015).

Here, we studied the spatial extent and frequency of severe drought events in under warming climate using the five CMIP5-GCMs. The projections of droughts using the SPI and SPEI are significantly different under the future warming climate. Dissimilarities in the projection of drought using SPI and SPEI are mainly due to the lack of consideration of the role of temperature in the SPI under the warming climate (Vicente-Serrano et al., 2010).

More frequent severe drought events based on SPEI are projected by the end of the 21st century under both the RCP 4.5 and RCP 8.5. Due to projected increase in monsoon rainfall (Jayasankar et al., 2015; Turner and Annamalai, 2012), SPI shows less frequent droughts in the end period as it neglects the effect of atmospheric water demand. Under the warming climate, the temperature is projected to increase, which affects the atmospheric water demand (PET) and drought conditions (Greve et al., 2014; Scheff and Frierson, 2014). Under the RCP 8.5, the majority of the country shows high-frequency of severe drought events (more than three severe events per decades) in the end period. The area affected by severe drought is projected to increase by 150% with warming under the RCP 8.5 by the end of the 21st century. However, the area under severe drought based on SPI is projected to decrease in the end period under the RCP 4.5. The risk of severe drought is more (~60% change in area) in the RCP 4.5 compared to the RCP 8.5 scenario (~30% change in area) in the near period and high risk of severe drought is projected (more than 100% change in area) in the RCP 8.5 during the mid and end period. Under the warming climate, there is an increase in the precipitation, and more than 2-degree rise in temperature leads to more atmospheric water demand and an increase in drought severity by the end of the 21st century. Overall, this study suggests that the severity of drought in India is projected to increase under wetter and warmer future climate.

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