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A long-term drought assessment over India using CMIP6 framework : present and future perspectives

AASHNA VERMA[!], AKASH VISHWAKARMA[!], SANJAY BIST*, SUSHIL KUMAR** and R. BHATLA[!,***@]

[!]*Department of Geophysics, Institute of Science, Banaras Hindu University, Varanasi, India*

**India Meteorological Department, MoES, New Delhi, India*

***Department of Applied Mathematics, School of Vocational studies and Applied Science,*

Gautam Buddha University, Greater Noida, India

****DST-Mahamana Centre of Excellence in Climate Change Research,*

Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India

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[@]**e mail : rbhatla@bhu.ac.in**

सार — **भविष्य के जलवायु परिदृश्यों के लिए सूखे की विशेषताओं और प्रसार परकिए गए अनुसंधान में उल्लेखनीय प्रगति हुई है। हालाँकि, जलवायु परिवर्तन के संबंध में सूखा शमन पर अध्ययन काफी हद तक अपर्याप्त रहे हैं। यह अध्ययन जलवायु परिवर्तन के दो परिदृश्यों के तहत सूखे के मौसम संबंधी गुणों के आधार पर सूखे की परिघटनाओं की गंभीरता और आवृत्ति पर केंद्रित है: साझा सामाजिक आर्थिक मार्ग (एसएसपी2 4.5 और एसएसपी5 8.5)। हमने ऐतिहासिक (1901-2014) और भविष्य (2025-2100) के वर्षा डेटा एकत्र करने के लिए छठे अंतर्राष्ट्रीय युग्मित मॉडल अंतर-तुलना परियोजना के छठे चरण (सीएमआईपी6) सामान्य परिसंचरण मॉडल (जीसीएम) का उपयोग किया है। तुलनात्मक अध्ययन के लिए संदर्भ डेटा के रूप में आईएमडी के ग्रिडेड वर्षा का उपयोग किया गया है। हमने भारतीय क्षेत्र में भविष्य के सूखे के परिदृश्यों का विश्लेषण करने के लिए दो अलग-अलग सामाजिक आर्थिक साझा मार्गों (एसएसपी) के तहत मानकीकृत वर्षा सूचकांक (एसपीआई) का निर्माण किया है। हमारे परिणाम भविष्य के वर्षों के लिए एसपीआई मूल्यों में क्रमिक वृद्धि दर्शाते हैं, जो भारतीय क्षेत्र में सूखे की परिघटनाओं की गंभीरता में वृद्धि का संकेत देता है। यह वृद्धि SSP5 8.5 परिदृश्य के तहत अधिक स्पष्ट है, जो उच्च ग्रीनहाउस गैस उत्सर्जन और जलवायु परिवर्तन शमन के सीमित प्रयासों को माना जाता है। इसके अलावा, हमारे परिणाम बताते हैं कि भविष्य की अवधि के पूर्वार्द्ध में बड़े शुष्क दौर आने की संभावना है, विशेष रूप से एक्सेस-ईएसएम के मामले में, जो हमारे विश्लेषण में उपयोग किए गए जीसीएम में से एक है। इसके विपरीत, NOR-ESM-MM मॉडल इंगित करता है कि भविष्य की संपूर्ण अवधि में शुष्क मौसम की आशंका है। कुल मिलाकर, हमारा अध्ययन भारतीय क्षेत्र में सूखे की परिघटनाओं पर जलवायु परिवर्तन के संभावित प्रभावों के बारे में बहुमूल्य अंतर्दृष्टि प्रदान करता है।**

ABSTRACT. Research on the characteristics and spread of droughts has progressed significantly for future climate scenarios. However, studies on drought mitigation in relation to climate change have been largely inadequate. This study focuses on the severity and frequency of drought events based on meteorological properties of drought under two climate change scenarios: Shared Socioeconomic Pathway (SSP2 4.5 and SSP5 8.5). We utilized the Sixth International Coupled Model Inter-comparison Project sixth phase (CMIP6) ensemble General Circulation Models (GCMs) to collect historical (1901-2014) and future (2025-2100) precipitation data. IMD gridded precipitation was used as a reference data for comparative studies. We constructed the Standardized Precipitation Index (SPI) under two different Socioeconomic Shared Pathways (SSPs) to analyze future drought scenarios in the Indian region. Our results show a gradual increase in SPI values for future years, indicating an increase in the severity of drought events in the Indian region. The increase is more pronounced under the SSP5 8.5 scenario, which assumes high greenhouse gas emissions and limited climate change mitigation efforts. Furthermore, our results suggest that major dry spells are likely to occur in the first half of the future period, particularly in the case of ACCESS-ESM, one of the GCMs used in our analysis. In contrast, the NOR-ESM-MM model indicates that dry spells are anticipated throughout the entire future period. Overall, our study provides valuable insights into the potential impacts of climate change on drought events in the Indian region.

Key words – Drought, SPI, CMIP6, Climate Scenarios.

1. Introduction

The monsoon is a meteorological phenomenon that is characterized by a seasonal reversal of surface winds. During summer, winds typically blow from the southwest, while in winter, they shift to blow from the northeast. This reversal of wind is caused by the seasonal variation in solar heating and the differences in thermal inertia between land and ocean, which create a distinct temperature gradient. As a result, this gradient establishes conditions that promote the formation of convective currents in the summer hemisphere. Over time, these currents produce latent heat, which draws in additional moisture from the surrounding oceans, thus maintaining the wet season. The term "monsoon" has its origins in the Arabic word "Mausim," which means "season". This seasonal change in wind direction happens at an interval of six months, shifting from summer to winter and vice versa. Monsoons are known for causing significant precipitation and are regarded as major disruptions in normal global atmospheric circulation. According to Gadgil *et al*. (2003), the Indian monsoon system is unique compared to other monsoon systems because of differences in the center of action, air masses involved, and fallout mechanism.

The southwest monsoon significantly influences the climate of India. The majority of rainfall in India occurs during the four monsoon months, from June to September, with significant temporal and spatial variations. The Indian climate has notable monsoon seasons, and the residual seasons are often discussed relative to the monsoon: pre-monsoon (March-May), southwest monsoon (June-September), post-monsoon (October-November), and winter (December-February). During other months, water scarcity can lead to crop productivity loss, biodiversity loss, electrical problems, and other issues. According to international norms, as stated in PIB press release by Ministry of Water Resources, River Development and Ganga Rejuvenation on the issue of "Shortage of Water", when the per capita water availability falls below 1700 m per year, a country is classified as water-stressed. If it is less than 1000 m^3 per capita per year, the country is considered water scarce, and below 500 m^3 as absolute scarcity (Kriplani *et al*., 2003a).

The southwest monsoon is the most significant feature of the Indian climate, lasting four months (JJAS), but the actual period varies depending on the onset and withdrawal dates for a particular place. The season varies from less than 75 to more than 120 days over West Rajasthan and South Western regions of the country, respectively. The onset of the southwest monsoon typically takes place around June 1^{st}, starting from Kerala and advancing along the Konkan coast in early June, eventually covering the entire country by mid-July. However, the onset of the southwest monsoon occurs about a week earlier over Islands in the Bay of Bengal. While there is regularity in onset and distribution within the country, inter-annual and intra-annual variations are observed. The monsoon is mainly influenced by global and local phenomena, such as El Nino, northern hemisphere temperatures, sea surface temperature, snow cover, etc. The El Nino southern oscillation (ENSO) and Himalayan snow cover greatly impact the Asian summer monsoon. The Indian monsoon weakens during the warm phase (El Nino) and strengthens during the cold phase (La Nina) (Kriplani *et al*., 2003b). Excessive snow during the preceding winter is unfavorable for the subsequent summer monsoon, while deficient snow is favorable. The multiple phases of active and break monsoon are also correlated with the monsoon rainfall. Long intense breaks are often associated with a pronounced decrease in rainfall in most parts of India, resulting in drought-like conditions (Kriplani *et al*., 2003a).

Drought is a pervasive natural calamity that leads to a shortage of water resources, reduction in underground water treasury, and limited plant yield (Swain *et al*., 2017). The emergence of drought is a slow process as it develops over months to years and is expressed by three primary characteristics: intensity, duration and regional extent (Tsakiris, 2017). El Nino is highly responsible for producing weaker monsoonal rainfall over the Indian subcontinent, although its presence does not always guarantee drought (Bhatla *et al*., 2015). The radiative imbalance in the atmosphere also determines the epochal nature of droughts (Bhatla *et al*., 2022). Extreme droughts have an enormous impact on human life, affecting social and monetary issues and influencing a broad range of sectors (Swain *et al*., 2017). According to IMD, India as one single unit is considered drought-affected if the area receiving rainfall with a deficiency of 26% or more exceeds 20% of the total area of the country, which is 6,57,556 km^2 (Verma *et al*., 2021).

Assessing the uncertainties and understanding the deficiencies of climate models are fundamental to developing adaptation strategies. The main objective of this study is to understand how well Coupled Model Inter-Comparison-Phase 6 (CMIP6) climate model simulations replicate ground-based observations uncertainties and understanding the deficiencies of climate models are fundamental for predicting future drought frequencies over the Indian subcontinent.

2. Data and methodology

Assessment of the performance of the CMIP6 has been done by comparing the model-simulated climate data with the daily gridded rainfall observational data (IMD4)

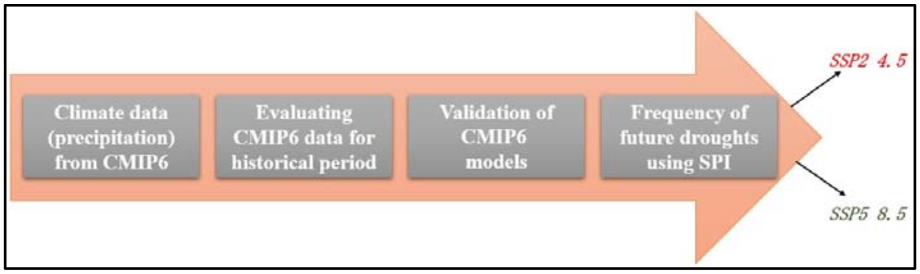


Fig. 1. The proposed flowchart to assess drought frequencies for the future years

TABLE 1

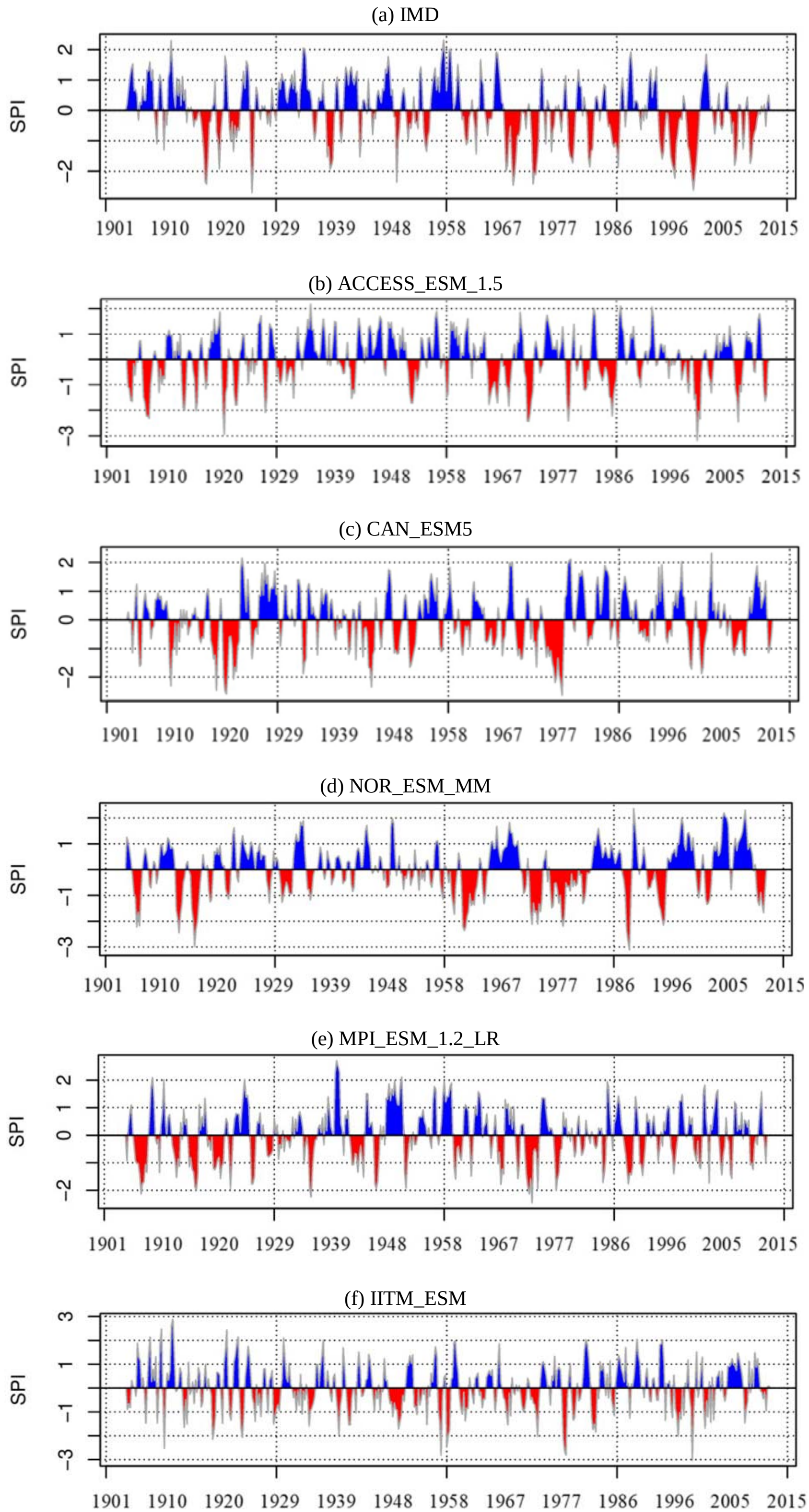
CMIP6 models along with their research institute and resolution used in this study

S. No.	Models	Source	Horizontal Resolution	
1.	Can-ESM5	Canadian Earth System Model	2.8 × 2.8	Swart *et al*. (2019)
2.	Nor-ESM2-MM	Norwegian Earth System Model	0.94 × 1.25	Tjiputra *et al*. (2020)
3.	ACCESS-ESM1.5	Australian Community Climate and Earth-System Simulator	1.2 × 1.9	Ziehn *et al*. (2017)
4.	IITM-ESM	Indian Institute of Tropical Meteorology Earth system Model	1 × 1	Krishnan R *et al*. (2021)
5.	MPI-ESM 1.2-LR	Max Planck Institute Earth System Model	1.9 × 1.9	Mauritsen *et al*. (2019)

at a high resolution of 0.25° × 0.25° (Pai *et al*., 2014) gathered from India Meteorological Department (IMD) for the historic period (1901 to 2014). The rainfall data over the Indian subcontinent (6.5° N-37.5° N; 66.5° E-101.5° E) were considered for interpolation to gridded rainfall data (Rajeevan & Bhate, 2009). Daily precipitation data is analyzed for the Indian summer monsoon period (JJAS) in this study. The analysis of future precipitation was carried out using CMIP6-GCM data. Presently, simulated precipitation from 5 CMIP6-GCM is readily available for the Indian at a resolution of 0.25 × 0.25 using EQM (Empirical Quantile Mapping) bias correction technique (Mishra *et al*., 2020). In this study, two Socio-economic Shared Pathways, SSPs (SSP2 4.5 and SSP5 8.5) were considered. The SSPs represent a range of future greenhouse gas emission and land-use change scenarios estimated from integrated assessment models, with SSP2 4.5 (+4.5 W m^{-2}; medium forcing or middle-of-the-road-pathway) and SSP5 8.5 (+8.5 W m^{-2}; high-end forcing pathway) used in this study.

Among 10 CMIP6 (Gusain *et al*., 2020, Li *et al*., 2022, Samantaray *et al*., 2022) models five were selected and evaluated [Can-ESM5, MPI-ESM 1.2-LR, Nor-ESM2-MM, ACCESS-ESM1.5 (Balu *et al*., 2023; Dixit *et al*., 2022) and IITM-ESM]. The general information of each of the five models and their research institute along with the horizontal resolution is summarized in Table 1. And for more detailed information on the development of the CMIP6 model, O'Neill *et al*. (2016) can be referred to. These models should be compared with the observational values of the study area in a common base period to evaluate the performance of their simulations of precipitation. According to the study historical period, years 1901-2014 were selected as a common base (historical) period. And for the reference data, IMD precipitation has been used. In spite of notable enhancements, encompassing advancements in physics and resolution refinement, these models remain inadequate for predicting India's localized monsoonal attributes. This inadequacy primarily stems from their coarse resolution, which hinders the accurate representation of intricate topographical features and their interplay with various system components (Aadhar *et al*., 2020).

The Standardized Precipitation Index (SPI; McKee *et al*., 1993; Hao *et al*., 2013; Verma *et al*., 2022) is used to characterize drought (Dixit *et al*., 2022, Papalexiou *et al*., 2021). It is widely used and has been endorsed as the world standard for determining meteorological drought by the World Meteorological Organization (WMO and GWP, 2016). The standardization approach represents a generic method for transforming the time series of a given variable into standardized anomalies and can also be applied to other types of drought index such as the Standardized Precipitation Evapotranspiration Index (SPEI) (Danandeh Mehr *et al*., 2020), Standardized Soil



Figs. 2. (a-f). SPI values derived from (a) IMD, (b) ACCESS-ESM 1.5, (c) CAN-ESM5, (d) NOR-ESM-MM, (e) MPI-ESM 1.2-LR and (f) IITM-ESM respectively for the historical period, *i.e*., 1901-2015

TABLE 2

Categories of drought as determined by SPI values

SPI value	Drought category
x ≤ -1	Drought
-1.5 < x ≤ -1	Moderate drought
-2 < x ≤ -1.5	Severe drought
x ≤ -2	Extreme drought

Moisture Index (SSMI; Hao and Agha Kouchak, 2013) and the Standardized Runoff Index (SRI, hydrological drought; Shukla and Wood, 2008).

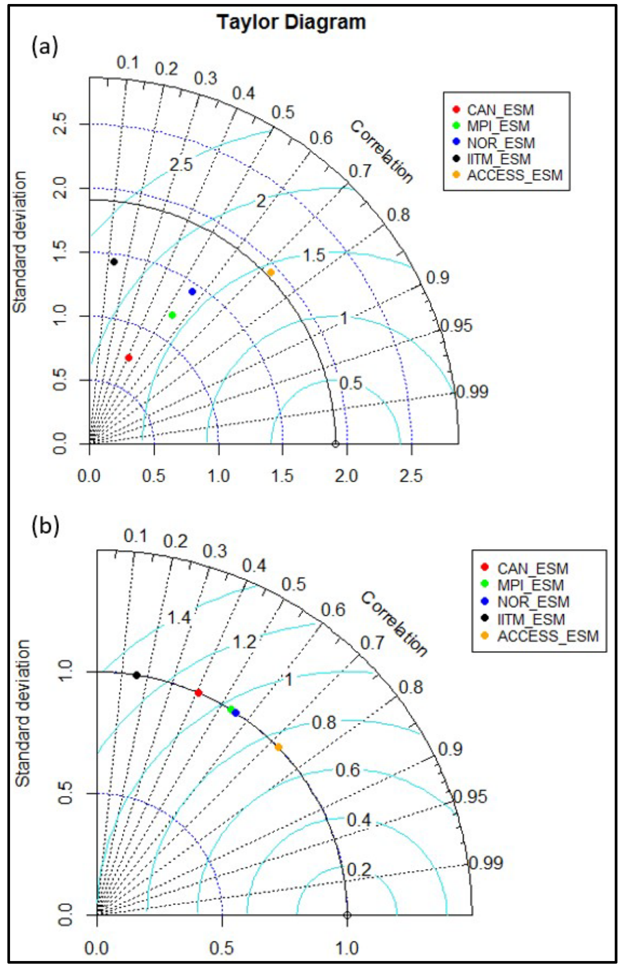
The precipitation data used is modified in such a way that we get one normalized value for each month during monsoon period (JJAS) from 1901 to 2014. These resulting values are either negative, depicting dry conditions or positive, depicting wet conditions. Second, a drought event is defined when the SPI is continuously negative for three months or more and reaches an SPI value of -1.0 or less at some time during the event (following McKee *et al*., 1993). The event starts when the SPI first falls below zero and ends with the first positive value of SPI following a value of -1.0 or less. The associated maximum negative value reached in a given event can then be used to define four drought categories: drought, moderate drought, severe drought and extreme drought as depicted in Table 2 (McKee *et al*., 1993, Azizi & Nejatian 2022), noting that in this paper we only present results on drought and extreme drought categories.Therefore, regarding the research aim and the proposed approach (Fig. 1), after evaluating the study area climatic models, precipitation data under the appropriate model under the scenarios of SSP2 4.5 and SSP5 8.5 were simulated. Finally, the severity-duration of SPI drought index was determined under climate change scenarios in the future period compared to the base period.

3. Results and discussion

Rainfall data was subjected to annual rainfall departure analysis for identification of drought years and the extent of deficit of annual rainfall. A year is considered a drought year if the total amount of annual rainfall over an area is deficient by more than 25% of its normal value.

3.1. *Temporal variation of SPI using historical precipitation data (1901-2014)*

The SPI estimated at the Indian subcontinent in this study region for the period 1901-2014 for different models



Figs. 3(a&b). (a) Taylor diagram of the annual precipitation over the Indian subcontinent in CMIP6 models during the period 1901-2014 and (b) Taylor diagram of the SPI indices for all CMIP6 models in reference to the IMD data

and IMD data (reference) are shown in Fig. 2. The time series plots of the indices indicate the significant drought events that occurred in this period, matching quite well with the major drought years as mentioned by IMD drought report in Table 3. From the IMD SPI plot and analysis report it was observed that the years 1901, 1904, 1905, 1907, 1913, 1918, 1920, 1941, 1951, 1965, 1966, 1972, 1979, etc. show more significant negative SPI values, hence contributing to drought years. These years are classified as moderate and severe drought years. As seen in Fig. 2(a), Major monsoonal droughts were recorded during 1982, 1983, 1986, 1987, 1992, 2002, 2004, 2009, 2014 and 2015 all over India (IMD). In general, according to Namias (1991), these droughts occur because of significant large-scale disturbances in the atmospheric circulation patterns. Many studies also show that long-term droughts are linked with the pacific Sea

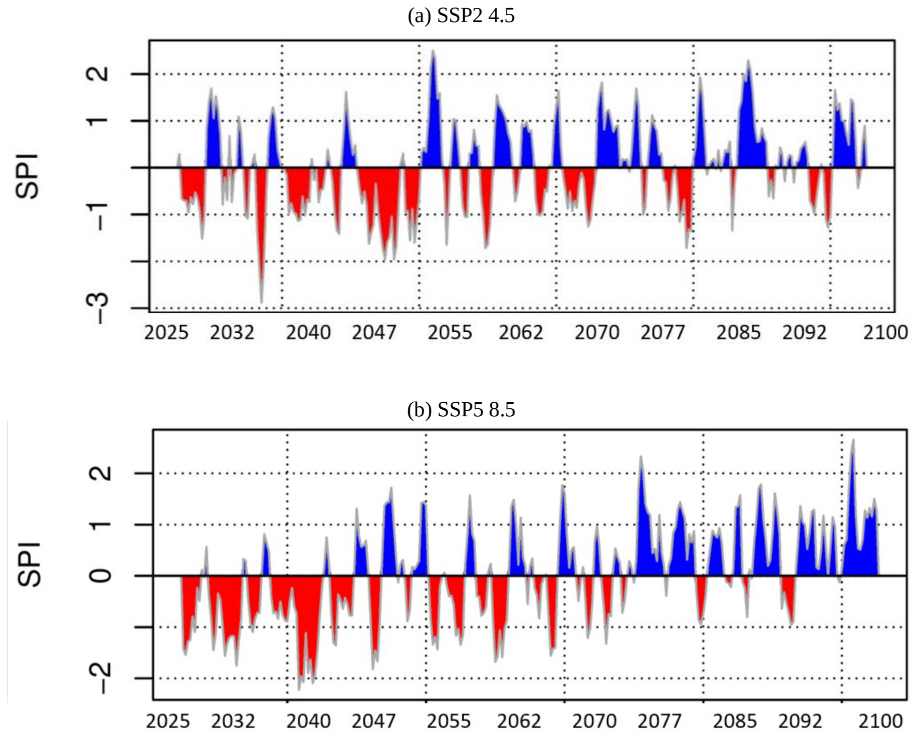
TABLE 3

Drought years with percentage area of the country affected by drought with their ranks. (*Source* : IMD drought report)

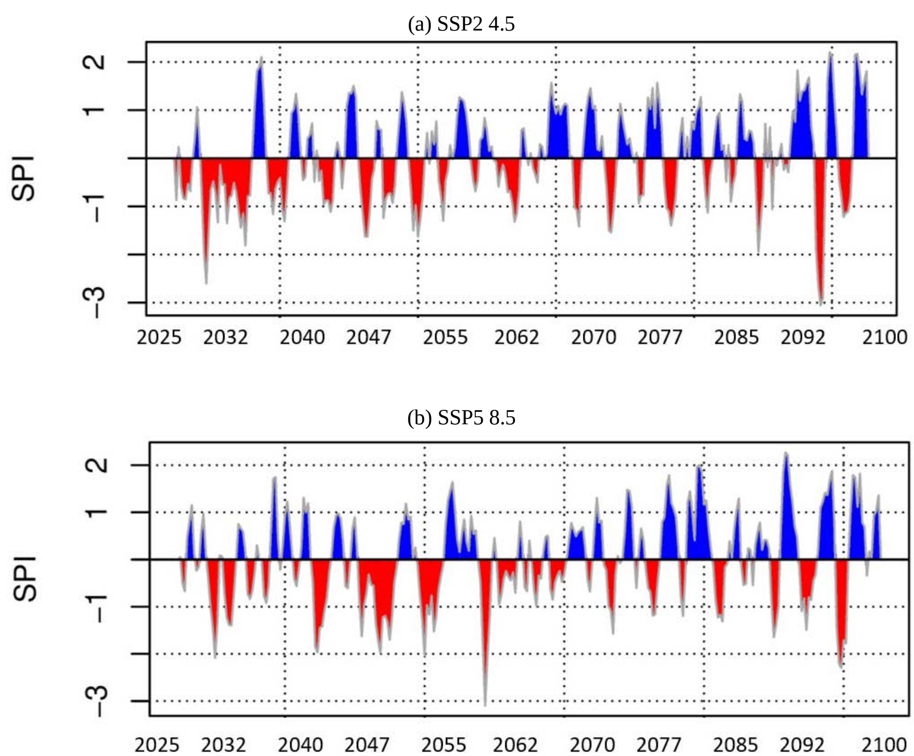
S. No.	Year	Areas affected in percentage of total area of the country by			Rank as per drought area	% Department of ISMR	Rank As per % departure of ISMR
		Moderate drought	Severe drought	Total			
1.	1877	30.6	28.9	59.5	3	-33.3	1
2.	1891	22.4	0.3	22.7	24	-6.3	26
3.	1899	44.1	24.3	68.4	2	-29.4	2
4.	1901	19.3	10.7	30	16	-13.1	16
5.	1904	17.5	16.9	34.4	14	-11.8	18
6.	1905	25.2	12.0	37.2	9	-17.4	10
7.	1907	27.9	1.2	29.1	18	-10.0	20
8.	1911	13.0	15.4	28.4	21	-14.7	12
9.	1913	24.5	0	24.5	22	-10.0	21
10.	1915	18.8	3.4	22.2	25	-9.4	22
11.	1918	44.3	25.7	70	1	-24.9	3
12.	1920	35.7	2.3	38	8	-16.7	11
13.	1925	21.1	0	21.1	27	-3.3	27
14.	1939	17.8	10.7	28.5	2.	-8.7	23
15.	1941	35.5	0	35.5	10	-13.3	14
16.	1951	35.1	0	35.1	12	-18.7	7
17.	1965	38.3	0	38.3	7	-18.2	9
18.	1966	35.4	0	35.4	11	-13.2	15
19.	1968	21.9	0	21.9	26	-11.3	19
20.	1972	36.6	3.8	40	6	-23.9	4
21.	1974	27.1	6.9	34	15	-12.0	17
22.	1979	33.0	1.8	34.8	13	-18.4	8
23.	1982	29.1	0	29.1	17	-14.5	13
24.	1985	25.6	16.7	42.3	5	-7.1	25
25.	1987	29.8	17.9	47.7	4	-19.4	5
26.	2000	27.2	-	27.2	23	-19.0	6
27.	2002	19.0	10.0	29	19	-8.0	24

surface temperature (SST) anomalies like ENSO (Dai, 2013). These factors also help us to understand future drought scenarios and frequencies.

The CMIP6 ACCESS-ESM 1.5 very finely perceives the drought episodes of 1907, 1913, 1918, 1920, 1965, 1966, 1972, 1979, 1982, 1986, 1987, 2002, 2004, 2009 and 2014 [also proven via RegCM 4.7 (Bhatla *et al.*, 2019)] as depicted in Fig. 2(b). Hence, it would not be wrong to say that the model estimations became more precise for later years. Whereas CAN-ESM5 and MPI-ESM 1.2-LR found drought years for the initial time scale with great accuracy but the predictions became a bit vague by end of the decade. NOR-ESM-MM successfully projected drought years 1901, 1904, 1905, 1907, 1913, 1920, 1965, 1972, 1979, 1987 and 2014. IITM-ESM on the other hand gave comparatively poor results. Frequency and duration of major droughts were very low all over India [Figs. 2(b-f)]. India witnessed extreme drought in 1995 that prolonged till 2004, which can be clearly seen in ACCESS-ESM 1.5 and feebly in IITM-ESM [Figs. 2(b&f)]. Also the extreme drought of 1999 is clearly captured by ACCESS, IITM and CAN models. To authenticate the analysis Taylor diagrams (Taylor, 2001) have been plotted for the historical period (1901-2025), for annual precipitation. The degree of resemblance of model schemes data to reference data is determined by calculating CC (Correlation Coefficients) between the IMD data and various CMIP6 models as well as STD (Standard Deviation) and RMSE (Root Mean Square Error) for all the models and IMD data. When models have relatively high CC, low RMSE, and the least distribution of SD, the model scheme's data is close to IMD data. As shown in Fig. 3, the Taylor diagram



Figs. 4(a&b). (a) SPI values derived from ACCESS-ESM 1.5 for the future period, *i.e.*, 2025-2100 for SSP2 4.5 and (b) SSP5 8.5



Figs. 5(a&b). (a) SPI values derived from NOR-ESM-MM for the future period, *i.e.*, 2025-2100 for SSP2 4.5 and (b) SSP5 8.5

represents the performance of CMIP6 models in reproducing the various drought years via SPI using precipitation. The performance of individual models showed great differences. In Fig. 3(a), ACCESS-ESM 1.5 and NOR-ESM exhibited the highest correlation coefficients of 0.72 and 0.56 respectively. Meanwhile, the normalized standard deviation of these models is around 2.0 and 1.5 respectively, which is comparatively good. Also from Fig. 3(b) the same conclusions can be made regarding these two models. That means these two models can reasonably simulate the drought projections using Standardised Precipitation Index over the Indian subcontinent for the future time period.

We all are well aware of the fact that the simulation performance of these models is hampered and influenced by many other factors. In addition to oversimplifying uncertainties in climate models or physical processes, many other factors can influence performance estimates. It should be noted that when interpolating CMIP6 data from stations, errors, *i.e.*, downscaling issues, can occur by comparing the variable grid scale of the climate model to the point scale of the station data (DeGaetano and Castellano, 2017; Padulano *et al*., 2019). So, according to the evaluation results, ACCESS-ESM and NOR-ESM exhibited good performance in depicting the annual circle of precipitation, as well as the SPI values. Thus, the 2 models' performance in simulating drought conditions over India was assessed for the future timescale (2025-2100).

3.2. *Temporal variation of SPI using precipitation data for future years (2025-2100)*

As previously mentioned, the grid outputs of two CMIP6 models, namely ACCESS-ESM 1.5 and NOR-ESM-MM, were used in this study to obtain projected precipitation (and consequently SPI index) time series for the future period (2025–2100) for two socioeconomic pathways (SSP2 4.5 and SSP5 8.5). Figs. 5, 6 (a&b) display how the climate models estimated SPI over India. Differing largely from each other, ACCESS-ESM shows different drought frequencies all over India and did not show any SPI value less than -2 (*i.e.*, for extreme droughts). However, the second model, NOR-ESM-MM kind of underestimated drought frequencies over India. But showed 4-5 extreme droughts during 2025-2100. As depicted in Fig. 4(a), projected SPI pattern by ACCESS model under SSP2 4.5 scenario, it is very clear that the dry spells are very likely to occur in the beginning of the future time scale. And extreme drought conditions can be seen during 2037 (An *et al*., 2022), with SPI values reaching up to -3. Also, under SSP5 8.5 scenario, these drought spell durations are magnified but none of them are extreme events as shown in Fig. 4(b). If we compare these drought frequencies with the reference period, a significant decrease is observed. Similarly, projected SPI values for NOR model, depict regular distribution of dry and wet periods throughout the century for both the scenarios as seen in Figs. 5(a&b). But extreme drought conditions are likely to occur by the end of century during 2094-2095 for SSP2 4.5. It is also evident from Fig. 6 that the number of moderate drought events likely to occur according to the ACCESS model are 45 and 49 under SSP2 4.5 and SSP5 8.5 scenarios respectively. But the NOR model kind of underestimated these statistics. Also both the models are showing close figures for the number of severe drought events for both the scenarios.

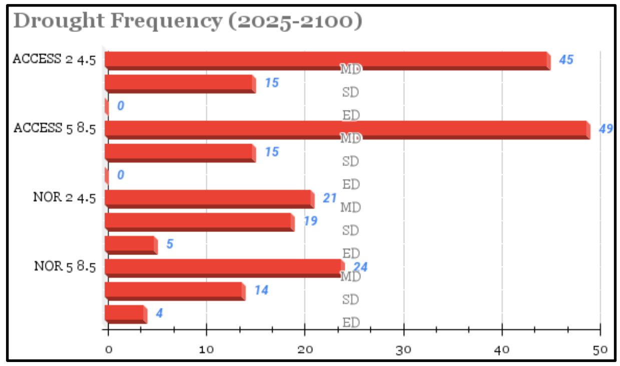


Fig. 6. Drought frequencies of each category of drought for the future period (2500-2100) under both scenarios

4. Conclusions

This study estimated future drought frequencies over the Indian region from a pair of CMIP6 GCMs for two SSP scenarios (SSP2 4.5 and SSP5 8.5). Selection and validation of the models were based on the results from the historical (1901-2014) outcomes when compared to IMD observational datasets. For this purpose, drought severity levels for 3 months' duration are estimated using Standardized Precipitation Index (SPI), for the future period: 2025-2100, for two emission scenarios. These multi-model ensemble projections depicted gradual increase in SPI values for future years. This increase was greater for SSP5 8.5 than SSP2 4.5. Since, SPI only considers precipitation, therefore it is advisory to use various drought indices for near accurate results. The conclusions drawn are as follows.

As a result of calculating the drought index for the future time scale, both the SSP2 4.5 scenario and the SSP5 8.5 scenario predicted that moderate drought is more likely to occur frequently. Considering the SPI values, the frequency and duration of moderate drought are much longer for the ACCESS-ESM 1.5 model compared to the NOR-ESM-MM. When comparing the outcomes of both the models, it was observed that the frequency of occurrence of extreme droughts is much higher in NOR-ESM-MM for both the scenarios. Finally, major dry spells are expected to occur in the first half of the future period in case of ACCESS-ESM, whereas the results of NOR-ESM-MM show dry spells are anticipated across the entire future period. There is no expectation for ED events by ACCESS model. Due to uncertainties in climate change data, there is no guarantee that the droughts proposed in this study will occur in the future. This study is important for depicting future drought trends using SSP scenarios and considering drought mitigation measures. In addition to this, more research is needed to predict future droughts in India using more drought predictive indicators or other analytical methods to indicate the possibility of various droughts and to understand the potential interconnections between droughts scenarios and their impact on climate change or *vice versa*.

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