MAUSAM, **75**, 2 (April 2024), 583-596

MAUSAM

DOI : https://doi.org/10.54302/mausam.v75i2.6323
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 632.112 : 551.58 (211/213) (540.61)

Agro-climatic zone-wise drought hazards in Karnataka under historical and future climate scenarios

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(*Received 13 July 2023, Accepted 23 November 2023*)

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सार – इस अध्ययन में ऐतिहासिक और भविष्य के जलवायु परिदृश्यों के तहत कर्नाटक के कृषि-जलवायविक क्षेत्रों (एसीजेड) में सूखे के संकटों का स्थानिक-कालिक विश्लेषण किया गया। भारत मौसम विज्ञान विभाग के 1989-2019 के उच्च-विभेदन ग्रिड डेटा का उपयोग सूखा की ऐतिहासिक घटना के विश्लेषण के लिए किया गया। समन्वित क्षेत्रीय जलवायु डाउनस्केलिंग प्रयोग प्रतिनिधि एकाग्रता मार्ग (आरसीपी) 4.5 और 8.5 परिदृश्यों के डेटा का उपयोग निकट (2031-2060) और अंतिम अवधि (2061-2099) अवधि में भविष्य के सूखे के संकटों का विश्लेषण करने के लिए किया गया। मानकीकृत वर्षा सूचकांक (एसपीआई) का उपयोग 1, 3, 6, 9 और 12 महीने की विभिन्न संचय अवधि में सूखे की आवृत्ति की गणना करने के लिए किया गया था। इसके बाद, एसीजेड-वार सूखा संकट सूचकांक (डीएचआई) की गणना की गई और ArcGIS का उपयोग करके भू-स्थानिक रूप से मानचित्रित किया गया। परिणामों से संकेत मिलता है कि सभी संचय अवधियों के लिए मध्यम सूखे की घटनाओं की घटना की आवृत्ति सबसे अधिक है, इसके बाद गंभीर और अत्यधिक सूखे की घटनाएं होती हैं। 1989-2019 के दौरान,मध्यम, गंभीर और अत्यधिकसूखे क्रमशः 54.8%, 28.3% और 16.7% थे। अंतिम अवधि में आरसीपी4.5 और 8.5 परिदृश्यों के तहत मध्यम सूखे की आवृत्ति में क्रमशः 2.6% और 2.4% की वृद्धि का अनुमान लगाया गया है। ऐतिहासिक और भविष्य दोनों जलवायु परिदृश्यों के तहत, लंबी संचय अवधि (एसपीआई-9 और एसपीआई-12) में अत्यधिक सूखे की आवृत्ति देखी गई, जबकि छोटी संचय अवधि (एसपीआई-1 और SPI-3) में मध्यम सूखे की आवृत्ति अधिक देखी गई। ऐतिहासिक परिदृश्य के तहत, चरम श्रेणी में सूखे की आवृत्ति दक्षिणी संक्रमण, मध्य शुष्क और उत्तर पूर्वी शुष्क क्षेत्रों में अधिक थी, उत्तरी शुष्क, दक्षिणी संक्रमण और तटीय क्षेत्रों में गंभीर श्रेणी और उत्तरी संक्रमण, पहाड़ी और दक्षिणी शुष्क क्षेत्र में मध्यम श्रेणी थी। कर्नाटक के 30 जिलों में से, चित्रदुर्ग, उडुपी, तुमकुरु, बल्लारी, कोप्पला, रायचूरू और गडगा जिलों में DHI बहुत अधिक है। यह अध्ययन कर्नाटक राज्य के कृषि-जलवायु क्षेत्रों में सूखे परिदृश्यों पर जलवायु परिवर्तन के संभावित परिणामों पर प्रकाश डालता है और राज्य के लचीलेपन को मजबूत करने के लिए क्षेत्र विशिष्ट सूखा अनुकूलन और शमन रणनीतियों का आग्रह करता है।

ABSTRACT. This study performed the spatio-temporal analysis of drought hazards across the agro-climatic zones (ACZs) of Karnataka under historical and future climate scenarios. The India Meteorological Department's high-resolution gridded data for1989-2019 was used for historical drought occurrence analysis. Coordinated Regional Climate Downscaling Experiment ensemble data of the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios were used for analysing future drought hazards in the near (2031-2060) and end term (2061-2099) periods. The standardised precipitation index (SPI) was used to calculate the frequency of droughts at different accumulation periods of 1, 3, 6, 9, and 12 months. Subsequently, the ACZ-wise drought hazard index (DHI) was calculated and mapped geospatially using ArcGIS. The results indicated that moderate drought events have the highest frequencies of occurrence, followed by severe and extreme drought events for all accumulation periods. During 1989-2019, 54.8%, 28.3% and 16.7% of droughts were moderate, severe, and extreme, respectively. An increase of 2.6% and 2.4% in the frequency of moderate droughts is projected under the RCP4.5 and 8.5 scenarios, respectively, in the end term. Under both historical and future climate scenarios, a high frequency of extreme droughts was observed in the long accumulation periods (SPI-9 and SPI-12), whereas the frequency of moderate droughts was observed to be high in the short accumulation periods (SPI-1 and SPI-3). Under the historical scenario, the frequency of droughts in the extreme category was high in the southern transition, central dry, and north eastern dry zones, severe category in the northern dry, southern transition, and coastal zones, and moderate category in the north transition, hill, and southern dry zones. Among the 30 districts of Karnataka, Chitradurga, Udupi, Tumakuru, Ballari, Koppala, Raichuruand Gadaga districts have very high DHI. This study sheds light on the potential consequences of climate change on drought scenarios in the Karnataka state's agro-climate zones and urges for zone specific drought adaptation and mitigation strategies to strengthen the State resilience.

Key words – IMD gridded data, IPCC scenarios, RCP 4.5, RCP 8.5, SPI generator.

1. Introduction

The drastic ongoing changes in climate due to anthropogenic emissions have led to an increase in the frequency of climate hazards such as heatwaves, floods, and droughts. Of the footprints for these hazards, the footprints for droughts are larger than those for other hazards (WMO and GWP, 2016). Droughts are the greatest threat to sustainable development, affecting an estimated 55 million people, as well as livestock and crops, per year worldwide. Compared to the two previous decades, droughts have increased by 29% since 2000 (WHO, 2021). In 2022, more than 2.3 billion people experienced water stress, with 160 million children experiencing severe and protracted droughts. (Drought in Numbers, 2022). The Intergovernmental Panel on Climate Change's Assessment Report 6 states that variations in precipitation deficits in most regions in the world are majorly caused by atmospheric dynamics that varyon inter-annual, decadal, and longer time scales (Seneviratne *et al*., 2021). According to a United Nations report, more than 75% of the global population might be affected by droughts by 2050, and 4.8-5.7 billion individuals-an increase from the current 3.6 billion-will be residing in regions with limited access to water for at least one month each year (Drought in Numbers, 2022). This along with other factors, such as declining crop productivity, sea-level rise and overpopulation, could lead to the migration of up to 216 million people by 2050 (Drought in Numbers, 2022).

India is one of the nations in the world that has been severely affected by droughts (Drought in Numbers, 2022). The erratic and uneven distribution of the Indian monsoon both in space and time leads to severe hydrological imbalance (Nanda *et al*., 2020). In India, droughts have been occurring once every 3 years (Mishra *et al*., 2016), with a 57% increase in drought-prone areas since 1997. Moreover, one third of India's districts have experienced more than four droughts in the last decade. With 50 million people being affected by droughts each year, India's gross domestic product reduced by 2%-5% over the period of 20 years during 1998 to 2017 (UNDRR, 2021).

Timely determination of the likely extent and magnitude of drought through systematic analysis supports the framing of effective adaptation strategies for managing droughts. Drought indices are used for quantitatively defining drought characteristics by scientists and by policymakers for framing adaptation and mitigation policies (Selim *et al*., 2012), analysing drought risk, and for drought warnings. These indices are also used for contingency planning (Lalmuanzuala *et al*., 2022). To initiate programmes on drought relief and quantify deficit in water resources, thereby assessing drought severity in a region (Nanda *et al*., 2020). Several studies have used different types of drought indices, ranging from simple to more complicated ones (Thomas *et al* 1993; Sánchez *et al.* Martínez-Fernández, 2016; Seleiman, 2021).

The Standard Precipitation Index (SPI) by Thomas *et al*., (1993) is a powerful, flexible index (World Meteorological Organization 2012), recommended by the Lincoln Declaration on Drought as the internationally preferred index for drought analysis (Hayes *et al*., 2011). This index quantifies the actual rainfall as a standardised departure from the rainfall probability distribution function and indicates potential drought events across space and time scales (1, 3, 6, 9, 12, 24, 48 and 60 months). These events at different timescales in turn reveal the impact of droughts on various water resources. The indices for short accumulation periods (SPI-1 to SPI-3) indicate reduced soil moisture, those for medium accumulation periods (*e.g*., SPI-6) indicate reduced stream flow and reservoir storage, and those for long accumulation periods (SPI-12 to SPI-24) indicate reduced reservoir and groundwater recharge. Several studies in India have used SPI as an effective drought assessment and monitoring indicator across various scales, such as the state, city, district and agro-climatic zone (ACZ), under the historical climate scenario (Sanatan *et al*., 2011; Nandargi and Aman 2017; Abhilash *et al* 2019; Prasenjit *et al* 2021; Lalmuanzuala *et al*., 2022; Vengateswari, *et al*., 2021). To perform improved drought vulnerability assessments that lead to effective adaptation strategies, temporal and spatial variability of droughts under future climate scenarios is also needed.

With this scope, this study examined the drought characteristics of Karnataka, one of India's most water-stressed and drought-prone states. Only a few studies have evaluated drought characteristics, with limited focus on a particular area or zone (Adhikari *et al* 2012; Sanjay *et al* 2019; Sridhara *et al*., 2021; Archana and Shweta 2021; Harishnaika *et al*., 2022; Kudari *et al* 2022). This highlights the lack of information on drought characteristics for the whole state. In this study, the drought frequencies were calculated using SPI under historical and future climate scenarios for all ACZs and

TABLE 1

Characteristics of ACZs in Karnataka

ACZs	Districts	Climate	Rainfall Range in mm	Major Crops
North eastern transition	Bidar	Tropical monsoon, semi-arid	830–890	Jowar, bajra, cotton, sugarcane and pulses
North eastern dry	Kalaburagi, Raichuru, Ballari, Yadagir, and Koppala	Semi-arid	633.2–806.6	Jowar, bajra, oilseeds, cotton and pulses
Northern dry	Vijayapura, Gadaga, and Bagalkote	Semi-arid	464.5–785.7	Jowar, maize, bajar, groundnut, cotton, wheat, sugarcane and tobacco
Central dry	Tumakuru, Chitradurga, and Davanagere	Semi-arid	453.5–717.7	Ragi, rice, jowar, pulses and oilseeds
Eastern dry	Bengaluru Rural, Bengaluru Urban, Kolar, Ramanagara and Chikkaballapur	Semi-arid	679.1–888.9	Ragi, rice, pulses, maize, mulberry and oilseeds
Southern dry	Mysuru, Kodagu, Chamarajanagaraand Mandya	Semi-arid to sub-humid	670.6–888.6	Rice, ragi, pulses, millets and sugarcane
Southern transition	Hassan, Shivamogga and Chikkamagaluru	Semi-arid	611.7–1053.9	Rice, ragi, pulses, jowar and tobacco
North transition	Dharwada, Belagavi and Haveri	Semi-arid	619.4–1303.2	Rice, jowar, groundnut, pulses, sugarcane, and tobacco
Hill	Uttara Kannada	Per humid	904.4–3695.1	Rice and pulses
Coastal	Dakshina Kannada and Udupi	Per humid	3010.9-4694.4	Rice, pulses and sugarcane

Source: Karnataka Agriculture Department

the drought hazard index (DHI) was calculated and mapped spatially to highlight the ACZs prone to droughts, especially severe droughts.

2. Study area

Karnataka is a southern Indian state with an area of 1,91,790 km^2 and a population of 64 million. It is located between latitudes 11.5° N and 18.5° N and longitudes 74° E and 78.5° E (Census of India, 2011). The state has 30 districts, and 18 of them, *i.e.*, approximately 54% of the geographical area is drought prone (Planning, Programme Monitoring, and Statistics Department, Government of Karnataka, 2020). Further, Karnataka has the second largest arid and semi-arid area in India after Rajasthan. The rainfed agricultural land, which covers around 80% of the state's taluks, is vulnerable to droughts. This is crucial because Karnataka produces 74% of its oilseeds and approximately 55% of its food grains through rainfed agriculture (Srinivasareddy *et al*., 2019). The agriculture sector's gross state value added growth rate decreased from 14.2% in 2017-18 to 4.8% in 2018-19. This can be attributed to reduced food grain production due to droughts, which affected 156 and 100 *taluks* during the *rabi* and *kharif* seasons, respectively (Economic Survey of Karnataka, 2019). The state experiences various climatic conditions, including sub-humid to humid tropical in the Western Ghats, humid tropical monsoon in the coastal plains and arid to semi-arid in the plateau regions. It receives little rain from the northeast

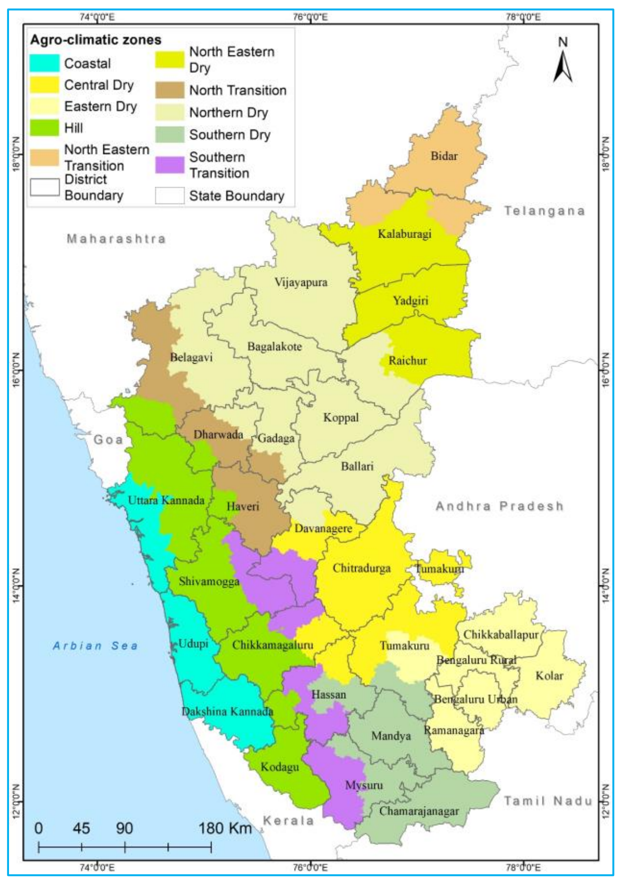

Fig. 1. ACZ map of Karnataka

TABLE 2

CORDEX models used for analysing drought changes

CORDEX South Asia Regional Climate Models (RCM)	RCM Description	Contributing CORDEX Modelling Centre	Driving CMIP5 Atmosphere-Ocean Coupled General Circulation Models	Contributing CMIP5 Modelling Centres
Indian Institute of Tropical Meteorology (IITM)-RegCM4 (Six ensemble members)	The Abdus Salam International Centre for Theoretical Physics RCM version 4.4.5 (RegCM4;Giorgi et al., 2012)	Centre for Climate Change Research, IITM, India	CanESM2	Canadian Centre for Climate Modelling and Analysis (CCCMA), Canada
			GFDL-ESM2M	National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory (GFDL), USA
			CNRM-CM5	Centre National de Research Me’ te’ orologiques (CNRM),France
			MPl-ESM-MR	Max Planck Institute for Meteorology (MPl-M),Germany
			IPSL-CM5A-LR	Institut Pierre-Simon Laplace (IPSL), France
			CSIRO-Mk3.6	Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
SMHI.RCA4 (10 ensemble members)	Rossby Centre Regional Atmospheric model version (RCA4; Samuelsson *et al*., 2015)	Rosssy Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden	MIROC5	Model for Interdisciplinary Research On Climate (MlROC), Japan Agency for Marine-Earth Sci. & Tech., Japan
			NorESM1-M	Norwegian Climate Centre, Norway
			HadGEM2-ES	Met Office Hadley Centre for Climate Change, United Kingdom
			CanESM2	CCCMA, Canada
			GFDL-ESM2M	NOAA, GFDL, USA
			CNRM-CM5	CNRM, France
			MPl-ESM-LR	MPl-M, Germany
			IPSL-CM5A-MR	IPSL, France
			CSIRO-Mk3.6	CSIRO, Australia

monsoon between October and December and a maximum of 869 mm of rainfall from the southwest monsoon between June and September (CSTEP, 2022). On the basis of soil types, topography, major crops and vegetation types, Karnataka is divided into 10 ACZs (Fig. 1). The characteristics of ACZs, namely districts, general climate, annual average rainfall and major crops, are listed in Table 1.

3. Data and methodology

Rainfall data is required to analyse drought characteristics using SPI. This study used the India Meteorological Department’s gridded rainfall data, available at 0.25° × 0.25° horizontal resolution and considered the best alternative to the rain-gauge-based observations (Rajeevan *et al*., 2006). To assess the drought conditions under the historical climate scenario, the gridded data over Karnataka were extracted for the period 1989-2019. The future drought characteristics were analysed by considering climate data projected from the Coupled Model Intercomparison Project 5 (CMIP5) family of Coordinated Regional Climate Downscaling Experiment (CORDEX) South Asia simulations (http://cccr.tropmet.res.in) under two scenarios, Representative Concentration Pathway (RCP) 4.5 (intermediate) and 8.5 (worst case) (Table 2). The ensemble mean of bias-corrected 15 models was analysed to study the drought changes in the near (NT; 2031-2060) and end terms (ET; 2061-2099) under both RCP 4.5 and 8.5 scenarios, relative to the historical period.

The present study used SPI to quantify precipitation deficits for both short and long accumulation periods to evaluate drought severity and characteristics in all districts and ACZs of Karnataka. Precipitation anomalies in the short accumulation period are used to evaluate soil moisture, whereas those in the long accumulation period are used to evaluate groundwater, stream flow and reservoir storage. The whole analysis included the following three major steps:

(*i*) Computing SPI values by using the rainfall data and identifying moderate, severe and extreme drought occurrences at different accumulation periods.

(*ii*) Calculating drought frequency by dividing drought occurrences in each accumulation period by the total drought occurrences in the same accumulation period and drought category.

Fig. 2. ACZ-wise percentage of drought occurrence frequency under historical and future climate scenarios

TABLE 3

SPI accumulation periods and characteristics

SPI accumulation periods	Characteristics
SPI-1	The shortest accumulation period that can be used to assess soil moisture and crop stress, especially during the growth season
SPI-3	Indicates moisture conditions over the short and medium accumulation periods, with a seasonal estimation of precipitation
SPI-6	Indicates seasonal and medium-term trends in precipitation
SPI-9	Indicates inter-seasonal precipitation patterns over the medium accumulation period
SPI-12	Indicates long-term precipitation patterns

(*iii*) Calculating DHI and spatial mapping.

The drought analysis was performed using the SPI generator application (https://drought.unl.edu/ monitoring /SPI/SPIProgram.aspx). Climate Data Operators were used to transform the daily data from historical and future climate scenarios to monthly data, which served as inputs for the SPI generator application. The drought indices were computed as per the Thomas *et al.* (1993) classification system at 1, 2, 3, 6 and 12 months. The purpose of using SPI at different accumulation periods is presented in Table 3.

The long-term historical and future climate data were fitted into a probability distribution and transformed into a normal distribution, leading to the mean SPI for the

TABLE 4

Weight and rating scores for each drought class based on the normal cumulative probability distribution of SPI

Drought classes	SPI values	Weight	Percentage of occurrences	Rating
Extreme wet	Greater than 1	0	0	0
Wet	0 to 0.99	0	0	0
Moderate	−1.49 to −1	1	<= 9.0	1
			9.1–10.0	2
			10.1–11.0	3
			>= 11.1	4
Severe	−1.99 to −1.5	2	<= 3.5	1
			3.6–4.5	2
			4.6–5.5	3
			>= 5.6	4
Extreme	Lesser than −2	3	<= 1.5	1
			1.6–2.0	2
			2.1–2.5	3
			>= 2.6	4

location and desired period being zero. Positive and negative SPI values indicate greater than and less than median precipitation, respectively. A drought event occurs when the SPI value becomes continuously negative, with an intensity of −1.0 or less. The event ends with a positive SPI value (World Meteorological Organization, 2012). The probability distribution of SPI values was given weights (Ws) and ratings (Rs) to construct the DHI (Kim *et al*., 2015). Risk is typically described as the likelihood of event occurrence, which is expressed on a scale from 0 to 1. The severity and occurrence probabilities were used to provide W and R scores for the drought hazard assessment on the basis of cumulative distribution function. The SPI intervals were used to calculate the W scores, with 1, 2 and 3 W scores representing moderate, severe and extreme droughts, respectively; for SPI>0, W=0. The interval of cumulative probability in each drought range was partitioned, and R scores from 1 to 4 in increasing order were assigned (Table 4). In this manner, DHI was computed for all ACZs and geospatially mapped by using the ArcGIS tool.

4. Results and discussion

This study captured the characteristics and spatial variability of droughts in all ACZs of Karnataka under both historical and future climate scenarios. The frequency of drought occurrence at the accumulation periods of 1, 3, 6, 9 and 12 months was calculated under the historical and future climate scenarios. Droughts are classified as moderate, severe, and extreme on the basis of SPI values. Subsequently, the DHI was calculated to identify the most affected ACZs under historical and future climate scenarios. The drought occurrence frequency percentage for all ACZs under historical and future climate scenarios is shown in Fig. 2. The results indicated that all zones experienced moderate droughts once in 2 years, and most zones experienced severe droughts once in 3 years. The frequency of moderate droughts was higher in the short accumulation period (SPI-1 to SPI-3) than in the long accumulation period (SPI-6, SPI-9 and SPI-12). Conversely, the frequency of extreme droughts was higher in the long accumulation period than in the short accumulation period.

4.1. *Frequency of droughts under the historical climate scenario*

The average frequency of moderate droughts during 1989-2019for all accumulation periods was 54.8% (range: 53.3% - 55.2 %), which was more than moderate (28.3%) and extreme drought (16.7%) frequencies. The detailed analysis of drought frequency for different SPI accumulation periods is presented below.

SPI-1 accumulation period: Moderate, severe, and extreme drought frequencies were 54.8%, 30.2% and 14.9%, respectively, with severe drought frequency being the highest for this accumulation period compared to others.

(*i*) Moderate droughts were more frequent in the hill, southern dry and north eastern dry zones.

(*ii*) Severe droughts were more frequent in the coastal, northern dry and southern transition zones.

(*iii*) Extreme droughts were more frequent in the north transition, coastal, and eastern dry zones.

SPI-3 accumulation period : The frequency of moderate, severe and extreme droughts for this accumulation period was 55.9%, 27.7% and 15.2%, respectively. The moderate drought frequency was the highest for this accumulation period compared to others.

(*i*) Moderate droughts were more frequent in the hill, southern dry and eastern dry zones

(*ii*) Severe droughts were more frequent in the northern dry, southern transition, north eastern transition, and north eastern dry zones.

(*iii*) Extreme droughts occurred more frequently in the southern transition, coastal and north transition zones.

SPI-6 accumulation period : The frequency of moderate, severe, and extreme droughts for this accumulation period was 54.7%, 29.6% and 15.7%, respectively.

(*i*) Moderate droughts were frequent in the hill, southern dry, north transition, and eastern dry zones.

(*ii*) Extreme droughts were observed frequently in the southern transition, coastal, central dry and north eastern dry zones.

(*iii*) Severe droughts were frequent in the northern dry, north eastern transition and north eastern dry zones.

SPI-9 accumulation period : The moderate, severe, and extreme drought frequencies during this accumulation period were 53.3%, 27.8% and 18.9%, respectively. Extreme drought frequency was the highest for this accumulation period compared to the other periods.

(*i*) Moderate droughts were more frequent in the hill, southern dry, north transition and eastern dry zones.

(*ii*) Severe droughts were more frequent in the northern dry, north eastern dry, southern transition and coastal zones.

(*iii*) Extreme droughts were more frequent in the southern transition, central dry and north eastern transition zones.

SPI-12 accumulation period : Moderate, severe and extreme drought frequencies during this accumulation period were 55.2%, 26.0%, and 18.8%, respectively.

(*i*) Moderate droughts were more frequent in the north transition, hill and southern dry zones.

(*ii*) Severe droughts were more frequent in the northern dry, southern transition and coastal zones.

(*iii*) Extreme droughts were observed more frequently in the southern transition, central dry and north eastern dry zones.

The central dry and southern transition zones experienced more extreme drought events, and the hill zone experienced more moderate drought events for all SPI accumulation periods.

4.2. *Frequency of droughts under future climate scenarios*

Drought frequencies were calculated under RCP 4.5 and 8.5 scenarios for the NT and ET. According to the results obtained, slight changes in moderate drought frequency are expected for all accumulation periods in the NT. The detailed analysis of moderate, severe, and extreme drought frequencies under RCP 4.5 and 8.5 scenarios is discussed below.

4.2.1. *RCP 4.5 scenario*

The frequency of moderate droughts is expected to be higher for all smaller accumulation periods in both NT and ET, with the frequencies being 58% for both SPI-1 and SPI-3 in the NT and 59% for SPI-1 and 60% for SPI-3 in the ET. However, for longer accumulation periods (SPI-12), the moderate drought frequency is 54% and 56% in both ET and NT, respectively.

The hill zone is expected to witness an increase in moderate drought frequency for SPI-1 and SPI-3, as well as a decrease for SPI-6, SPI-9 and SPI-12 in the ET. Severe droughts are expected to decrease in frequency for all accumulated periods and both time periods. The highest severe drought frequency of 35% and 32% is projected in north east dry zone in the NT and ET, respectively. Extreme droughts may increase slightly or remain the same in both NT and ET.

4.2.2. *RCP 8.5 scenario*

An increase in the frequency of moderate droughts is projected for all accumulation periods in both the NT and ET periods. The north transition zone is expected to witness an increase in the frequency of moderate droughts for SPI-1, SPI-3 and SPI-6, while the frequency is projected to decrease forSPI-9 and SPI-12 under NT and ET.

The trends in the frequencies of severe and extreme droughts are projected to be similar under RCP 4.5 and 8.5 scenarios in both NT and ET.For the SPI-1 accumulation period, a decrease in moderate drought frequency and an increase in extreme drought frequency (7% to 12%) is projected for the hill zone. In the south transition zone, extreme drought frequency is projected to increase from 13% to 15% in the ET. The extreme drought frequency is projected to increase to 19% in the ET for Eastern dry zone.

4.3. *ACZ-wise drought analysis for the historical and future climate scenarios*

North eastern transition zone : Bidar is a district under this zone, with jowar, bajra, cotton, sugarcane and pulses being the major crops. The district witnessed moderate, severe, and extreme droughts at a frequency of 58.3%, 29%-30.6% and 11.1%-21%, respectively during the historical period.

Under RCP 8.5 scenario, the moderate drought frequency is projected to increase across all accumulation periods, whereas the extreme drought frequency may decrease from 11.1% during the historical period to 4.9% in the future period of the 2080s. The increase in future drought frequency (under both RCP 4.5 and 8.5 scenarios) at the short accumulation period was observed to be greater than that at the long accumulation period.

Northern eastern dry zone : This zone covers Ballari, Kalaburagi, Koppala, Raichuru and Yadagiri districts. The major crops grown in this zone are jowar, bajra, oilseeds, cotton, and pulses. The frequency of extreme droughts in this ACZ was 19%, whereas that of severe drought swas 23% during the historical period. Extreme droughts were recorded in Ballari and Raichur in 1996, Kalaburagi in 2005 and Koppala in 2015 and 2016.

The frequency of extreme droughts is projected to increase in the future period of the 2040s and 2080s to 20% and 21%, respectively, under the RCP8.5 scenario; however, severe droughts are projected to decrease. Ballari had the highest severe drought frequency for the SPI-9 accumulation period (49%) during the historical period and the frequency may increase to 54.55% (NT) and 58.6% (ET) under the RCP8.5 scenario. Raichuru had a moderate drought frequency of 49.3% during the historical period and this frequency is projected to increase to 52.7% (NT) and 56.3% (ET) under the RCP 4.5 scenario and to 51.4% (NT) and 55.3% (ET) under the RCP 8.5 scenario. Similar trends were observed in Kalaburagi and Raichur.

Northern dry zone : Bagalkote, Gadaga, and Vijayapura districts come under this zone and jowar, maize, bajra, groundnut, cotton, wheat, sugarcane, and tobacco are the major crops grown here. In the year 2000, these districts witnessed extreme drought, with an SPI of below -2 for the SPI-1, SPI-3, SPI-6 and SPI-9 accumulation periods; the least SPI-1 value of -3.9 was recorded in Gadaga.

In this ACZ, a moderate drought frequency of 46% was observed for the SPI-9 accumulation period during the historical period and this is projected to decrease in the 2040s to 43% and to 37% in the 2080s under both RCP 4.5 and RCP 8.5 scenarios. For the SPI-6 accumulation period, a 17% extreme drought frequency was observed during the historical period, with a projected increase to 20% in the 2040s and 2080s under both RCP4.5 and RCP 8.5 scenarios. In Gadaga, a 34.9% extreme drought frequency was observed during the historical period, which is projected to decrease to 33.9% (NT) and 26.9% (ET) under the RCP 8.5 scenario. Severe droughts in Gadaga are expected to decrease in the NT and increase in ET. An increase in moderate and severe droughts is projected in Vijayapura.

Central dry zone : This ACZ consists of Chitradurga, Davanagere, and Tumakuru districts. Ragi, rice, jowar, and pulses are the principal crops grown in this zone. In Chitradurga, an SPI-6 value of -3.26 was recorded in 2003, with 1995 and 2004 also witnessing extreme droughts. In Davanagere, 1989, 1996 and 2015 were extreme drought years, while Tumakuru recorded the lowest SPI-12 value (-3.2) in 2002.

In this zone, a 55% (SPI-6) moderate drought frequency was recorded during the historical period; the frequency may increase marginally to 56% in the 2040s as well as the 2080s, under both RCP scenarios. The extreme drought frequency was 24% (SPI-12) during the historical period and is projected to increase in the 2040s to 27% and in 2080s to 24% under the RCP4.5 scenario. However, a decrease to 22% is projected under the RCP 8.5 scenario. In Chitradurga, a 53.6% (SPI-12) moderate drought frequency was observed during the historical period, which is projected to increase to 54.7% and 55.5% in the NT and ET respectively, under the RCP4.5 scenario. The frequency may further increase to 57.6% (NT) and 55% (ET) under the RCP8.5 scenario in Chitradurga.

Eastern dry zone : This zone consists of Bengaluru Urban, Bengaluru Rural, Chikkaballapura, Kolar and

Ramanagara. In Bengaluru Urban and Bengaluru Rural, 1992, 1996, 2001, and 2002 were extreme drought years (SPI-3 : -3.51 in 2001 and -3.61 in 1996), whereas1989 and 2002 were extreme drought years in Chikkaballapura (SPI-12 : -3.6 in 2002). Kolar witnessed extreme drought in 2002 and 2018 and the worst drought in 2015 (SPI-6 : -3.22). In Ramanagara, 1989, 2002 and 2008 were extreme drought years (SPI-1 : -3.84).

The frequency of severe droughts is projected to decrease for all accumulation periods in this ACZ. The SPI-12 analysis revealed that the frequency of extreme droughts was 17% during the historical period, which may increase to 19% (NT) and 18% (ET) under RCP 4.5 and to 26% (NT) and 28% (ET) in the 2080s under the 8.5 scenarios. In Bengaluru Urban and Bengaluru Rural, a decrease in the frequency of moderate droughts was noted in the SPI-12 analysis 59% during the historical period, which reduced to 50.4% and 44.4% in the 2040s and 2080s, respectively. According to the SPI-6 analysis, the frequency of moderate droughts may increase in Chikkaballapura in the 2040s and 2080s under both RCP 4.5 and RCP 8.5 scenarios.

Southern dry zone : This zone consists of Chamarajanagara, Kodagu, Mandya, and Mysuru districts. In Chamarajanagara, 2001 was an extreme drought year, with SPI values less than -2 for all accumulation periods and the least value of -4.03 forSPI-6. In Kodagu, 2004 was an extreme drought year, and 1989, 2006 and 2014 were extreme drought years in this ACZ.

The frequency of moderate droughts was 60% (SPI-9) in this ACZ during the historical period and is projected to decrease in the future. Compared to the historical period, a mild increase in extreme droughts was observed in the future period. The SPI-6 analysis revealed that the frequency of severe droughts in Kodagu was the least among all districts (16%) during the historical period. The frequency is projected increase by 27.1% in the 2040s and by 29.5% in the 2080s under the RCP 4.5 scenario; under the RCP 8.5 scenario, the frequency is projected to increase by 26.1% in the 2040s and by 30.8% in the 2080s.The frequency of moderate droughts in Mandya for the SPI-12 accumulation period was 60% during the historical period, and the frequency is projected to decrease in the future (54% and 56% in the 2040s and 2080s, respectively, under the RCP8.5 scenario).In Chamarajanagara, the severe drought frequency was 13.2% for the SPI-3 accumulation period and is projected to increase in the future (13.7% and 14% respectively, in the 2040s and 24.6% and 25.4% respectively, in the 2080s under both scenarios).

North transition zone : This zone consists of Dharwada, Belagavi and Haveri districts. The major crops of this ACZ arerice, jowar, groundnut, pulses, sugarcane and tobacco. During the year 2000, the SPI-1, SPI-3, SPI-6, and SPI-9 values were -2.51, -2.43, -2.5 and -2.22, respectively. Dharwada witnessed droughts in 1989 and 1990, while 1989, 2002 and 2016 were extreme drought years in Haveri. In Belagavi, -2.54, -2.98 and -2.97 were the SPI-1, SPI-3 and SPI-6 values during 1995.

This ACZ has the highest frequency of moderate droughts at 72%, which his projected to decrease to 58% (2040s) and 66% (2080s) under the RCP4.5 scenario and to 65% (2040s) and 47% (2080s) under the RCP 8.5 scenario. The SPI-9 values indicate that the frequency of extreme droughts was 20% during the historical period and is projected to decrease in the future. The SPI-12 values indicate that Belagavi had the least frequency of severe droughts, with an estimated increase to 13.5% and 17.9% (2040s and 2080s, respectively) under the RCP 4.5 scenario and to 15.5% and 17.9% (2040s and 2080s, respectively) under the RCP8.5 scenario. In Haveri, the frequency of extreme droughts was 17.1% during the historical period, with an projected increase in the future. The SPI-9 values in Dharwada revealed that the frequency of moderate droughts was 61.5%; the frequency is projected to decrease in the future (35.9% and 41.1% in the 2040s under RCP 4.5 and RCP 8.5 scenarios, respectively and 41.1% and 51% in the 2080s under RCP 4.5 and RCP 8.5 scenarios, respectively).

Hill zone : This region consists of only the Uttara Kannada district. Rice and pulses are the staple crops of this region. The drought frequency has increased over time in this ACZ. The SPI-3 and SPI-9 values were the least at -2.61 and -2.66 in 2011, thereby recording extreme drought. In this ACZ, 1991, 2003 and 2015 were extreme drought years, and 2003, 2011 and 2015 were drought years.

The frequency of moderate droughts was 61% during the historical period, which is projected to decrease to 55.5% and 55.6% in the 2040s and 2080s, respectively, under the RCP4.5 scenario. Under the RCP8.5 scenario, the frequency of moderate droughts is projected to increase to 65% in the 2040s and 60% in the 2080s. The frequency of severe droughts was 31.7% in this ACZ, which is projected to increase to 35% in the 2080s under both RCP4.5 and 8.5 scenarios. Compared with the frequency of extreme droughts during the historical period (7.3%), the frequency of extreme droughts is projected to decrease to 4.5% and 5% in the 2040s and 2080s, respectively, under the RCP8.5 scenario.

Coastal zone : This zone consists of the two districts of Dakshina Kannada and Udupi. Rice, pulses and sugarcane are the major crops of this region. Udupi

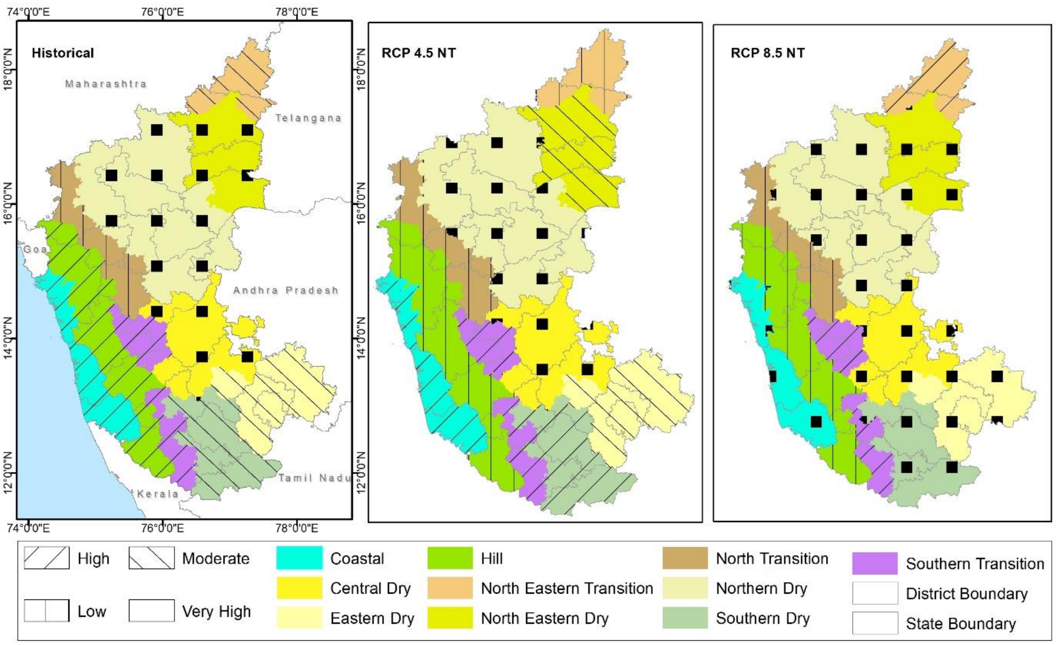

Fig. 3. DHI map under RCP 4.5 and 8.5 scenarios for historical and NT periods

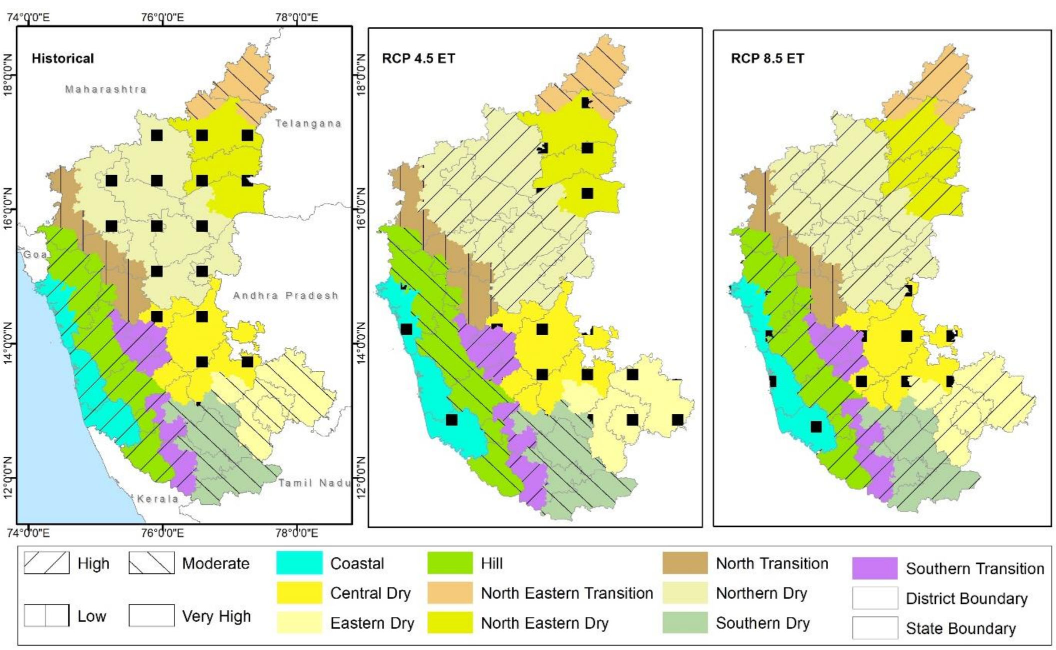

Fig. 4. DHI map under RCP 4.5 and 8.5 scenarios for historical and ET periods

recorded the lowest SPI-3 and SPI-9 values of -2.73 and -2.84 in 2015 and 2016, respectively. During 2004 and 2007 also Udupi recorded a low SPI value -2.74 and -2.46 indicating severe drought. Dakshina Kannada recorded the lowest SPI values in 2004 for all accumulation periods (SPI-1: -4.15, SPI-3: -4.26, SPI-9: -3.74and SPI-12: -3.94). A 50% frequency of moderate droughts was observed during the historical period, which is projected to increase to 56% and 62% in the 2080s under the RCP4.5 and 8.5 scenarios, respectively. A marginal increase, *i.e*., 64.7% and 64.2% in the frequency of moderate droughts is projected in Dakshina Kannada in the 2040s and 2080s, respectively, compared with that recorded during the historical period (62.8%). Severe droughts may increase in Dakshina Kannada in the future, whereas such events are projected to decrease in Udupi.

TABLE 5

District-wise DHIs under historical and future (NT and ET) climate scenarios

Zones	Districts	Historical	RCP 4.5 NT	RCP 4.5 ET	RCP 8.5 NT	RCP 8.5 ET
Central dry	Chitradurga	Very High	High	High	Very High	Very High
	Davanagere	High	Very High	High	High	Very High
	Tumakuru	Very High	Very High	Very High	High	High
Coastal	Dakshina Kannada	Moderate	Moderate	High	High	High
	Udupi	High	Very High	High	Very High	Very High
Eastern dry	Bengaluru Rural	High	Very High	High	Moderate	High
	Bengaluru Urban	High	High	Very High	Very High	Moderate
	Chikkaballapura	High	Moderate	Very High	High	High
	Kolar	Moderate	Low	High	Moderate	Moderate
	Ramanagara	Moderate	High	High	Very High	High
Hill	Uttara Kannada	High	Moderate	Moderate	Moderate	High
North eastern transition	Ballari	Very High	Moderate	High	Very High	High
	Bidar	High	Moderate	Moderate	High	Moderate
	Kalaburagi	High	High	Very High	High	Very High
	Koppal	Very High	Moderate	High	Very High	Moderate
	Raichuru	Very High	High	Very High	Very High	Very High
	Yadagiri	High	Moderate	Moderate	High	Moderate
North transition	Belagavi	Low	Moderate	Low	Low	Low
	Dharwada	Low	Low	Low	Low	Low
	Haveri	Moderate	High	High	Very High	High
Northern dry	Bagalakote	High	High	High	Very High	High
	Gadaga	Very High	Very High	High	Very High	High
	Vijayapura	High	High	Moderate	High	High
Southern dry	Chamarajanagara	Moderate	Very High	Moderate	Very High	High
	Kodagu	Low	Moderate	Moderate	Low	Moderate
	Mandya	High	Very High	High	Very High	Very High
	Mysuru	Moderate	High	Moderate	High	Moderate
Southern transition	Chikkamagaluru	High	High	High	Very High	High
	Hassan	High	High	Moderate	High	High
	Shivamogga	Moderate	High	Moderate	Moderate	Moderate

4.4. *Drought hazard index*

In this study, DHI values were classified into low, moderate, high, and very high and spatial maps were produced for the historical and future climate scenarios (Figs. 3&4). A very high DHI was observed in the central dry (Chitradurga and Tumakuru) and north eastern dry zones (Ballari, Koppala and Raichuru) during the historical period. The severity of droughts was high in the north eastern dry zone, whereas moderate droughts were observed in the southern dry and southern transition zones. A low DHI was observed in the north transition zone (Dharwada and Belagavi). The severity of droughts remained high in the central dry and coastal zones during both NT and ET under both scenarios. In the north transition zone (Bidar), the severity of droughts remained high in the NT; however, in the ET, the severe droughts reduced to moderate ones. In the eastern dry zone, the severity of droughts decreased from high to moderate in Bengaluru Urban, whereas in Kolar, the severity of droughts remained moderate in the ET but was high in the NT. In the north eastern dry zone districts of Koppala and Yadagiri, the severity of droughts reduced to moderate in the ET, whereas it remained high in Ballari, Yadagiri, and Raichuru. In the north transition zone districts of Dharwada and Belagavi, the severity of droughts remained low during both historical and future periods, whereas in Haveri, the drought severity was high in the NT and ET. In the northern dry zone, the drought severity remained high during both historical and future periods. In the southern dry zone districts of Kodagu and Mysuru, the severity of droughts was moderate during the historical period and remained the same during the NT and ET, whereas in Chamarajanagar and Mandya, the severity was high during both historical and future periods. The south transition zone districts of Hassan and Chikkamagaluru exhibited high severity of droughts during both historical and future periods, whereas the severity was moderate in Shivamogga. The district-wise DHIs under historical and future climate scenarios are tabulated in Table 5.

5. Conclusion

The evaluation of actual rainfall’s standardised departure with respect to the rainfall probability distribution function-SPI-permits comparisons among zones at different accumulation periods. This study analysed drought characteristics of Karnataka under historical and future climate scenarios. The analysis of drought frequency and severity in Karnataka indicated more frequent moderate droughts under all climate scenarios in almost all ACZs/districts. Compared with the increase in the frequency of droughts for the accumulation periods of SPI-9 and SPI-12, a greater increase in frequency was observed for the accumulation periods of SPI-1, SPI-3 and SPI-6 in the future. Moreover, the moderate drought frequency is projected to increase under the future climate scenarios compared to the historical period. The changes may potentially affect soil moisture groundwater, crop production and ultimately affect food production and agriculture income (Banerjee 2014; Goldin 2016; Das *et al.*, 2020). Frequent and prolonged droughts exert more stress on rural livelihoods, leading to farmers in rural areas moving in search of livelihoods (Singh 2019; Debnath & Nayak, 2022).

It is essential to map drought consequences & interlinks at the micro level in the state. Rainfed agriculture production in the state should be stabilised or expanded by appropriate dry-land production technology, changes in cropping pattern, and risk-reduction measures. Integrated soil, water and forest management practises such as soil conservation, watershed development/ efficient water management practices and forestry initiatives should be adopted in high risk zones. Some crops may be better suited to specific climate conditions. Drought-resistant agricultural varieties should be researched further. Diversifying crops helps reduce the hazards brought on by extreme weather events (Paria *et al*., 2022). Farmers should be well-informed on climate resilient crop variety, crop rotation, and diversification options.

The expected changes in droughts in different agro-climatic zones in the near/long term, as well as the potential consequences, necessitate a shift in public policy from drought relief to drought adaptation/mitigation efforts. The zone/district-level drought information should be incorporated into the state's knowledge management and decision support system in order to scientifically monitor and manage the reoccurring drought situation in the near future. These scientific findings should be used to implement climate change adaptation strategies such as shifting planting dates, selecting drought-tolerant crop types, and investing in better soil and water management approaches. Additionally, better monitoring and early warning systems and capacity building on to use water-saving practises/technologies help farmers prepare for and adapt to drought conditions.

Acknowledgment

The authors wish to express their sincere gratitude to the India Meteorological Department and Indian Institute of Tropical Meteorology Pune for the open source access of gridded rainfall and CORDEX data. The authors are grateful to CSTEP for financial support to conduct this work and CSTEP's Communications and Policy Engagement Team for their support and feedback.

Disclaimer : The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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