



Analyzing the long-term variability and trend of aridity in India using non-parametric approach

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Abstract

Aridity is a climatic phenomenon characterized by shortage of water availability in a given time and space resulting in low moisture and reduced carrying capacity of ecosystems. It is represented by a numerical indicator known as Aridity Index (AI), a function of rainfall and temperature. Aridification is a slow and steady effect of climate change and assessing its spread and change is vital in context of global climatic variations. Aridity is predominantly significant for agrarian countries like India, where a slight rise in drylands area can have a significant impact on the economy and community sustenance. AI is an inclusive indicator of climatic conditions in most arid and semi-arid regions. It helps in identifying and interpreting large scale trend in temperature and precipitation; and thus, classifying region into different climatic classes. The present study assessed long-term AI based on precipitation and temperature data obtained from the India Meteorological Department at the resolution of 1×1 degree for years 1969–2017. AI is estimated as a ratio of mean precipitation to mean potential evapotranspiration, calculated using Thornthwaite method. The results highlight the trend of aridity over pan-India with Innovative Trend Analysis and Mann–Kendall test. The study concludes that there is a relatively slow, however steadily progressive drier conditions being established in most of the regions. A shift from ‘Semi-arid’ towards ‘Arid’ class appeared in central mainland. The north-eastern Himalaya showed decrease in humid conditions (‘Humid’ to ‘Sub-humid’). The study implies that there is a rising aridity trend over the years due to changing climatic conditions. The shifts in aridity can have serious implications on agriculture, long-term water resource utilization and land use management plans. Our results have scope for future landscape management studies in drylands and better adaptation methods in arid regions.

Keywords Aridity index (AI) · Climate change · Thornthwaite · Potential evapotranspiration (PET) · Mann–Kendall test

1 Introduction

In the recent years, researchers have paid more attention to climatic variations due to global warming and climate change. From the pre-industrial conditions, global warming has reached approximately 1°C (between 0.8 and 1.2°C) and is increasing at 0.2°C per decade mostly due to human

activities. It is projected to reach 1.5°C between 2030 and 2050 if current conditions are not mitigated (IPCC 2019; 2021). The climate change has led to drastic variations in temperature and rainfall pattern (Miseckaite et al. 2018). However, climatic variations are not uniform around the world. With rising global temperature, an increase in aridity is projected in most parts around the world (Haider and Adnan 2014; Zarch et al. 2015). Numerous scientific studies have shown a rise in aridity and drylands at regional and global scale (Feng and Fu 2013; Huang et al. 2017; Pravalie et al. 2021).

There is a serious threat to densely populated agricultural nations like India due to the impacts of global warming (Maharana et al. 2021). India is one of the most vulnerable countries to climate change effects (Eckstein et al. 2019). A report by Ministry of Earth Sciences

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(MoES) showed that natural ecosystems, agricultural productivity, and freshwater resources in India are under tremendous stress due to long term changes in the temperature and rainfall pattern (Krishnan et al. 2020). The spatial extent and rate of drought events are also rising in central India, southwest coast, southern peninsula and north-eastern India (Kumar et al. 2010; Krishnan et al. 2020). Several climatic studies in India (Mallya et al. 2016; Aadhar and Mishra 2018; Mujumdar et al. 2020) demonstrated a rising frequency and intensity of droughts during the twenty-first century; and at the same time, flood intensity is also projected to increase in the major river basins (Nepal and Shrestha 2015; Mujumdar et al. 2020; IPCC 2021). Temperature and rainfall vary spatially and temporally across the country due to varied topography. Rainfall and temperature variability are a major concern for people who rely on the monsoon and its distribution for economic sustenance. Throughout the country, diverse climatic conditions are experienced as flood in one region and drought in another location (IPBES 2018; IPCC 2021). The country is influenced by two rainfall seasons; highly dependent on southwest-summer monsoon having around 80% of rainfall in the months from June to September (Kumar et al. 2010). During October–December, northeast monsoon takes over the general control over climate of the country. Thus, climate is highly reliant on rainfall and temperature variations which ultimately depicts the dynamics of wetness (humid) and dryness (arid) conditions.

Former climatic studies (Kumar et al. 1997; Arora et al. 2005; Jain and Kumar 2012) have indicated that there is an increasing trend in average annual temperature. Rainfall studies (Thapliyal and Kulshrestha 1991; Lal et al. 2001) show no particular trend in the mean precipitation but rise in extreme rainfall events are observed all over the country. There is a general increasing trend in temperature, decreasing range of diurnal temperature and more extreme rainfall events; the warmer climate leads to more intense and extreme rainfall (Mondal et al. 2015; Radhakrishnan et al. 2017). Short-duration extreme rainfall events have increased and overall rainfall during monsoon has decreased (Roxy et al. 2017; Mukherjee et al. 2018).

In India, more than half of the population depends on agriculture in semi-arid and arid regions. Agriculture is considered highly sensitive to changes in climate, and can compromise future food security and economy of the nation (Nath et al. 2017; Prabhakar et al. 2019). Thus, it is important to keep an account of spatio-temporal variations of the climatic variables. With the warming climate, researchers need to focus more on the long-term distribution and pattern of the climatic variables (Pal and Al-Tabbaa 2010). Long-term monitoring of aridity can help shape resilience by adopting different strategies to fight

against climate change (Sahour et al. 2020; Chai et al. 2021). Aridity is simply defined as “the degree to which a climate lacks moisture; it is contrary to humidity” (Ramachandran et al. 2015). However, it is expressed as a function of precipitation, temperature and potential evapotranspiration (PET) (Thorntwaite 1948; Zarch et al. 2015; Trabucco and Zomer 2018). PET is calculated with the help of various empirical equations and play a major role in the hydrological cycle (Verma et al. 2008). Aridity changes depend upon inter-annual variations of PET and precipitation (Nouri and Bannayan 2019). Increase in aridity often leads to land degradation and loss of biodiversity, and such variations make land more susceptible to drought and water scarcity (Huang et al. 2017; Pour et al. 2020). Aridity assessment is important for examining drought conditions, monitoring climate change and managing agricultural lands (Haider and Adnan 2014; Marani-Barzani et al. 2017). Impact of climate variations on aridity is more prevalent on certain types of land use such as drylands where agriculture production and water availability for crop irrigation is hindered (Copeland et al. 2017). Expansion of arid lands can have serious implications on agriculture and forestry. Aridity shift might negatively impact farmlands and drylands by increasing their management expenses (Salvati et al. 2012). Drylands are often associated with aridity and accounted for more than half of the warming in the continents; it leads to water scarcity and land degradation (Huang et al. 2017). Aridity assessment is therefore necessary to understand landscape characteristics and water resources distribution.

Climate studies have predicted a global increase in aridity which might lead to aridification in different parts around the world (Zarch et al. 2015; Huang et al. 2016; Ahmed et al. 2019; IPCC 2019; 2021). Lickley and Solomon (2018) conducted a global aridity assessment indicating that arid and semi-arid regions are affected more severely with the change in aridity as compared to humid regions. Arid regions are becoming more and more arid. This change is caused by long term variations in temperature and driven by extreme events of rainfall. In India, aridity assessment studies are either based on a comparatively shorter time span or estimated only for sub-parts of the country. For instance, Ramarao et al. (2019) performed a quantitative assessment of long-term aridity from 1951 to 2005 in only semi-arid region of India. The study revealed a 10% increase in the area of semi-arid regions as compared to previous decades. The results indicate that precipitation outpaces the PET changes and significantly influences AI. Another study by Raju et al. (2013) calculated aridity of the period 1971–2005 at the district level and observed a rise in mean temperature. The study identified contrasting changes in aridity at the district level such as increase in arid region of Gujrat and decrease in arid

region in Haryana. There is a notable increase in the semi-arid region of various states, i.e., Madhya Pradesh, Tamil Nadu and Uttar Pradesh. Moreover, the spatio-temporal analysis of aridity is restraint to few regions of India (Dave et al. 2019; Ramarao et al. 2019).

Meteorological studies are mostly limited to temperature or rainfall pattern. However, the overall climatic conditions are better expressed using climate indices such as aridity index (AI) (Croitoru et al. 2013; Kimura and Moriyama 2019). The present study focuses on a holistic approach to interpret and examine aridity changes over the entire terrestrial region of India. Our aim is to focus on the trend of annual rainfall, dynamics of aridity and extent of drylands in India over the last five decades at the state level. The study is intended to examine the long-term changes in the AI and to identify any particular trend of rising aridity. The study is conducted with the help of long-term (1969–2017) daily gridded datasets of temperature and precipitation. The resulting maps are spatially analyzed to assess aridity shifts; focusing on areas with increasing aridity and trend. The study identifies spatio-temporal changes in aridity, the extent of drylands and evaluates annual, seasonal and monthly AI trend.

2 Methodology

2.1 Study area

The study is conducted over the entire terrestrial region of India. The country is the seventh-largest in area (around 3,287,590 sqkm) with the second largest population (of 1.38 billion) in the world. The country lies geographically to the north of the equator between 08° 04' and 37° 06' N latitude and 68° 07' and 97° 25' E longitude (Nag and Sengupta 1992). From north to south, India extends 3214 km and from east to west approximately 2933 km. It has a diverse landscape and varied climatic regions, ranging from tropical in the South to alpine and temperate in the North (Senapati et al. 2013). However, the country observes four seasons; summers, monsoon, autumn and winters. The country receives 117 cm rainfall, out of which almost 80% of rainfall is perceived during monsoon season (Praveen et al. 2020). It is comprised of 28 states and 8 union territories. However, Indian Meteorological Department (IMD) has divided the country into six homogenous precipitation zones and 34 meteorological sub-divisions used in this study (refer to Fig. 1).

India has experienced extreme weather conditions in the past decades. The country has observed a rise of 0.7 °C in mean temperature from 1901 to 2018; a decline in monsoon; and an increase in extreme rainfall events, droughts, and flash floods (Krishnan et al. 2020). It is evident that

past droughts in the country have affected more than half of country's crop and led to decrease in productivity. Aridity shift and land degradation are some of the major repercussions of climate change (Emam et al. 2015).

2.2 Data and tools

The daily gridded temperature and precipitation data with a resolution of 1 × 1 and 0.25 × 0.25 degree respectively was obtained from the India Meteorological Department (IMD), Pune for the years 1969–2017. The yearly data file comprises of 365/366 raster bands with respect to non-leap/leap years respectively. In the pre-processing, we used ENVI 4.7 and R 3.6.2, and the post-processing was done using ArcGIS 10.1.

2.3 Methods

The IMD daily gridded temperature and precipitation data (1969–2017) is used for computing spatio-temporal distribution of aridity. The precipitation data is further utilized to assess annual rainfall trend by innovative trend analysis (ITA) to depict the influence of rainfall variability on aridity. The aridity is grouped in five classes, namely, hyper-arid (< 0.05), arid (0.05–0.2), semi-arid (0.2–0.5), dry sub-humid (0.5–0.65) and humid (> 0.65) (UNEP 1992) representing different climatic regions. The daily gridded time series of temperature and precipitation data was converted into monthly data. PET was estimated using Thornthwaite equation using temperature data. AI was calculated using precipitation and PET data. The monthly AI maps generated were categorized into mean annual, decadal and seasonal maps. Further, to analyze the trend in the mean monthly, annual and seasonal aridity, non-parametric MK test was used.

2.3.1 Aridity index computation

The index, proposed by the United Nations Environment Programme (UNEP), and also used by Food and Agriculture Organization (FAO), is defined as “a ratio of annual precipitation (P) and potential evapotranspiration (PET)” (UNEP, 1992).

$$AI = \frac{P}{PET} \quad (1)$$

2.3.2 PET estimation (Thornthwaite method)

Thornthwaite method (1948) is applied on the long-term temperature data to estimate PET (Nastos et al. 2013; Tsiros et al. 2020). It is preferred over the other methods of PET estimation as it is one of the most widely utilized and

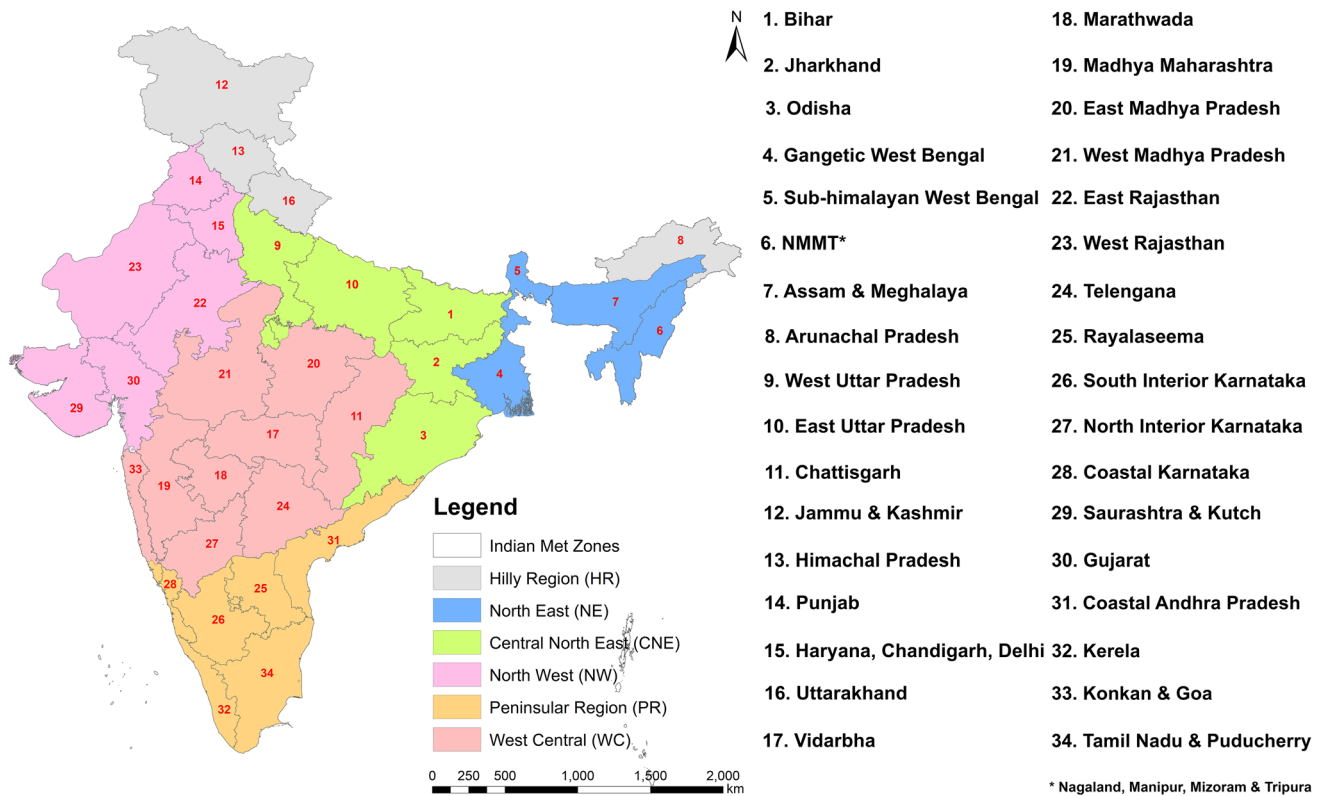


Fig. 1 The map of India showing Indian Meteorological Department (IMD) meteorological zones & sub-divisions

reliable method based on long-term temperature data. It is often used to understand trend and seasonal variations over larger terrains like Indian region. The other methods are often limited due to lack of other local climatic variables data. For larger areas, Thornthwaite method is preferably used to estimate PET. However, the lack of consideration of other local climatic variables (radiation, wind speed, humidity) may affect its accuracy. It requires two variables to compute PET; Empirical exponent (denoted as ‘a’) and Heat index (denoted as ‘I’). PET is expressed as a function of mean monthly temperature (Thornthwaite 1948). It is the combination of evaporation and transpiration from soil and plants when the water supply is not limited (Abiyi et al. 2019).

$$PET = 16 \left(\frac{10t}{I} \right)^a \text{ mm/month} \tag{2}$$

where, t = mean monthly air temperature (°C), I = annual heat index, and a = empirical exponent.

Heat index (I): Monthly heat index (i) is calculated using the formula

$$i = \left(\frac{t}{5} \right)^{1.5.14} \tag{3}$$

And, the annual heat index (I) is the sum of each monthly heat indices (i).

Empirical exponent (a)

$$a = 675 \times 10^{-9} \times I^3 - 771 \times 10^{-7} \times I^2 + 1792 \times 10^{-5} \times I + 0.49239 \tag{4}$$

2.3.3 Mann–Kendall (MK) test for trend detection

Mann Kendall (MK) is a non-parametric test which gives a monotonic trend, either increasing or decreasing over time (Sahour et al. 2020). It is a robust and effective to the effects of extreme outliers; it performs well with skewed (not normally distributed) variables and can handle missing values or no data (Mishra et al. 2009; Zhang et al. 2008). It is the most widely used non-parametric test for depicting monotonic trends in environmental variables (Karmeshu 2012; Mondal et al. 2012; Yadav et al. 2014; Ahmad et al. 2015; Zhang et al. 2008; Ullah et al. 2019; Kocsis et al. 2020). The test is established on the assumption that there is no correlation, and measurements are independent of each other. In the hypothesis testing, significance level (p-value) of 5% was used in the study for rejecting the null hypothesis (Patra et al. 2012). The statistic S of Kendall’s tau test as given below:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(X_j - X_k) \tag{5}$$

With

$$\text{sgn}(x) = 1 \quad \text{if } x > 0$$

$$\text{sgn}(x) = 0 \quad \text{if } x = 0$$

$$\text{sgn}(x) = -1 \quad \text{if } x < 0$$

The mean of S is $E[S] = 0$ and the variance (V) is given by the following equation:

$$V = \frac{\left\{ n(n-1)(2n+5) - \sum_{j=1}^p t_j(t_j-1)(2t_j+5) \right\}}{18} \tag{6}$$

where, p represents the number of the tied groups and t_j is the number of data points in the j^{th} tied group.

The statistic S is considered normal distributed after the Z-transformation is incorporated as follows:

$$z = \frac{S - 1}{V} \quad \text{if } S > 0 \tag{7}$$

$$z = 0 \quad \text{if } S = 0 \tag{8}$$

$$z = \frac{S + 1}{V} \quad \text{if } S < 0 \tag{9}$$

where z is the test statistics. The statistic S is related to Kendall’s tau as given by the following equation:

$$\text{Tau} = S/D \tag{10}$$

where,

$$D = \left[1 \div 2n(n-1) - \frac{1}{2} \sum_{j=1}^p t_j(t_j-1) \right]^{1/2} [1/2 n(n-1)]^{1/2} \tag{11}$$

2.3.4 Innovative trend analysis (ITA)

Sen (2012) was the first to develop an Innovative Trend Analysis (ITA) method that uses cartesian coordinate system (Sen 2012). The temporal data must be classified into two classes for ITA technique to work. Equation 12 (Wu and Qian 2017) was used to represent the actual trend indicator:

$$\varphi = \frac{1}{n} \sum_1^n \frac{10X_j - X_i}{\mu} \tag{12}$$

where, number of entire observations is given by n, marker of trend is denoted by φ , data of the first sub-series is denoted by X_i , data of the second sub-series is denoted by X_j and average value of the data of the first subseries is denoted by μ . The positive and negative values of φ can be used to identify a growing or declining trend. The x-axis in

the ITA plot was the information from the first subseries (X_i), while the y-axis was the information from the second subseries (X_j). If indeed the climatic or hydrological data series is shown in the middle of the 1: 1 (diagonal) line, there seems to be no trend.

If the tendency is growing or declining is determined by the location of the information series on the 1:1 line. Whether they are just above diagonal line, it might be regarded a positive or growing trend. The information series is on a falling or declining trend when it is below the diagonal line. If the data does not exhibit a monotonic trend, it enables the detection of tendencies in low, moderate, and high classes depending on the position of the points of data for comprehensive trend identification.

2.3.5 Wavelet transformation

Analyzing time series using wavelet transformations is a method for examining multi-scale frequency features. The major variability pattern, frequency, and frequency change over time were all resolved by the wavelet transformation for the time series data at various scales. The application of wavelet analysis in environmental research was widespread around the world, particularly in geophysics, remote sensing, and signal analysis (Torrence and Compo 1998; Chou et al. 2022). Wavelet analysis is superior to Fourier transformation at handling non-stationary variations in various frequencies (Grinsted et al. 2004). The constantly shifting area of non-stationary signals can be managed effectively using the wavelet function. Using this approach, it was possible to solve data exhibiting local stationary signal characteristics and obtain periodic variations within a given ratio. Wavelets are mostly utilized for time–frequency and time scale analysis because of their time–frequency features. Continuous wavelet transformation (CWT) and discrete wavelet transformation (DWT) are two subcategories of wavelet transformation. Since the CWT offers higher signal feature extraction capabilities, it has been extensively utilized in various environmental studies to calculate the periodic change of wavelets (Grinsted et al. 2004). The sinusoidal signal from the time series data, both abrupt and constant, is produced by the continuous wavelet transform with derivative of Gaussian analysis. Therefore, in this work, continuous wavelet transform with derivative of Gaussian was employed to identify the periodic variation in aridity index (Eq. 13).

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi * \left[\frac{(n' - n)\delta t}{s} \right] \tag{13}$$

where, W_n = power spectra, $x_{n'}$ = time series, ψ = mother wavelet (derivative of Gaussian), n' = transitional value, n = total time index, n = local time index, s = wavelet

scale, * = complex conjugation, N = time index, Δt = sampling interval.

3 Results

3.1 Mean annual rainfall trend

Rainfall pattern was observed through ITA to know the consequences of rainfall in aridity condition. The depiction of the ITA for the mean yearly rainfall is shown in Fig. 2a, b. Different trend observed (no trend, rising, and reducing

trend) in the low, middle, and high phases of annual rainfall are shown in Fig. 2a, b. In terms of values plotted on the 1:1 axis, eight subdivisions (Jammu & Kashmir (J & K), East Rajasthan, Rayalaseema, Gangetic West Bengal, Himachal Pradesh, Delhi & Chandigarh, Punjab, Haryana and West Rajasthan) at the low level exhibited no trend. At the lowest level, 14 subdivisions had a declining trend, whereas 12 subdivisions exhibited an increasing trend. Three subdivisions (Haryana, Marathwada, Rayalaseema and Delhi & Chandigarh) and fourteen subdivisions had no trend and a rising trend in yearly rainfall at the high level. Of the three levels, the majority of sub-divisions (17 sub-

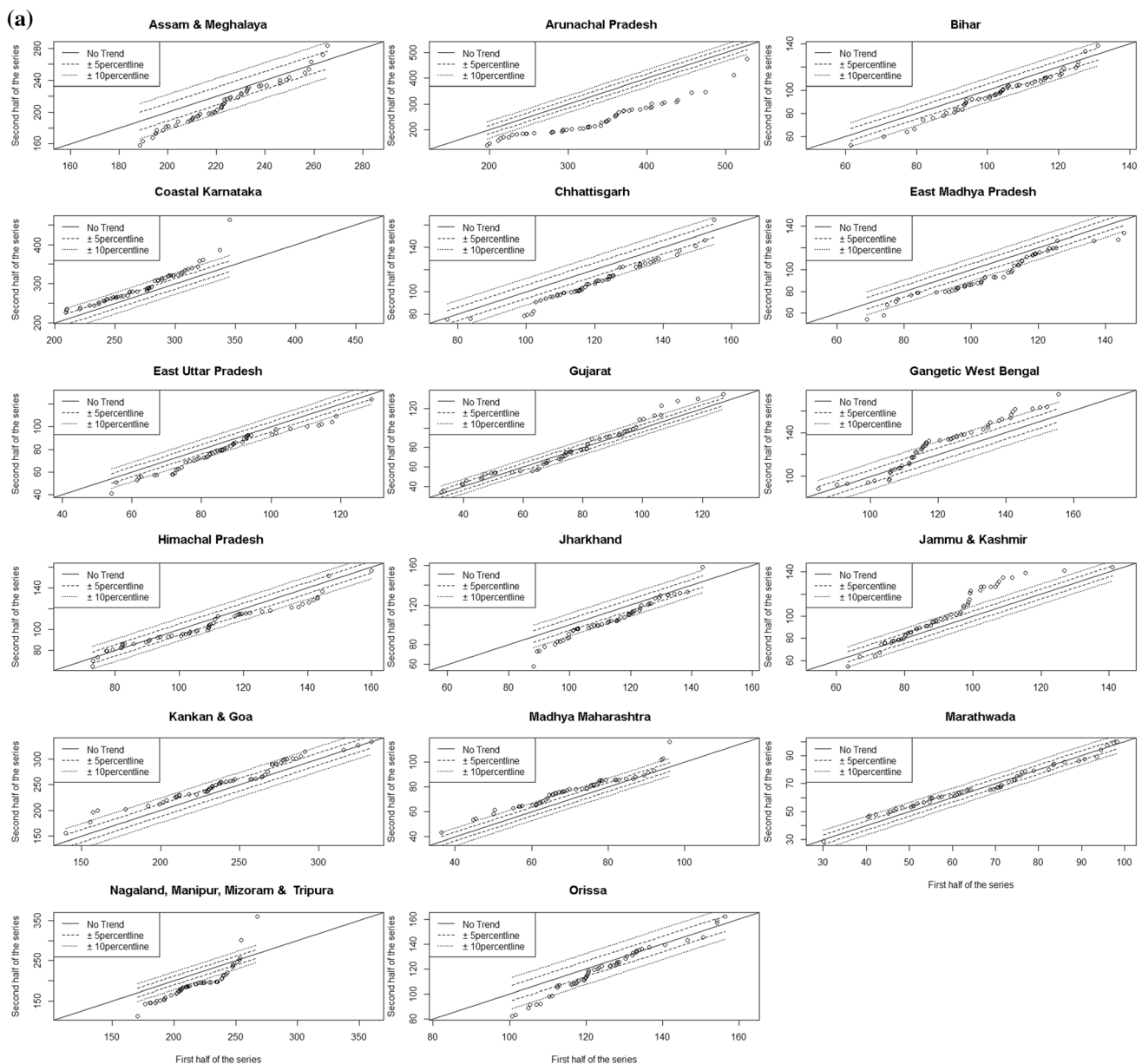


Fig. 2 a Mean annual rainfall results of innovative trend analysis (ITA) for meteorological subdivisions of IMD. **b** Mean annual rainfall results of innovative trend analysis (ITA) for meteorological subdivisions of IMD

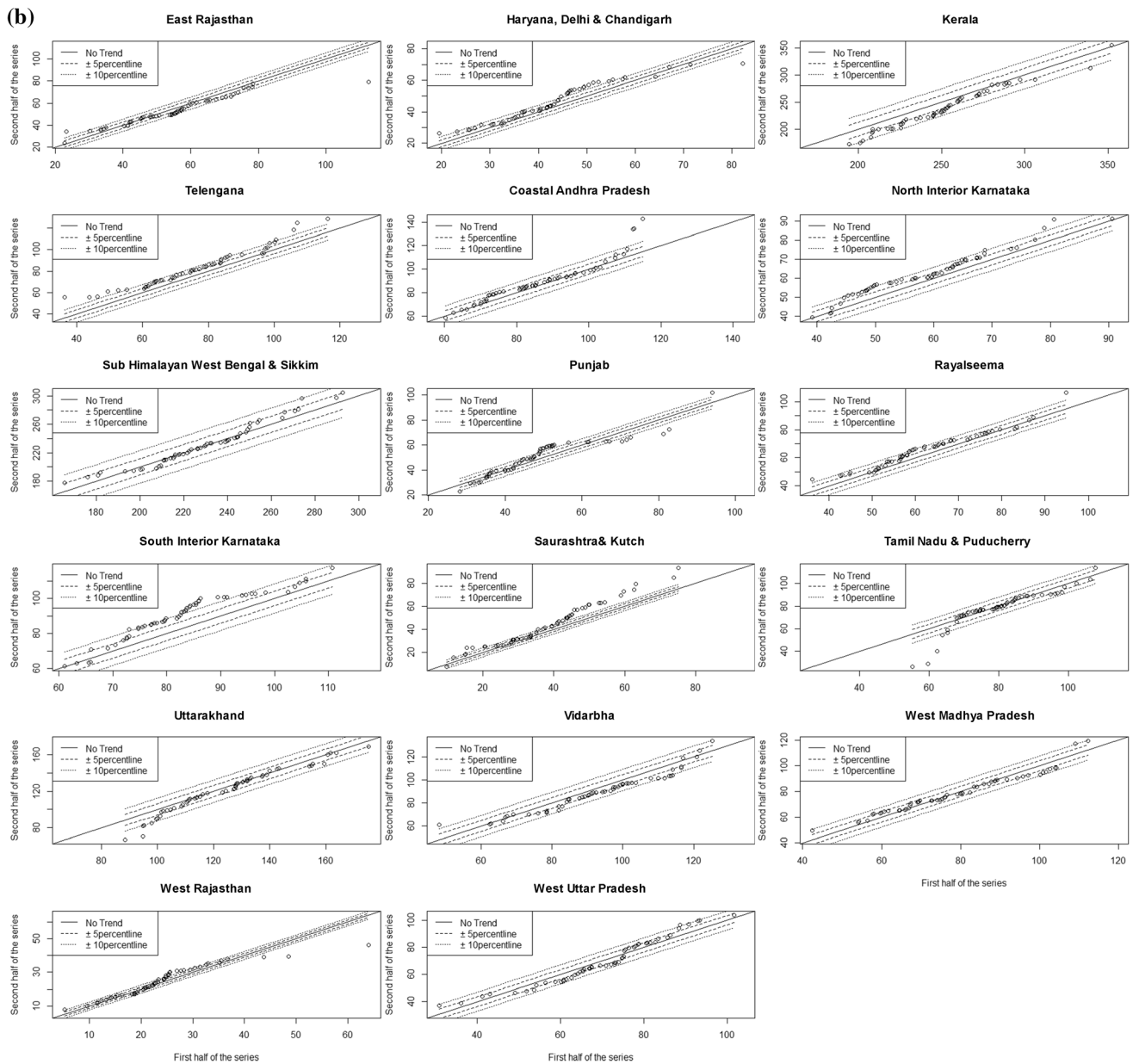


Fig. 2 continued

divisions) showed a trend toward decreasing yearly rainfall (East Rajasthan, Himachal Pradesh, Assam & Meghalaya, Orissa, Mizoram & Tripura, Chhattisgarh, West Madhya Pradesh, Nagaland, East Uttar Pradesh, Kerala, Manipur, Bihar, Punjab, Jharkhand, East Madhya Pradesh, and Arunachal Pradesh). The mean annual rainfall was significantly higher or lower in the remaining subdivisions, with the exception of 15, which had no discernible increasing or falling tendency overall (Table 1). The mean annual rainfall significantly decreased in Nagaland-Manipur-Mizoram-Tripura ($p < 0.05$), Bihar, East Uttar Pradesh, Chhattisgarh, Jharkhand, East Madhya Pradesh, and Kerala ($p < 0.1$), Arunachal Pradesh ($p < 0.01$), Assam and

Meghalaya ($p < 0.1$) (Table 1). Surprisingly, Arunachal Pradesh was the only division to show a consistent declining trend. The ITA’s slope in India ranged from 0.02 to 1.71 for the years 1969–2017 (Table 1). Arunachal Pradesh saw the largest ($- 2.82\%$) decline in mean annual rainfall. There was a definite declining tendency between 1969 and 2017.

3.2 Extent of drylands over the decades

The Intergovernmental Panel on Climate Change (IPCC) claims that drylands will get drier and desertification will be irrevocable. Human driven climatic variations are the

Table 1 Trend slope and trend indicator for innovative trend analysis during 1969–2017

State	Trend slope	Trend indicator	State	Trend slope	Trend indicator
Arunachal Pradesh	– 1.71	– 2.82	Sub Himalayan West Bengal & Sikkim	0.02	0.09
Nagaland, Manipur, Mizoram and Tripura	– 0.47	– 1.16	Marathwada	0.08	0.19
East Madhya Pradesh	– 0.16	– 0.91	Punjab	0.1	0.23
Chhattisgarh	– 0.25	– 0.89	West Rajasthan	0.02	0.23
East Uttar Pradesh	– 0.2	– 0.87	Gujarat Region	0.08	0.25
Jharkhand	– 0.18	– 0.71	Coastal Andhra Pradesh	0.04	0.37
Assam & Meghalaya	– 0.25	– 0.59	Rayalseema	0.059	0.44
Kerala	– 0.27	– 0.58	Kankan & Goa	0.22	0.59
Bihar	– 0.15	– 0.55	Haryana, Delhi & Chandigarh	0.07	0.69
Orissa	– 0.13	– 0.45	Gangetic West Bengal	0.19	0.71
Himachal Pradesh	– 0.05	– 0.42	North Interior Karnataka	0.08	0.74
East Rajasthan	– 0.05	– 0.35	Coastal Karnataka	0.34	0.75
Vidarbha	– 0.05	– 0.35	South Interior Karnataka	0.14	0.81
Tamil Nadu	– 0.02	– 0.27	Madhya Maharashtra	0.18	0.87
Uttarakhand	– 0.09	– 0.24	Telangana	0.14	0.87
West Uttar Pradesh	– 0.05	– 0.12	Jammu & Kashmir	0.13	0.95
West Madhya Pradesh	– 0.02	– 0.01	Saurashtra & Kutch	0.13	1.46

major factors of land degradation and desertification in most arid and semi-arid regions (Huang and Kong 2016). The AI maps of 49 years period (1969–2017) were divided into five decades; 1969–1978, 1979–1988, 1989–1998, 1999–2008, and 2009–2017. Decadal maps are prepared by taking mean of the annual AI maps after observing the maps for no outliers. The classification scale of UNEP (1992) is used to differentiate climatic regions in the maps (refer to Table 2). India is majorly covered with arid and semi-arid regions (refer to Fig. 3). Arid and semi-arid regions are extremely sensitive to climate change and land degradation (Ramachandran et al. 2015; Li et al. 2017; Kimura and Moriyama 2019).

A shift in aridity is observed towards more arid conditions particularly in the regions of Uttar Pradesh and Madhya Pradesh; and a change in the humid conditions in some parts of North-eastern India where humid regions are

shifting towards semi-arid and sub-humid region over the decades. Overall, the average area of dryland classes (arid, semi-arid & sub-humid) has increased from 3,436,400 to 3,521,100 sqkm and the mean decadal humid area has decreased from 193,600 sqkm to 157,300 sqkm from the decade 1969–1978 to 2009–2017 respectively (refer to Fig. 4). Several studies depicted an increase in global drylands and a rising aridity in different regions around the world (Huang et al. 2016; Lickley et al. 2018).

3.3 Annual AI periodic analysis

Figure 5 shows the continuous wavelet transform with gaussian aridity derivative on a yearly basis from 1969 to 2017. To understand the periodic volatility, a specific yearly aridity for the Indian monsoon zones was observed. Stronger and weaker powers are indicated by the colors red

Table 2 Percentage distribution of area statistics of aridity classes over the decades. The downward (↓) and upward (↑) arrow shows decreasing and increasing trend respectively with respect to the base decade 1969–78

Class (%)	1969–1978	1979–1988	1989–1998	1999–2008	2009–2017
Hyper-arid	2.28	3.26 (↑)	0.98 (↓)	2.93 (↑)	0.98 (↓)
Arid	41.37	39.09 (↓)	43.65 (↑)	47.56 (↑)	46.25 (↑)
Semi-arid	48.86	47.56 (↓)	45.28 (↓)	42.35 (↓)	45.28 (↓)
Sub-humid	2.28	4.56 (↑)	5.21 (↑)	2.93 (↓)	3.26 (↓)
Humid	5.21	5.54 (↑)	4.89 (↓)	4.23 (↓)	4.23 (↓)

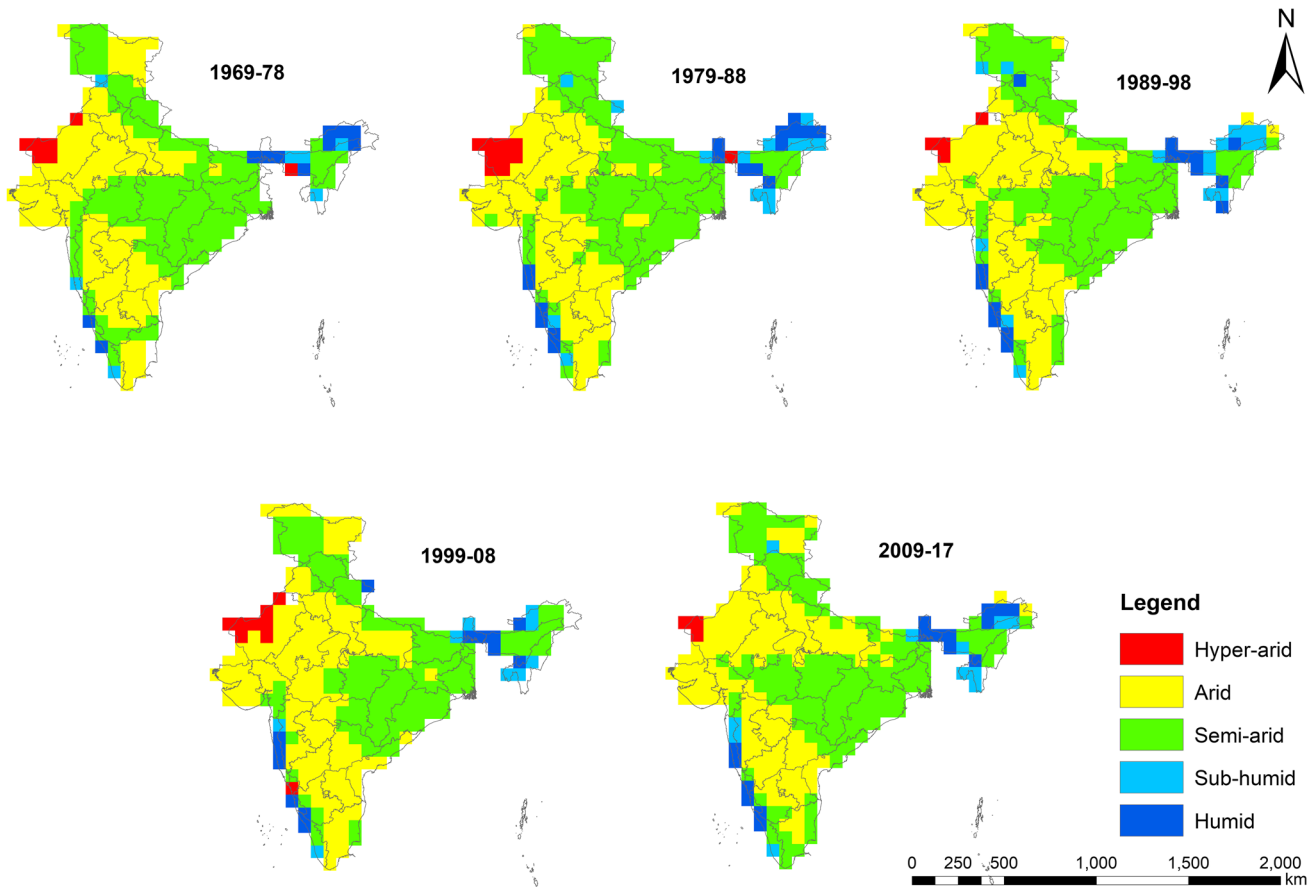
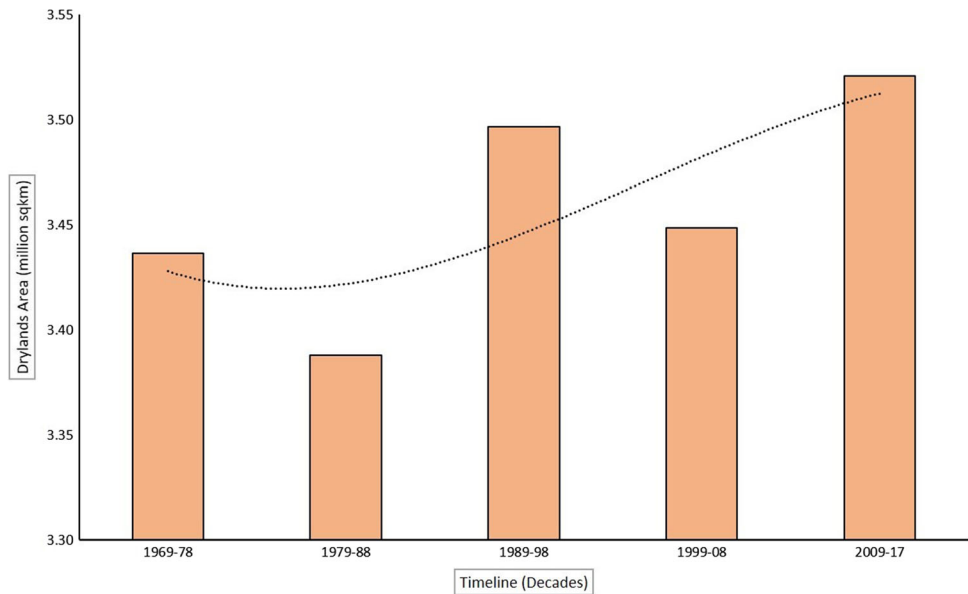


Fig. 3 Spatial distribution of average decadal Aridity Index (AI) from the decade 1969–78 to 2009–17. The classification scheme is based on UNEP Aridity Index, 1992

Fig. 4 The bar graph depicting the spread of drylands over the decades. The drylands consist of arid, semi-arid and sub-humid regions (FAO 2019)



and blue, respectively. A 5% significance level against the red noise is denoted by a thick black contour line. The cone of interest within which significance might be assessed is

shown by the conic concave area. The year is represented by the horizontal axis, and the wavelet transformation power spectrum is represented by the vertical axis. Hilly

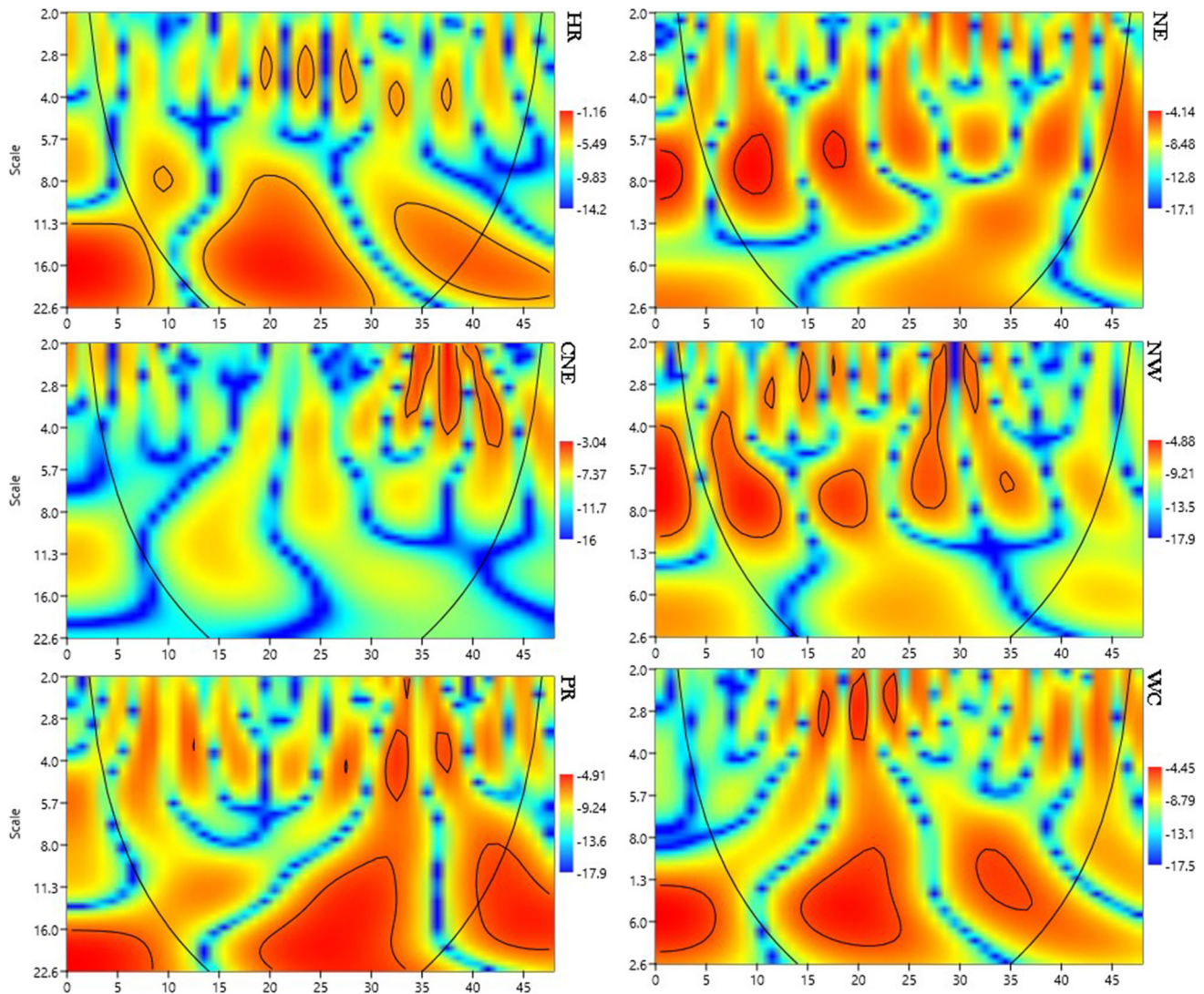


Fig. 5 Continuous Wavelet Transform with derivative of Gaussian of aridity (HR—Hilly regions; NE—Northeast; CNE—Central Northeast; NW—Northwest; PR—Peninsular region; WC—West Central)

areas, peninsular areas, and west central zones all showed a high range of volatile situations. In the central northeast, north west, and north east regions, weaker power spectrum was observed in the higher spectrum zone (> 8.0 band). Aridity becomes significantly cyclically volatile due to high rainfall dependence (Fig. 5).

3.4 Seasonal aridity and its trend

The IMD identifies four seasons in India; pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November) and winter (December–February). There is high seasonal variation in aridity, however the trend in each season is signifying dry conditions in more than half of the country (refer to Fig. 6). During pre-monsoon season, hyper-arid conditions are widespread in

the north-western region. Since the PET is highly dependent on temperature changes, the warming in summer contributes to the aridity index. During monsoon, most of the northeast and central regions are under sub-humid and humid conditions. Semi-arid and arid conditions prevail in North-western and Peninsular zones. Post-monsoon and winter season are highly dominated by hyper-arid, arid and semi-arid conditions due to less precipitation throughout the country.

There is an increasing aridity trend (decreasing AI value) over most of Delhi, Chandigarh, Haryana, Bihar, Kerala, Tamil Nadu, West Bengal and Uttar Pradesh, and some parts of Madhya Pradesh, Assam and Arunachal Pradesh in the monsoon season (refer to Fig. 7). It infers that PET outpaces precipitation during the monsoon. These results are supported by the observed decrease in the long-

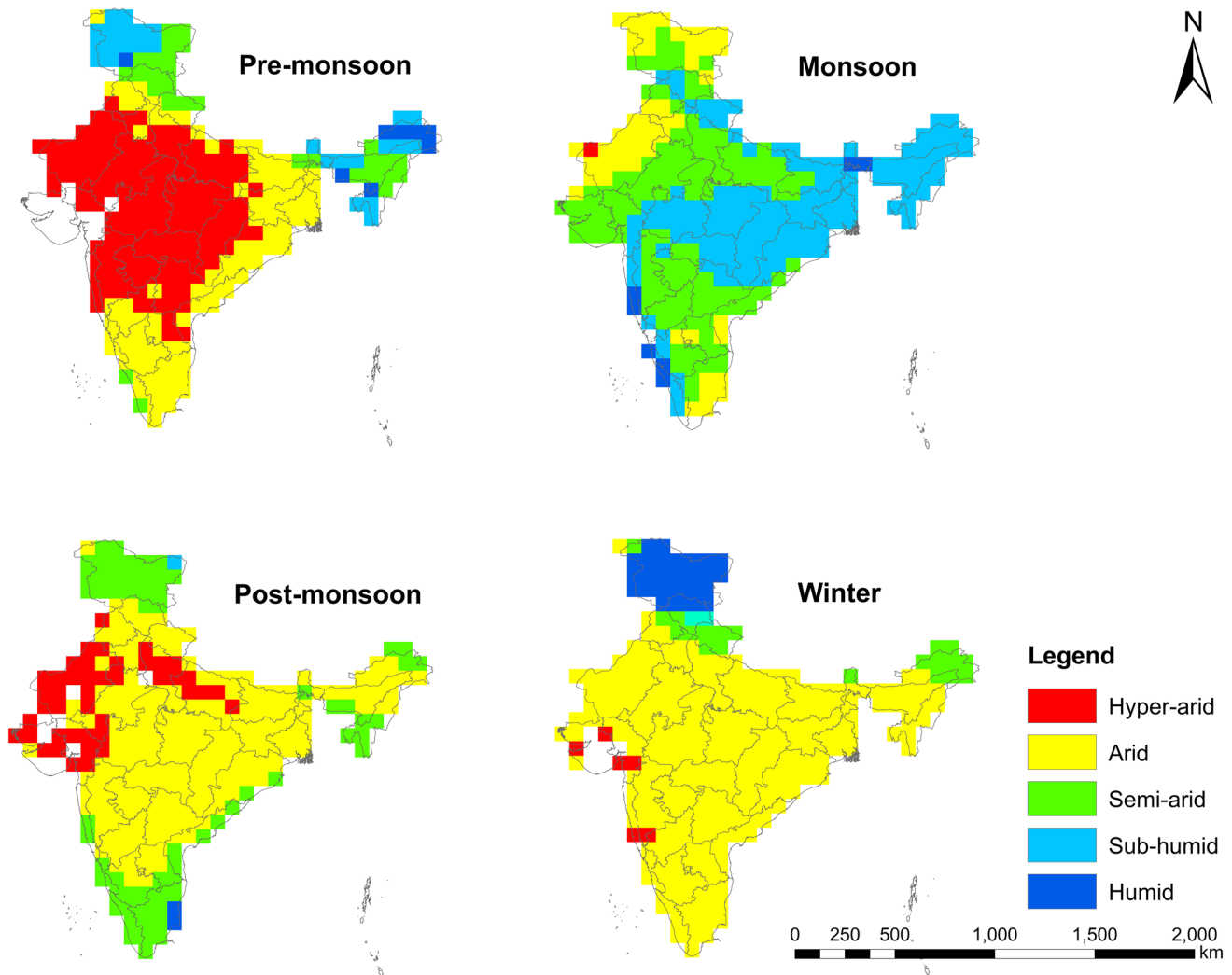


Fig. 6 The maps exhibiting average seasonal distribution of aridity changes from 1969 to 2017

term annual precipitation within the central and northern India (Kumar et al. 2010; Maharana et al. 2021; Deshpande and Kulkarni 2022).

3.5 Average monthly aridity and its trend

For each month, average long-term AI and its trend is estimated from the year 1969 to 2017. Hyper arid conditions are prevalent from January to May on account of rising temperature. Arid conditions are widespread in the months from October to December. Semi-arid conditions are dominant during the month of June and September, while humid conditions are extensive in the months of July and August due to the occurrence of southwest monsoon (refer to Fig. 8). Most of the change in aridity is not statistically significant (refer to Fig. 9). Regardless, there is a rising aridity trend observed in most of the months across the states (refer to Fig. 10).

4 Discussion

It is estimated that in many parts of India, the frequency of intensive rainfall has increased and the number of days in monsoon has decreased (Praveen et al. 2020). Various studies have reported that Central and North Eastern parts of India have observed a decreasing rate of monsoon (Maharana et al. 2021; Deshpande and Kulkarni 2022). These changes in precipitation and PET leads to long term impacts on wet/dry zones. Aridity is considered as an indicator of land that is more suitable for characterizing degree of wetness/dryness to assess drought conditions (Nyamtseren et al. 2018; Chai et al. 2021). In the average AI map (2009–2017), the arid (46.25%) and semi-arid (45.28%) areas cover more than 90% of the land, making the country prone to land degradation and drought like conditions. Based on AI ratio, drylands are defined as areas with AI value less than 0.65, it indicates water scarcity in

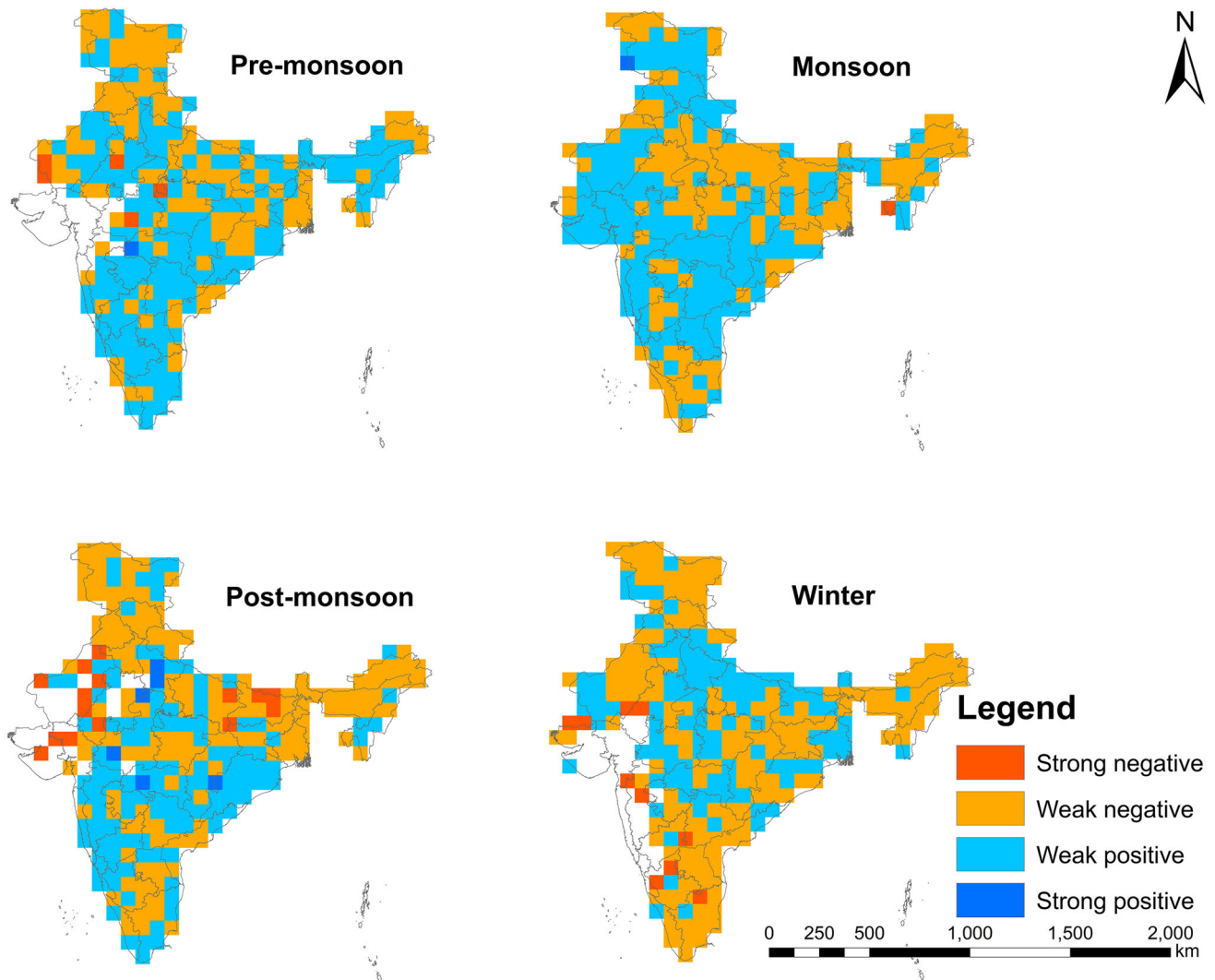


Fig. 7 The maps exhibiting seasonal trend of average aridity over the years. The trend range lies between -1 and 1 . It is further classified in strong negative or positive and weak negative or positive

the atmosphere and consists of arid, semi-arid and sub-humid regions (Zhang et al. 2021). Following this traditional definition of drylands, our study shows a considerable increase in the drylands area over the time. Any change in drylands directly affect agricultural practices and food security as they cover a large portion of land in India (Mishra 2014; Ochieng et al. 2016; FAO 2021). Therefore, the long-term changes in drylands area are to be prevented to check land degradation and desertification. It is already very challenging to recover from increasing dryland conditions in the current scenario due to water scarcity, high dependency on rainfall, and limited infrastructure and technology especially in rural India (Haider and Adnan 2014).

The annual average aridity trend suggests that the changes in aridity pattern have shifted the climate of central and north-east India towards the arid regime and,

western India towards a relatively humid regime. In recent years, western India has faced frequent floods due to the shift in its climatic conditions (Maharana et al. 2021) and India has experienced less rainfall during the monsoon season and increasing dry spells (Mishra 2020). Ramarao et al. (2019) reported expansion in the semi-arid area with relatively 10% larger area than the corresponding area during the previous decades and the newly formed semi-arid region accounting to 4% of total land area of the country. Several studies have reported similar pattern over south Asia since 1950s (Guhathakurta and Rajeevan 2006; Chung and Ramanathan 2006; Bollasina et al. 2011; Krishnan et al. 2013, 2015; Ramarao et al. 2015) which is attributed to declining precipitation trends over India (Chung and Ramanathan 2006; Bollasina et al. 2011; Sanap et al. 2015; Krishnan et al. 2015).

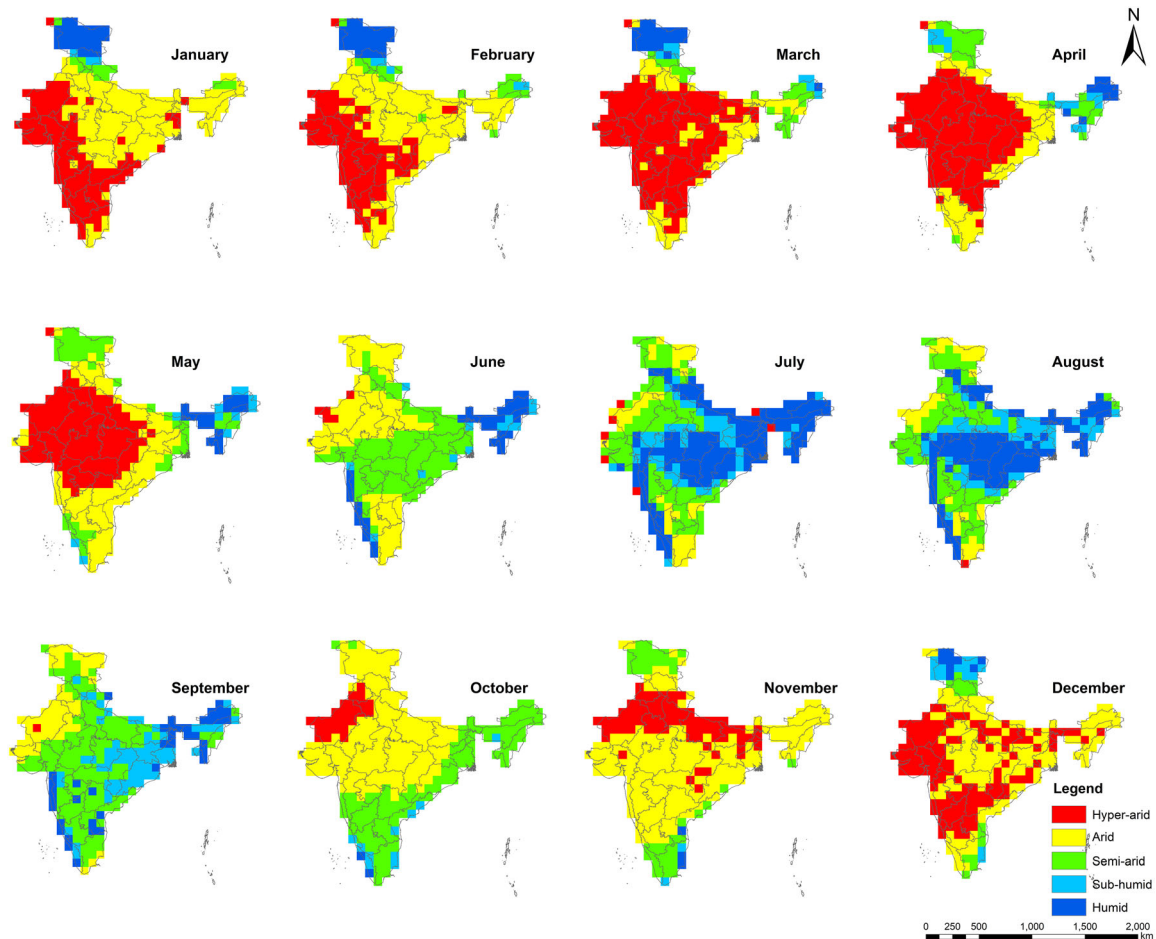


Fig. 8 Spatial spread of average monthly (January–December) aridity from 1969 to 2017

There is noticeable seasonal variation in the aridity throughout the climatic regions. A negative trend (increasing aridity) is observed in the monsoon season over north-western and north-eastern zones in the country. It is also depicted by computed monthly trend over the monsoon months of June, July, August and September. Such climatic variations can alter the ecological balance and disturb agro-ecosystems. (Salvati et al. 2012). The arid regions are slowly getting drier over the large part of India, putting a substantial pressure on water resources and management (Mishra 2020). Drought and extreme rainfall events are predominant in regions with increasing arid conditions and play a major role in crop failure (Pour et al. 2020). The aridity changes can have serious implications on agricultural production and irrigation facilities; it may severely affect our country's future food security and economic conditions (Raju et al. 2013). The AI variations in this study is consistent with previous studies over different parts of the country (Ramarao et al. 2019; Raju et al. 2013). In Northeast Indian, evident rising trends of have been found; and increase in over-all semi-arid and arid region of the country.

4.1 Limitations and future research

While the present study provides a comprehensive analysis of the long-term variability and trend of aridity in India, there are some limitations to be considered. Firstly, the study uses only two variables, precipitation and temperature, to estimate aridity index. Other factors such as soil moisture and vegetation cover can also affect aridity and should be considered in future research. Secondly, the study considers only the average values of AI over a period of 49 years and does not take into account interannual variability or extreme events such as droughts or floods, which can have significant impacts on the ecosystem. Thirdly, the study uses a non-parametric approach to analyze the trend, which may not be suitable for capturing complex patterns or sudden shifts in aridity.

In terms of future research, it would be useful to incorporate more variables and use more advanced modeling techniques to estimate aridity and its trends. Machine learning algorithms can be applied to capture non-linear relationships and better predict aridity under future climate scenarios. Additionally, studying the impact of aridity on

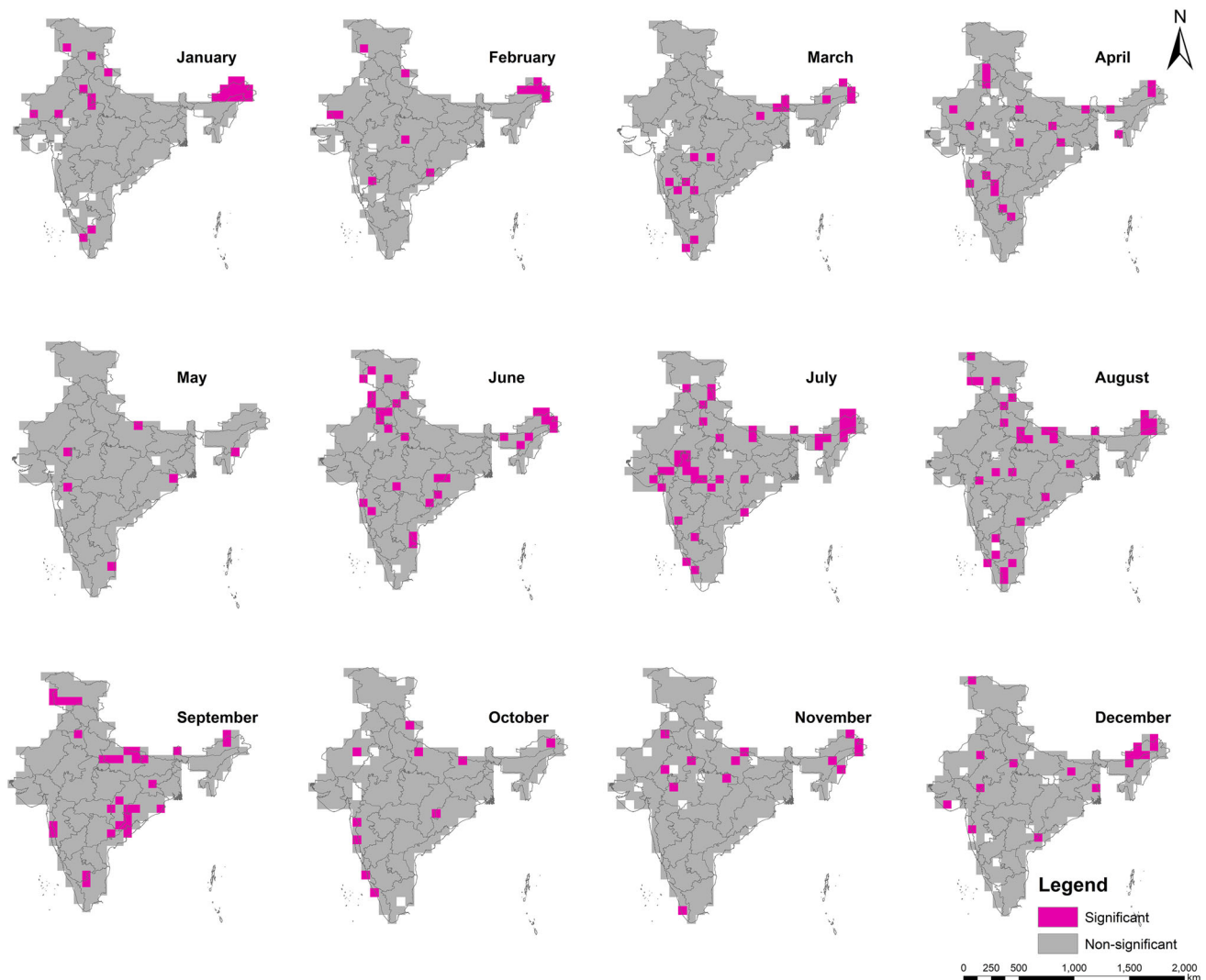


Fig. 9 Spatial spread of monthly aridity trend significance: statistical and non-statistical

agriculture and water resource management can provide insights into the adaptation strategies needed to mitigate the effects of climate change. Finally, a more detailed analysis of the spatial patterns of aridity and their drivers can inform land use management plans and conservation strategies in dryland regions.

5 Conclusion

This is a preliminary spatio-temporal study to comprehend and characterize aridity changes in terms of AI in India during the last five decades. AI is computed as a ratio of precipitation to PET. In the current study, Thornthwaite method is favored for the estimation of PET due to its simplicity and validation in Indian region over other empirical methods. However, it is often recommended to validate Thornthwaite PET with local climatic data of the

region. The scope of this study is wide and due to limited data availability on the country level, the validation was disregarded. The monthly AI maps obtained were converted into mean annual, decadal and seasonal maps. Further, non-parametric MK test has also been applied to examine the trend in the mean monthly, annual and seasonal aridity time series.

The study surmises that drylands are increasing with the change in aridity due to long-term climatic variations. The results show that climate is mostly arid to semi-arid in the country. However, there is an observed shift in semi-arid regions towards arid conditions particularly in the central mainland; and change in the humid conditions in parts of northeast Himalaya where humid regions are gradually moving towards sub-humid conditions over the decades. The study shows that drylands have increased from 3.44 million sqkm to 3.52 million sqkm during the last five decades which may exacerbate land degradation processes.

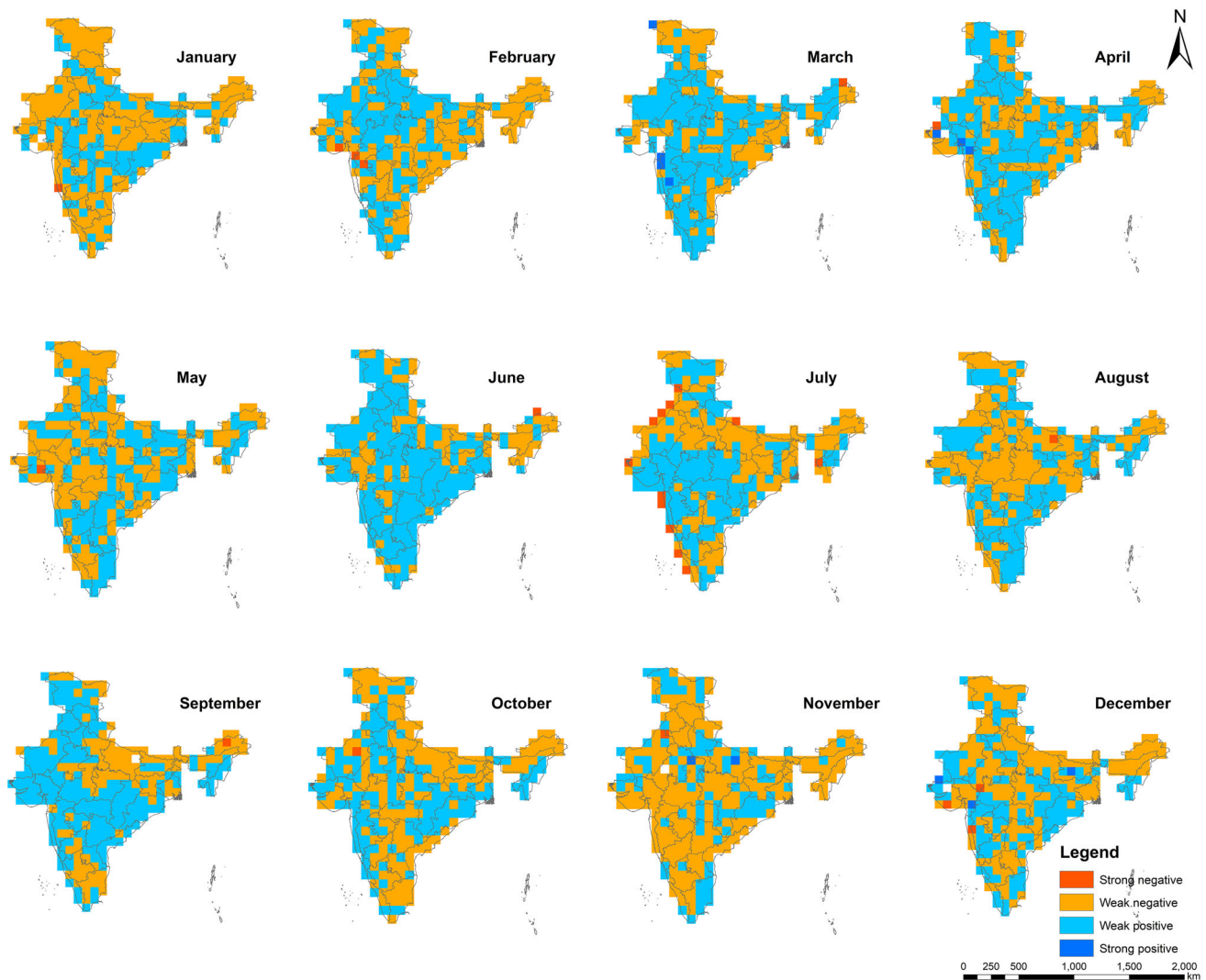


Fig. 10 Spatial spread of average monthly aridity trend from 1969 to 2017. The trend range lies between -1 and 1 . It is further classified in strong negative or positive and weak negative or positive

Approximately, 80 thousand sqkm drylands area has increased over the last five decades. Although, the trend is not statistically significant but there is an observed rise in aridity due to long-term changes in temperature and precipitation.

This study has future scope for drylands management and better adaptation-based studies for water resources conservation. The study can be taken further to assess other climatic indices and understand the role of human pressure on the arid environments. Remote sensing and GIS provide tools and techniques to scientific approaches and help understand long term spatio-temporal changes at the climate and landscape level. Such studies significantly support policy framing and climate change adaptations programs in arid and semiarid regions.

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Declarations

Conflict of interest The authors declare no competing interests.

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