

A Comparative Study of Temperature and Precipitation-Based Aridity Indices and Their Trends in Mongolia

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Abstract

Aridity is a major indicator for defining the area of land that is prone to drought, land degradation, and desertification. The present research explores spatiotemporal variations of aridity using four different equations: (1) de Martonne aridity index (IDM); (2) Thornthwaite aridity index (AI); (3) moisture coefficient by V. I. Mezentsev (MI) and (4) Hydrothermal coefficient by Selyaninov (HTC) over Mongolia based on the primary climatic data from 70 different stations in Mongolia for the last 55 years (1961–2015). Utilizing these data using RegCM4-HadGEM climate change scenario, this study explores how the aridity level is likely to change in the future. The results showed that the total area of drylands (i.e., hyper-arid, arid, semi-arid and sub-humid regions) determined by IDM, MI, AI and HTC is approximately 64.1%, 70.7%, 85%, and 98%, respectively. Out of the four aridity indices considered, the metrics defined by AI and MI showed high correlation with the NDVI derived dryland regions. Time series analysis of AI and MI both showed a decreasing tendency for the period of 1961–2015. In the central and the northeastern regions in Mongolia, significantly decreasing trends in the aridity indices were observed. With respect to the stations with significantly decreasing trends in aridity, the relative changes of the aridity index magnitude varied between 14% and 74%. The aridity index calculated using climate change scenarios also indicated that the aridity level is likely to increase in the twenty-first century in the central part of Mongolia, whilst the extra arid areas will stable. The study has implications for water resources management, agriculture and social and economic life of the people of Mongolia and the other regions globally where aridity presents a significant challenge for decision makers.

Keywords Aridity index · Drylands · Spatiotemporal trend · Relative change

Introduction

Aridity is a phenomenon defined by a shortage of moisture based on the average climatic conditions in a given region (Agnew and Anderson 1992). On the onset of the twenty-first century, the climatic aridity, dryness, and drought events are becoming a significant socio-environmental problem, and are affecting both ecosystem and the livelihood of populations in many regions, and especially in developing nations. An increase in aridity or dryness levels beyond a certain point can negatively affect the resilience to the climate change. To understand the various climatic mechanisms and to successfully describe the state of the climate, a set of climatic indices are used as statistical and diagnostic tools (Deniz et al. 2011). The aridity index is a numerical climatic metric that can be used for monitoring and prediction of the degree of dryness in a given region (Nastos et al. 2013; Tabari et al. 2014). Its changes are likely to affect the regional hydrological cycle, water resources availability

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and its management (Liu et al. 2012). This change can also induce desertification of the particular region and pose significant repercussions for people within that region.

Temperature and precipitation measurements are commonly used to derive primary climatic indices. This is mainly because (1) temperature and precipitation are the main indicators of climate and (2) compared to some of the other climatic variables, the records of temperature and precipitation are generally longer. Furthermore, the changes expected to result from climate warming can be well approximated by these two variables compared to the other variables such as cloud cover, wind fields, and humidity (Toros et al. 2008; Tabari et al. 2014). Although temperature and precipitation are useful parameters to study their overall trends due to climate change, the aridity, or equivalently, the humidity index, is better suited to assess the climate change and its significance with regard to bioclimatic conditions (Kafle and Bruins 2009). It is also noteworthy that climate change has the ability to transform dry/wet conditions, and has an adverse effect on regional land use, especially in terms of agricultural land use issues (Du et al. 2013; Wang et al. 2018). It is, therefore, conceived that a credible knowledge on how climate change can affect and also impact the dry and wet conditions and the overall extent of drylands is necessary from conservation and protection perspectives, and for developing proper adaptation strategies in vulnerable regions (Nicholson 2011).

Numerous studies have been conducted with an aim to determine the spatial distribution and spatiotemporal changes in aridity, largely based on aridity equations derived from temperature and precipitation data. Baltas (2007) used the Johansson Continentality Index, Kerner Oceanity Index, de Martonne (IDM) Aridity Index, and the Pinna Combinative (IP) Index to study the distribution of climatic indices in northern Greece for the period 1965–1995. They concluded that the Johansson index was a preferable metric to separate continental areas from oceanic climates. The study also found that IDM was more precisely able to define local climates than the IP. Paltineanu et al. (2007) detected a strong correlation between the IDM aridity index, crop evapotranspiration and irrigation water requirements of crops in Romania. Tabari et al. (2014) explored the spatial and temporal variations of the IDM and Pinna aridity indices over Iran and found a strong correlation between the two indices. They also found that about 63% of the data series had a decreasing trend in Iran. Wu et al. (2006) studied annual and seasonal trends in temperature, precipitation, potential evapotranspiration, and aridity index from 1971 to 2000 in China and found generally decreasing trends in potential evapotranspiration and the aridity index.

Besides using the global indices, some regions of the world have also used their own climate indices to define the dry and wet region. For instance, the use of the Selyaninov's

hydrothermal index (HTC) for the dry and wet climate zonation has been widely used in Russia (Perevedentsev et al. 2012). With a somewhat different focus, the climate humidity over the Western Siberia was assessed by the study of Mezentsev and Karnatsevich (1969) using a moisture coefficient (MI).

Several researches are currently monitoring aridity and drought conditions in Mongolian grassland using different methods including both temperature and precipitation indices, remote sensing data and dendrochronological reconstruction (Chang et al. 2017; Tong et al. 2018; Hessler et al. 2018), and meaningful results have been obtained. However, one index has performed well in one country and climate zones, other in other countries. It remains unclear which of different temperature and precipitation based aridity and/or drought indices can best describe Mongolia's aridity conditions, for further use by researchers, government departments, or stakeholders to effectively plan drought, land degradation and desertification prevention and mitigation actions. The aim of this study is to characterize the climate aridity using temperature and precipitation-based indices for the regions where full meteorological data are not available, in order to define ETo estimations. For this purpose, the IDM, UNEP aridity index (UNEP 1992) using modified Thornthwaite's potential evapotranspiration equation aridity (Palmer and Havens 1958), HTC by Selyaninov and MI by Mezentsev were calculated using the monthly temperature and precipitation data from 70 meteorological stations in Mongolia for the period 1961–2015. To investigate the temporal trends in the aridity indices, the non-parametric Mann–Kendall test modified by Hamed and Rao (1998) has been used. Additionally, the Pettitt's test has been utilized for change point detection within the time series of the aridity indices in the Mongolia region.

Data and Methods

Study Area

Mongolia is one of the largest land-locked countries in Eurasia, located between the latitudes of 41°35'N and 52°09'N and the longitudes of 87°44'E and 119°56'E. It occupies 1564 square kilometers of the land area. Mongolia's climate has a variation along the north–south gradient from being humid to an extra arid zone. The climate of the country is mainly of an extra-continental, with distinct seasonal and diurnal fluctuations in temperature and a clear seasonal pattern of precipitation. The annual average air temperature is about 0.7 °C compared with the mean temperature of the earth of about 14.4 °C. Air temperature is expected to change as much as 30 °C in 1 day, with the arrival of the brisk northwesterly winds (Batjargal 2007).

The regional temperatures of Southern Mongolia have increased by 0.1–3.7 °C over the past 60 years, spring precipitation has decreased by 17%, and summer precipitation has increased by 11% (Natsagdorj 2000). These changes in temperature and precipitation are likely to intensify the occurrence of drought, especially during the onset of vegetation green-up. Moreover, the frequency of drought in the spring and summer has been reported to increase as much as four times every 5 years in the Gobi region (Batima and Dagvadorj 2000). The drought has a disturbing effect not only on agricultural productivity and hydrological resources but also on natural vegetation; therefore, it may accelerate the desertification processes associated with destructive human activities (that is, overgrazing) in semi-arid grassland areas in Mongolia.

The monthly records of temperature and precipitation data provided by the National Agency for Meteorology and Environmental Monitoring (<http://namem.gov.mn>) have been used in this study. A total of 70 weather stations with a minimum record length of 40 years were considered. The spatial distribution of the selected stations has been illustrated in Fig. 1.

Aridity Indices

Aridity is the degree to which a climate lacks sufficient, life-promoting moisture, and is the opposite of humidity, in the climate sense of the term (American Meteorological Society 2006). The higher the aridity indices of a region, the greater the water resources variability (Tabari et al. 2014). An increasing aridity represents a higher frequency of the dry years over an area (Deniz et al. 2011). In this study, we apply the De Martonne aridity index, UNEP



aridity index, Selyaninov's hydrothermal coefficient and Mezentsev's moisture ratio calculated for the Mongolia based on temperature and precipitation dataset for the period 1961–2015.

The IDM, originally developed by de Martonne (1925), is calculated by the following equation:

$$I_{DM} = \frac{P}{T + 10} \quad (1)$$

where I_{DM} is the De Martonne aridity index (mm/°C), P is the annual mean precipitation (mm) and T is the annual mean air temperature (°C). The climatic classification based on the IDM values is shown in Table 1.

The UNEP aridity index (AI) calculated following the Thornthwaite (1948) approach. In this research we used a more simplified equation for calculation of potential evapotranspiration developed by Thornthwaite (1948), AI is given by

$$AI = \frac{P}{PET} \quad (2)$$

where P is the mean annual precipitation (mm) and PET is the mean average evapotranspiration, which is calculated as follows:

$$PET = 1.6 \times \left(\frac{10T_i}{J} \right)^c \quad (3)$$

where T_i is a monthly mean temperature (°C), J is a heat index which is constant for a given location and is the sum of 12 monthly index values i , where $i = \left(\frac{T_i}{5} \right)^{1.514}$ (°C); c is an empirically determined exponent which is a function of J : $c = 6.75 \times 10^{-7} J^3 - 7.71 \times 10^{-5} J^2 + 1.79 \times 10^{-2} J + 0.49$, °C. The climate classification is done using the UNEP (1992) classes which is similar to the climate types defined by UNESCO (1979). Table 2 shows the climatic classification based on the AI values.

The hydrothermal coefficient (HTC), proposed by (Selyaninov 1928), is widely used metric for drought monitoring,

Table 2 The classification of the climatic regions based on UNEP aridity index (UNEP 1992)

Climate Class	AI
Hyper-arid	< 0.05
Arid	0.05–0.20
Semi-arid	0.20–0.50
Sub-humid	0.50–0.65
Humid	> 0.65

largely applied in Russia. The ratio is expressed as a correlation between the amount of precipitation in the time period when average day temperature exceeds +10 °C and the sum of temperature in degrees in the very same period.

$$HTC = \frac{\sum R}{0.1 \times \sum T} \quad (4)$$

where $\sum R$ is a precipitation total for the growing season (mm), and $\sum T$ is the accumulated mean daily surface air temperatures above +10 °C for the same period (°C). The climatic classification based on the HTC values is shown in Table 3.

Russian scientist, Mezentsev (1955) and Mezentsev and Karnatsevich (1969), proposed to use the runoff constant to determine the climate humidity in regions with the sparse hydrological network. Their study developed an equation for Western Siberia and is given as:

$$MI = \frac{P}{(0.2 \sum T_{>10^\circ} + 306)} \quad (5)$$

where P is the sum of annual precipitation (mm) $T_{>10^\circ}$ is the sum of the mean temperatures above +10 °C (°C). The climatic classification based on the IDM values is shown in Table 4.

Aridity Zoning of Mongolia

To compare the performance of each selected index, the correlation analysis was done using NDVI-derived natural zone data, maximum temperature and precipitation. The NDVI data for the period of 2001–2015 are classified following Erdenetuya and Hudulmur (2009). The maximum temperature and

Table 1 Type of climate according to the de Martonne aridity index (Croitoru et al. 2013)

Climate type	I_{DM} values
Arid	$I_{DM} \leq 10$
Semi-arid	$10 \leq I_{DM} < 20$
Mediterranean	$20 \leq I_{DM} < 24$
Semi-humid	$24 \leq I_{DM} < 28$
Humid	$28 \leq I_{DM} < 35$
Very humid	$35 \leq I_{DM} < 55$
Extremely humid	$I_{DM} > 55$

Table 3 The classification of the climatic regions based on hydrothermal coefficient (Selyaninov 1928)

Climate type	HTC
Humid	HTC from 1.0 till 2.0
Sub-humid	HTC > 2.0
Dry	HTC < 1.0
Semi-arid	HTC from 1.0 till 0.7
Arid	HTC from 0.7 till 0.4

Table 4 The classification of humidity level based on Mezentsev equation (by Ivanov 1948)

Climate zone	Moisture region	MI
Arid	Insignificant moisture	0–0.2
	Poor moisture	0.2–0.3
	Low moisture	0.3–0.4
Dry or insufficient moisture	Insufficient moisture	0.4–0.5
	Irregular moisture	0.5–0.8
	Moderate moisture	0.8–1.0
Humid	Sufficient moisture	1.0–1.2
High humid	Moderately high moisture	1.2–0.5
	High moisture	1.5–2.0
Extra humid	Excess moisture	2.0<

All the indices were interpolated using regression kriging method (Hengl 2007) using DEM, surface slope, aspect, and long-term NDVI

precipitation data for the period of 1961–2015 were obtained from the National Meteorological Agency.

Methods of Trend Analysis

Mann–Kendall Test

Mann–Kendall test is a statistical test widely used for the analysis of trends in climatologic (Zhang et al. 2009; Mavromatis and Stathis 2011; Tabari et al. 2014; Chen et al. 2014) and in hydrologic time series (Yue and Wang 2004; Pasquini et al. 2006). There are two advantages of using this test. First, it is a non-parametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to the inhomogeneous time series (Tabari and Marofi 2011; Tabari et al. 2014). In the present study, the Mann–Kendall test was used to detect the temporal trends in four different aridity index time series. The test statistic (Z_{MK}) is given as:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (6)$$

In which,

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^n \text{sgn}(x_k - x_i) \quad (7)$$

$$\text{Var}(S) = \frac{[n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(t_i+5)]}{18} \quad (8)$$

where x_k and x_i are the sequential data values, m is the number of tied groups (a set of sample data having the same value), t_i is the number of data points in the i th group, n is

the length of the data set, and $\text{sgn}(\theta)$ is equal to 1, 0, -1 if θ is greater than, equal to, or less than zero, respectively (Tabari and Marofi 2011; Tabari et al. 2014).

The positive (negative) values of Z indicate increasing (decreasing) trends, and the value $Z_{1-\alpha/2}$ denotes a quantile of the standard normal cumulative distribution. The null hypothesis H_0 is accepted if $-Z_{1-\alpha/2} \leq Z_{MK} \leq Z_{1-\alpha/2}$ (Tabari et al. 2014).

For the serially correlated data, the Mann–Kendall test can be ambiguous (Gilbert 1987). If a time series has a significant serial correlation, the measure of the variance of S is preconceived (Hamed and Rao 1998). As suggested by Hamed and Rao (1998), the elimination of the serial correlation effect can be achieved by subtracting a non-parametric trend estimator from the initial time series X and then evaluating the autocorrelation between the ranks of the new time series. Serial correlation coefficients ($\rho(i)$ at lag(i)) that are different from zero at the 5% level are then used to assess the modified variance of S , $V \times (S)$ as:

$$\text{Var} \times (S) = \text{Var}(S) \cdot \text{Cor} \quad (9)$$

where Cor represents a correction due to autocorrelation in the data and

$$\text{Cor} = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-1)(n-i-1)(n-i-2)\rho_s(i) \quad (10)$$

The significance of trends found in this study was evaluated at the 5% significance level. Decreasing trend for aridity index indicates that the climate is getting more arid and vice versa.

Pettitt's Change Point Test

This approach after Pettitt 1979 is widely used to detect a single change point in hydrological and climate series for continuous data series (Pohlert 2016). It is able to test the null hypotheses (H_0) that a given variable follows one or more distributions having the same location parameter (i.e., no change), against the alternative, i.e., a change point exists. The non-parametric statistic is defined as:

$$K_T = \max |U_{t,T}| \quad (11)$$

where

$$U_{t,T} = \sum_{i=1}^t \sum_{j=t+1}^T \text{sgn}(x_i - x_j) \quad (12)$$

The change point of the series is located at K_T , provided that the statistic is significant. The significance probability of K_T is approximated (Pohlert 2016) for $p \leq 0.05$ with

$$p = 2 \exp \left(\frac{-6K_T^2}{T^3 + T^2} \right) \quad (13)$$

Relative Change

The relative change (RC) of the aridity index (Tabari et al. 2014) is determined as follows:

$$RC = \frac{n \times \beta}{|\bar{x}|} \times 100 \quad (14)$$

where n is the length of the dataset record, β is a trend magnitude observed in the series and $|\bar{x}|$ is the absolute average of the data series.

The non-parametric Theil–Sen’s estimator (Theil 1950; Sen 1968) was also used to obtain the magnitude of the trends, which can be written as follows:

$$\beta = \text{Median} \left(\frac{x_i - x_j}{i - j} \right) \quad (15)$$

where $1 < j < i < n$.

Future Aridity

The assessments of future changes in aridity were made using HADGEM and ECHAM5 global climate models which showed a relatively well-simulated climate of Mongolia compared to other global climate models (MARCC 2010). Therefore, the model output at 30 km of resolution has been used for initial and boundary conditions, obtained from the previous study. Then, climate model results are dynamically downscaled from the global scale (180–250 km) to the regional scale (30 km). The climate baseline period selected is from the years 1961–1991 for the entire territory of Mongolia. Future change in aridity is determined with respect to the climate baseline period. Climate change projection is based on RCP8.5 scenarios, which use the assumption that CO₂ concentration is expected to reach 720 ppm depending on world population, technology and development pathway (Gomboluudev 2007).

Results and Discussion

Spatial Distribution of Aridity Index

The spatial distribution of the IDM index over the Mongolia region has been illustrated in Fig. 2a. It is evident that the IDM values are accounting for the entire range of the climate classification categories. For a total of 21 out of 69 stations, the IDM has a value lower than 10.0, which indicates an arid climate at these sites. In opposite way, the highest values of the IDM that entails humid, very humid, and extremely humid climates are distributed to the stations that are located in the northern parts of the

country. About 25.5% of the country can be considered as arid, 17.0% as semi-arid, 7.6% as the Mediterranean, 7.0% as semi-humid, 12.8% as humid, 21.3% as very humid, and 8.7% as extremely humid. The IDM values ranged from about 2.5 for the station, Ehiingol located in the south to about 79 for the station Renchinlumbe located in the north.

According to the AI values, it is evident that about 22.7% of the entire area is classified as hyper-arid and arid climate (Fig. 2b) and at 17 out of the 69 stations studied, the values of the AI were less than 0.2 that implies a dry climate. The semi-arid climate has formal steppe vegetation, which is found in the middle region of the country. Only the regions located on the north and the east of the country had AI values higher than 0.5.

The spatial distribution of the HTC values (Fig. 2c) shows that about 35.6% of the country can be considered as extra arid, whereas 37.9% is arid, 25.5% is semi-arid, and only 1.0% is sub-humid. Among the 69 stations studied, a total of 26 stations exhibited HTC value that was lower than 0.4, which indicates an arid climate. The lowest value of HTC ranges from about 0.03 to 0.09 for the station that is found in the south of the country.

A map of MI values, shown in Fig. 2d, indicates that the area of insignificant and poor moisture occupies about 12.8% of the total territory of the Mongolia country, which coincides with generally arid lands. The semi-arid and dry climate is found on about 29.1% of the total area, and the area of land with humid climate is about 3% of the total territory.

The extra arid area identified by the AI is smaller than that found by the other methods, but the semi-arid area obtained by the AI is considerably the biggest. Overall, the spatial distribution of the AI and MI metrics is similar in this study region, while the climatic zones defined by IDM and HTC are different.

To evaluate how the selected indices represent climatic classification, we have compared the results of the four methods with the NDVI-derived natural zona for the whole country (Table 5). According to the results of the correlation analysis, it can be concluded that the AI and MI metrics are more appropriate for climate classifications since they present climate categories that define the vegetation cover condition more precisely as well as distribution of precipitation and temperature.

In accordance with the results, it is evident that the AI and MI metrics are highly correlated in the present study stations. The coefficient of determination (r^2), for example, is found to be equal to 1 in the arid and semi-arid regions and about 0.98 for all other locations. In the humid climates (i.e., for Renchinlumbe and Hatgal stations), the r^2 value of about 0.60 was obtained between the IDM and AI metric and the r^2 value for the AI metric with IDM and HTC for the stations was found to be between 0.60 and 0.79.

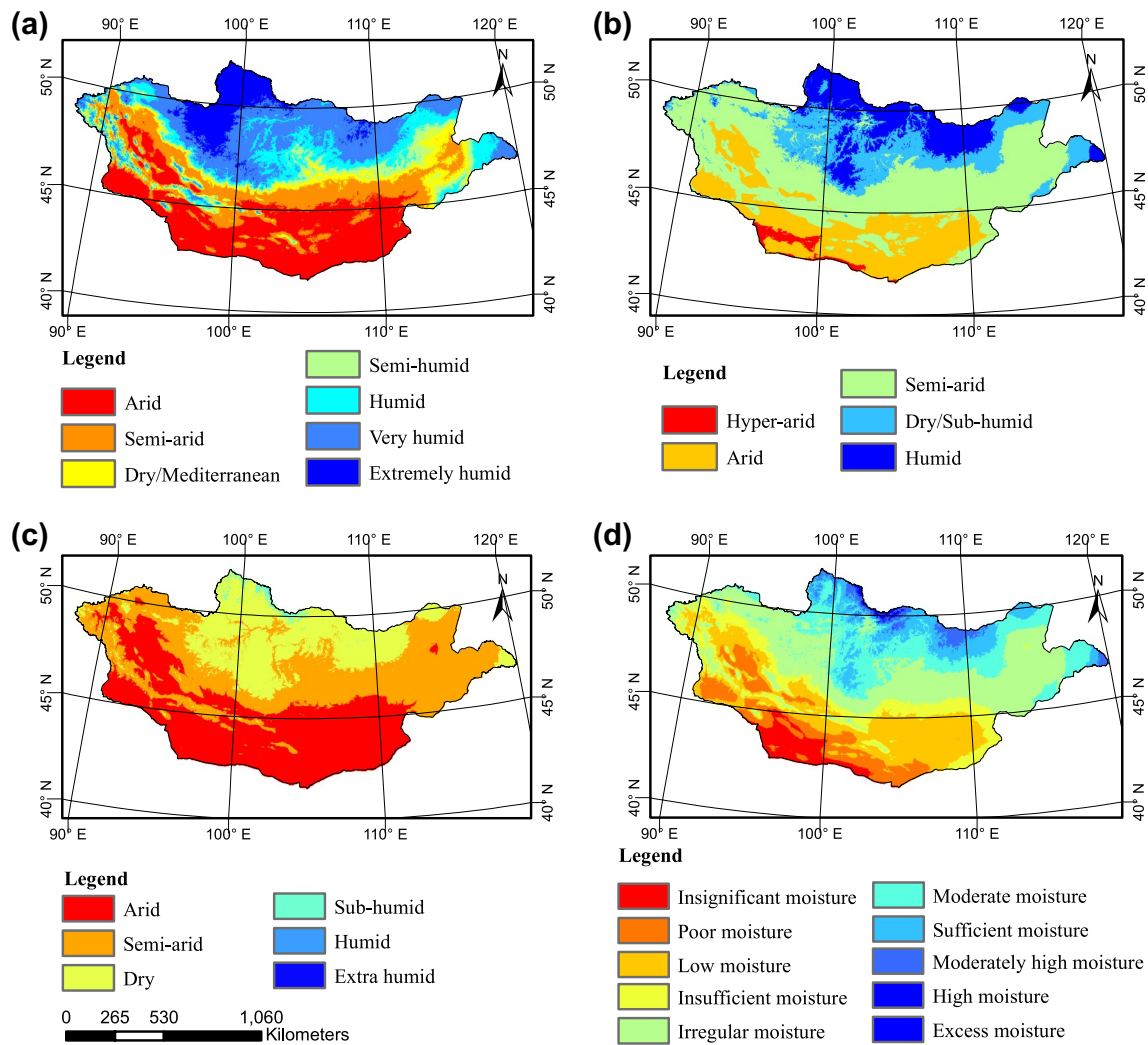


Fig. 2 Climate type map of Mongolia (1961–1991): **a** IDM; **b** AI; **c** HTC; **d** MI

Table 5 The matrix of Pearson's correlation coefficients for aridity indices

	Tmax	Precipitation	NDVI	IDM	HTC	MI
IDM	− 0.4390*	0.0494**	0.46**			
HTC	− 0.509*	0.9818**	0.61**	0.75*		
MI	0.9977**	0.072***	0.78***	0.52**	0.71***	
AI	0.35**	0.9913***	0.79***	0.60**	0.79**	0.98***

Significance level is associated with a symbol: "****" – 0.001, "***" – 0.01, "**" – 0.05

Similar to the variations in IDM, around 85.5% of the HTC series showed a decreasing tendency. Significant decreasing trends in the HTC series at the 5% level were also observed at 28 stations (Table 6). The relative changes of the HTC at the mentioned stations ranged between 18 and 72%. The stations located in central parts of Mongolia have the relative changes higher than 50% (Fig. 3).

Trend of Aridity

The results obtained from the Mann–Kendall test have been illustrated in Fig. 4. The arrow markers in the maps show the temporal trends that were detected by the Mann–Kendall test for the IDM, AI, HTC, and MI metrics over the present study period. The decreasing trend of the aridity indices means

Table 6 The trend and the magnitude of trends statistics obtained from the Mann–Kendall test and Sen’s slope estimator

Station	Mezentsev index		UNEP aridity index		De Martonne index		Selyaninov index	
	Z_{mk}	β	Z_{mk}	β	Z_{mk}	β	Z_{mk}	β
Renchinlhumbe	– 1.2	– 0.0004	– 1.5	– 0.001	– 6.6	– 2.0894	– 3	– 0.0018
Hatgal	0.3	0.0006	– 0.1	– 0.0001	– 2.2	– 0.2882	– 1.3	– 0.0015
Ulaangom	0.2	0.0004	– 0.5	– 0.0003	– 1.4	– 0.112	– 0.7	– 0.0003
Baruunturuun	– 0.6	– 0.0009	– 0.5	– 0.0006	– 3.2	– 0.3626	– 1.5	– 0.001
Ulgii	0	0	– 0.8	– 0.0005	– 1.3	– 0.0336	– 0.9	– 0.0003
Umnugobi	0.2	0.0003	– 0.8	– 0.0006	– 1	– 0.0404	– 1.1	– 0.0006
Zabhan	4.1	0.0019	3.1	0.0007	3	0.0487	1	0
Ylalt	4.3	0.0024	2.6	0.001	0.4	0.0082	0.2	0
Hovd	0.5	0.0006	– 0.4	– 0.0003	– 1	– 0.0354	– 0.6	– 0.0002
Dorvoljin	– 0.8	– 0.0009	– 1.3	– 0.001	– 1.5	– 0.0601	– 1.4	– 0.0006
Bayan-Uul	– 1.1	– 0.0012	– 1.5	– 0.0013	– 4.5	– 0.5619	– 2.3	– 0.0014
Tsetsen-Uul	– 1.2	– 0.0008	– 1.5	– 0.001	– 2.5	– 0.1816	– 2.9	– 0.002
Tosontsengel	0.2	0.0004	– 0.2	– 0.0002	– 3.4	– 0.755	– 1.3	– 0.0009
Tariat	1.2	0.0007	– 1	– 0.0007	– 2.7	– 0.1966	– 2.7	– 0.0021
Tarialan	0.8	0.0013	– 0.6	– 0.0007	– 0.6	– 0.0321	– 1	– 0.001
Moron	0.3	0.0006	– 0.9	– 0.0008	– 1.8	– 0.1106	– 1.7	– 0.0014
Kutag	– 1.7	– 0.0031	– 2.7	– 0.0029	– 2.9	– 0.1693	– 2.8	– 0.0024
Erdenet	0.7	0.0021	– 1.8	– 0.0011	– 2.4	– 0.0932	– 1.7	– 0.0018
Erdenemandal	– 3	– 0.0056	– 3.7	– 0.0049	– 3.8	– 0.2785	– 4	– 0.0039
Bulgan	– 1.3	– 0.0023	– 1.8	– 0.0029	– 2.2	– 0.1441	– 2	– 0.0023
Svhbaatar	– 1.4	– 0.0021	– 2.5	– 0.0022	– 2.5	– 0.1617	– 2.1	– 0.0016
Baruunharaa	– 1.8	– 0.0028	– 2	– 0.0025	– 2.8	– 0.2258	– 2	– 0.0018
Orhon	0	0.0001	– 1.7	– 0.0022	– 2.7	– 0.1812	– 2.1	– 0.002
Eroo	– 1.6	– 0.0032	– 2.1	– 0.0028	– 3.2	– 0.2651	– 2.5	– 0.0024
Ugtaal	2.8	0.0032	– 3.4	– 0.0015	– 3.2	– 0.0858	– 3.2	– 0.0019
Dadal	– 0.8	– 0.0017	– 1.3	– 0.0018	– 2	– 0.1786	– 1.9	– 0.0019
Dashbalbar	– 3.9	– 0.0073	– 4.3	– 0.0055	– 4.2	– 0.3006	– 4.2	– 0.0038
Binder	– 0.4	– 0.0012	– 1.1	– 0.0022	– 1.6	– 0.1466	– 1.4	– 0.002
Choibalsan	– 1.6	– 0.0031	– 2.3	– 0.0029	– 2.2	– 0.1497	– 2.2	– 0.0017
Duchinjl	3.2	0.0019	2	0.0008	0.8	0.0175	– 0.3	0
Zereg	– 0.3	– 0.0002	– 2.1	– 0.0003	– 2.5	– 0.0285	– 1	0
Baitag	0.9	0.0008	0.6	0.0003	0	– 0.0006	0.2	0
Tonhil	– 2.1	– 0.0009	– 2.4	– 0.001	– 3.6	– 0.0773	– 2.7	– 0.0011
Uliastai	– 0.7	– 0.0012	– 1.3	– 0.0013	– 1.9	– 0.1355	– 1.6	– 0.0014
Bayanbulag	4.4	0.0049	1.7	0.0014	– 1.6	– 0.0781	– 0.7	0
Altai	0	– 0.0001	– 0.2	– 0.0001	– 1.1	– 0.0722	– 0.7	– 0.0005
Tsetserleg	– 1.4	– 0.0021	– 2.3	– 0.0033	– 2.3	– 0.1548	– 2.6	– 0.003
Galuut	– 1.3	– 0.002	– 1.7	– 0.0023	– 2.5	– 0.2777	– 2.5	– 0.0025
Hujirt	– 1.8	– 0.0034	– 2.8	– 0.0036	– 3.3	– 0.2507	– 3.6	– 0.0033
Erdenesant	– 2.7	– 0.005	– 3.5	– 0.0041	– 3.5	– 0.2454	– 3.6	– 0.0033
Baynkhongor	– 0.9	– 0.0015	– 1.4	– 0.0016	– 2.1	– 0.1161	– 1.8	– 0.0013
Arvaiheer	– 1.1	– 0.002	– 1.6	– 0.0023	– 2.4	– 0.1289	– 1.9	– 0.0019
Zuun-mod	– 0.7	– 0.0006	– 1.6	– 0.002	– 2.7	– 0.1506	– 2.4	– 0.0021
Buyant-ukhaa	– 0.3	– 0.0008	– 1.4	– 0.0021	– 1.2	– 0.1051	– 1.7	– 0.0019
Ulaanbaatar	0.6	0.0004	– 1.3	– 0.0014	– 2.4	– 0.1293	– 2	– 0.0016
Maanit	– 0.9	– 0.0015	– 2	– 0.0023	– 2	– 0.1591	– 2.5	– 0.0021
Choir	– 3.8	– 0.0054	– 4.3	– 0.004	– 4.6	– 0.2167	– 4.4	– 0.0027
Bayan-obao	– 1.2	– 0.0024	– 2	– 0.0026	– 2	– 0.1282	– 1.9	– 0.0017
Undurkhaan	– 1.7	– 0.0025	– 2.3	– 0.0024	– 2	– 0.1148	– 2.5	– 0.0018

Table 6 (continued)

Station	Mezentsev index		UNEP aridity index		De Martonne index		Selyaninov index	
	Z_{mk}	β	Z_{mk}	β	Z_{mk}	β	Z_{mk}	β
Baruun-urt	0.6	0.0008	− 0.2	− 0.0002	− 0.8	− 0.0319	− 0.2	0
Khalhkhgol	1	0.0021	− 0.1	− 0.0001	0	0.0045	0.2	0
Matad	0	0.0001	0	0.0001	− 0.8	− 0.0438	0.3	0
Erdenetsagaan	− 0.7	− 0.0011	− 1.6	− 0.0016	− 2.1	− 0.0986	− 1.3	− 0.0009
Tooroi	2.9	0.0021	2.2	0.0008	2.2	0.0398	2.3	0.0004
Jinst	− 2.4	− 0.0014	− 3.3	− 0.0018	− 3.5	− 0.0888	− 3.1	− 0.0015
Saihan-obao	0.9	0.0008	− 0.5	− 0.0001	− 0.6	− 0.0129	− 0.3	0
Bogd	4.1	0.0035	2.8	0.0011	3.5	0.0681	0.1	0
Saikhan	1.3	0.0016	0.6	0.0002	0.5	0.013	0.5	0
Mandalgobi	− 2.6	− 0.003	− 3.1	− 0.0026	− 3.1	− 0.1228	− 3.4	− 0.0018
Tsogt-Oboo	− 0.9	− 0.0006	− 1.6	− 0.0007	− 1.6	− 0.0321	− 1	− 0.0003
Mandakh	0.1	0.0001	− 2	− 0.0003	− 2	− 0.0211	− 2.1	− 0.0006
Bayandelger	− 2.9	− 0.0038	− 3.3	− 0.003	0.8	0.0698	− 3.2	− 0.002
Sainshand	0.8	0.0007	0.2	0.0001	− 0.1	− 0.0032	− 0.1	0
Zamiin-Uud	0.7	0.0008	0.1	0.0001	− 0.1	− 0.0051	0.3	0
Ehiingol	0.9	0.0004	0.2	0	0.9	0.0038	− 1.7	0
Dalanzadgad	− 0.2	− 0.0001	− 1.2	− 0.0007	− 1.2	− 0.0355	− 1.4	− 0.0005
Gurbantes	0.1	0.0001	− 1.4	− 0.0005	− 1.1	− 0.0112	− 1.5	− 0.0005
Khanbogd	3.7	0.0021	2.1	0.0005	2.6	0.0266	1.8	0
Khubsgul	0.4	0.0004	− 1.6	− 0.0002	− 0.5	− 0.0029	− 1	0

Bold values indicate significant trends at the 95% confidence level

that arid climate conditions exist at the respective study sites. Around 84% of the IDM series showed a decreasing tendency. In a context of the well-being of humans, especially in drylands, the increase of aridity is likely to impact the livelihood of people in general, and in terms of economic sense, it can lead to increase risks for the production of livestock or other agricultural commodities. Significant decreasing trends in the IDM series at the 5% level were also found for a total of 36 stations, as shown in Table 6. The relative changes of the IDM at these stations were between 13 and 57%.

In terms of the MI and AI indices, there was a difference in the overall pattern where around 52% of MI and around 80% of AI metric registered decreasing tendency. The number of stations with a significantly decreasing trend at the 5% level was observed at only eight locations for the MI metric and 21 stations for the AI metric. The number of stations with a relative change over the 50% was identified for only at two stations for the AI and MI metric.

The significant increase of aridity was observed mainly in the middle and northern parts of the Mongolia country, which was largely occupied by the steppe and dry steppe ecosystems. With increasing aridity in these regions, the water deficiency is likely to increase quite significantly and, if so, this is likely to impact agriculture and livestock since these are the largest users of water. Compared to the humid regions, the arid and semi-arid regions are more sensitive

to water resource variability and availability (Zhang et al. 2010). Furthermore, the impacts of the changes in aridity, especially its increase, can exacerbate the extent and the level of desertification (Tabari et al. 2014).

In this study, the Pettitt's test was applied to determine the (temporal) position of change points in the time series of the selected 4 aridity indices, with significant trends. According to the results of the test, the MI series of the Dashbalbar, Choir and Mandalgobi stations registered a change point near the year 1998, Erdenemandal and Erdenesant near the year 1994, and Tonkhil, Jinst and Bayandelger near the years of 1987, 1982 and 1977, respectively. The change point for the AI time series registered change point at the sites of Baruunharaa, Eruu, Ugtaal, Tsetserleg, Hujirt and Erdenesant stations around the year 1994 and for stations, Choibalsan, Choir, Bayan-Ovoo, and Mandalgobi around the year 1998. The AI time series of Khutag, Erdenemandal, Sukhbaatar and Jinst registered a change point around the years of 1979, 1995, 1976 and 1982, respectively. The change point in the IDM series, however, for the stations Hatgal, Tosontsengel, Erdenet, Erdenemandal, Ugtaal, Choibalsan, Tsetserleg, Galuut, Hujirt, Erdenesant, Arvaiheer and Maanit was found to be around the year 1994. The IDM series for the stations Choir, Bayan-Ovoo and Mandalgobi stations showed a change point around the year 1996, and for the stations Tsetsen-Uul, Zereg and Ulaanbaatar, a change point was noted around the year 1995.

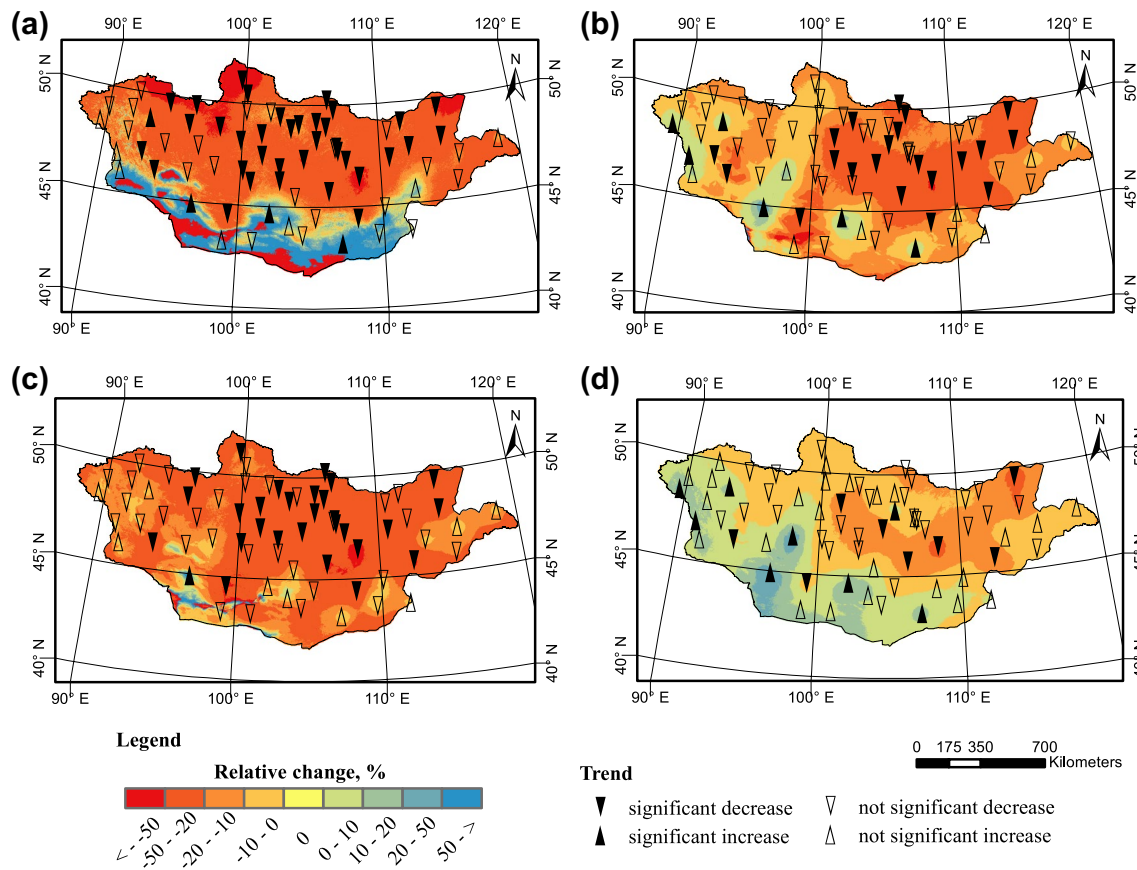


Fig. 3 Relative change (%) of the aridity indices over 1961–2015 (arrow markers show the trends detected by the modified Mann–Kendall test): **a** IDM; **b** AI; **c** HTC; **d** MI

When the HTC series were analyzed for change points, the results for the stations Dashbalbar, Choibalsan, Choir and Mandalgobi stations showed a change point near 1998, whereas a change point for Renchinlhumbe, Baruunharaa, Eruu, Ugtaal, Tsetserleg, Galuut, Hujirt and Erdenesant near 1994, and Tsetsen-Uul, Hutag, Erdenemandal, Tonhil, Zuun-Mod, Ulaanbaatar and Maanit was found near the year 1995.

In general, the change point years that were obtained for the aridity series were internally consistent with each other.

Future Changes in the Aridity Index

Good knowledge of how the climate is likely to change can affect the extent of drylands in the future, and this information is essential for the protection and survival of human lives and the developing climate change adaptation strategies (Nicholson 2011). This study has used the future climate change projections of Mongolia, estimated using the aggregate data of the HadGEM and ECHAM5 outputs for the 1961–1990 reference climate period under the RCP8.5 scenarios (<http://namem.gov.mn>). The future period was divided into 3 different time frames: (1) 2016–2035; (2)

2046–2065; and (3) 2080–2099, which could be termed as near-term, mid-term and far-term periods.

Figure 4 presents the temporal evolution of the AI defined climatic zones based on the ECHAM5 scenario. In the early twenty-first century (Fig. 4a), the hyper-arid zone is likely to cover about 3.3% of the total territory, and the arid zone is likely to cover 14.6%, while the semi-arid zone is likely to cover about 28.1%, the dry sub-humid zone is likely to cover about 14.9% and the humid region is likely to cover about 39.1%. In the mid-twenty-first century, the expected change could be even more significant. That is the drying areas are likely to be mainly distributed in the middle part of the country, southwestern parts of the Gobi, and in western Mongolia, whereas the coverage of the humid zone is expected to increase compared to the baseline period. In the late-twenty-first century, the area of the hyper-arid, arid and semi-arid zones can continue to expand and, in total, this can cover about 61.2% of the landmass in the Mongolia region.

In accordance with the present result, a similar change pattern was obtained for the results of the HadGEM scenario (Fig. 4b); however, the numerical analyses indicated that the area of the hyper-arid zone could nearly double in the early

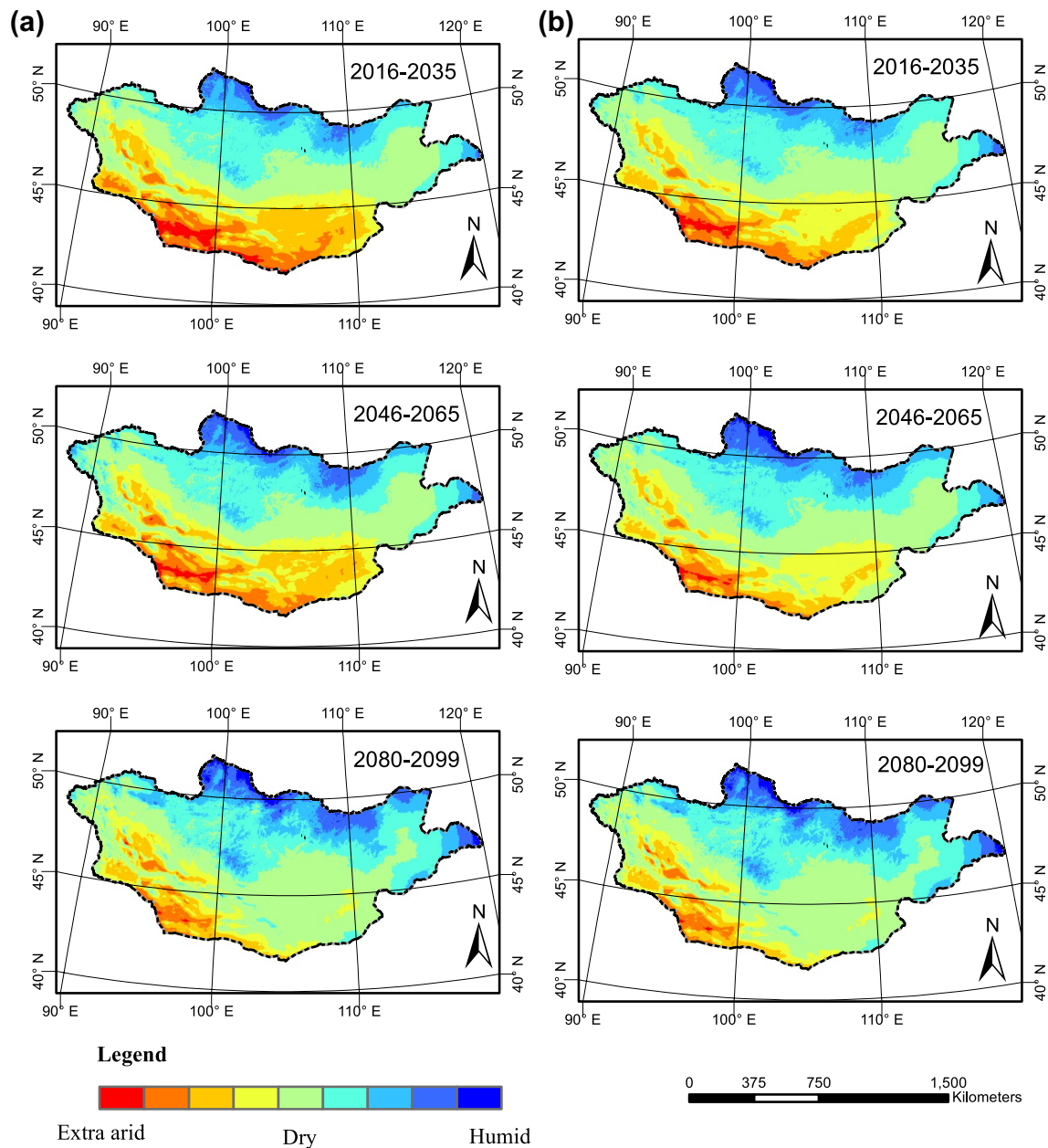


Fig. 4 Distribution of the future changes in climatic zones according to **a** ECHAM5; and **b** HadGEM scenarios

twenty-first century, while the coverage of arid, semi-arid and dry sub-humid climate may decrease (Fig. 4b). From the mid-twenty-first century, the changes are likely to show an increasing tendency of the drylands and the area of hyper-arid, arid and semi-arid land is likely to cover about 73.4% of the total territory by the end of the twenty first century.

Conclusion

In this paper, we investigated temperature and precipitation-based aridity indices and their trends in Mongolia using the annual de Martonne, UNEP, Mezentsev and

Selyaninov aridity indices series with respect to their spatiotemporal variations for the period 1961–2015. According to the results, the spatial assessment the total area of hyper-arid, arid, semi-arid and sub-humid regions by the IDM, MI, AI, and HTC metrics was found to be about 64.1%, 70.7%, 85% and 98%, respectively. The results of the regression analysis of selected indices with natural zonation of the country showed that MI and AI indices are more effectively representing climate types of Mongolia than the IDM and HTC.

The trend analysis, performed using the non-parametric Mann–Kendall test, showed that around 66% of the study stations within Mongolia could be characterized by a decreasing trend of the aridity index. Mostly concentrated in the central, southwest and western regions of Mongolia, the aridity indices showed a significant decreasing trend.

At the study stations with significant decreasing trends, the relative changes in the magnitude of the aridity indices varied between 14 and 74% for the period 1961–2015. According to the results of the Pettitt's test, which aimed to investigate the change points, if any, there was a change point around the year 1994 located in the greater part of the stations. This was indicated by significant changes in the aridity index.

The aridity index calculated using the climate change scenarios also indicates that the aridity level is likely to increase in the central part of the country during the twenty-first century. The increasing trend of the aridity can have an adverse impact on crop and grassland productivity, thus posing a risk to the livelihood of the dryland populations. The results of the present study are, therefore, of great importance for assessing water deficits and planning water resources and helpful for decision makers in devising practical measures to manage the aridity in sensitive areas, such as the Gobi region in Mongolia, Inner Mongolia, and Xinjiang in China.

Compliance with ethical standards

Conflict of interest None.

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