On the Stationarity of Annual Precipitation over China (1959–2018)

HONG WANG

Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

FUBAO SUN

Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, and State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, and Akesu National Station of Observation and Research for Oasis Agro-ecosystem, Akesu, and College of Resources and Environment, University of Chinese Academy of Sciences, and Center for Water Resources Research, Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Stationarity is an assumption that permeates training and practice in water-resource engineering. However, with global change, the validity of stationarity as well as uncertainty of nonstationarity in water-resource planning are being questioned; thus, it is critical to evaluate the stationarity of climate variables, especially precipitation. Based on the continuous observation data of precipitation from 1427 stations across China, 593 efficient grid cells ($1^\circ \times 1^\circ$) are constructed, and the annual precipitation stationarities from 1959 to 2018 are analyzed. The evaluated autocorrelation stationarity indicates that 92.24%–96.12% of the grid cells for an autocorrelation coefficient of lag 1–8 years of precipitation are indistinguishable from 0 [90% confidence level (CL)]. The mean stationarity indicates that 97.47% of the grid cells have a stable mean for 30 years (90% CL); beyond the confidence limits, they are mainly located in the northwest of China, where annual precipitation is less, and the average exceeding range is ± 3.78 mm. The long-term observation of annual precipitation in Beijing (1819–2018) and Shanghai (1879–2018) also yields autocorrelation and mean stationarities. There is no significant difference in the annual precipitations between the past 20 years (1999–2018) and the past 60 years (1959–2018) over China. Therefore, the annual precipitation in China exhibits a weak stationary behavior that is indistinguishable from the stationary stochastic process. The average variation in precipitation is $\pm 9.55\%$ between 30 successive years and 16.53% between 10 successive years. Therefore, it is valuable and feasible to utilize the historical data of annual precipitation as the basis of water-resources application.

1. Introduction

Stationarity is an assumption that natural systems fluctuate within an unchanging envelope of variability, and precipitation stationarity is an assumption that permeates training and practice in water-resource engineering (Burt et al. 2009; Khintchine 1934; Kolmogorov 1938; Koutsoyiannis and Montanari 2015; Milly et al. 2008; Montanari and Koutsoyiannis 2015; Nelson and

Matejcek 1995). Observation data of historical precipitation is an important basis for water resources planning, hydropower project construction, agricultural irrigation, social and economic development planning, and hydrological and climatic simulations (Benoit et al. 2018; Cordery et al. 2007; McCarl et al. 2008). To improve the reliability of the engineering design, it is necessary to analyze data from at least one climatic or hydrological time scale (approximately 30 years) (Arguez et al. 2012; Sun et al. 2018; WMO 2019), because the climate variables are considered as stationarity if the mean remains constant over the time scale (Arguez and Vose 2011; Griggs and Noguer 2002; Knox and Kundzewicz 1997; Sun et al. 2018). Moreover, the distribution density of observation stations must be guaranteed.

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Corresponding authors: Hong Wang, wanghong@igsnr.ac.cn; Fubao Sun, sunfb@igsnr.ac.cn

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However, with changes in climate and the underlying surface (e.g., land use, urbanization, dams, and water withdrawals), the stationarity of precipitation and water resources are being questioned (Milly et al. 2008, 2015; Richardson et al. 2018; Sadegh et al. 2016; Singh et al. 2016). In contrast, it has been asserted that stationarity is dead under currently changing climatic conditions and must no longer serve as a central and default assumption in water-resource risk assessment and planning (Milly et al. 2008, 2015). Nonstationarity implies a reduced representativity of experience (Montanari and Koutsoyiannis 2015) and data, and it is crucial to identify a suitable successor for planning human adaptation to changing climate (Milly et al. 2008, 2015). Some researchers believe that compared to climatic mechanisms, endogenous catchment mechanisms (e.g., groundwater table, baseflow, and vegetation) govern nonstationarity in rainfall–runoff relationships (Deb et al. 2019). Many studies have reported that nonstationarity of extreme precipitation and peak flow at subdaily and daily time scales (Dhakal et al. 2015; Gu et al. 2017; Jakob et al. 2011; Kharin et al. 2007; Lewis 2018; Prosdocimi et al. 2014; Seth and Sisson 2011; She et al. 2015; Ubaldi and Lussana 2017). Extreme precipitation is expected to increase by 7% per degree of temperature at daily time scales and it exhibits a higher increasing rate at subdaily time scales (Wang et al. 2018).

In contrast, it has been argued that stationarity is always relevant and that there are time-invariant mechanisms in hydrological systems (Koutsoyiannis and Montanari 2015; Montanari and Koutsoyiannis 2015). Given that an unnecessary resort to nonstationarity may imply a reduction in predictive capabilities, a pragmatic approach, based on the exploitation of past experience and data, is a prerequisite for setting up mitigation policies for environmental risks (Montanari and Koutsoyiannis 2015). Some researchers (Murphy and Ellis 2014) have also reported that precipitation or runoff remain stationary processes and resolving trends amidst natural variability are unlikely to change for several decades. Results showed that approximately 76% of the annual precipitation over global land surface showed little or no change, indicating stationary behavior (Sun et al. 2018). At the same time, some results showed that the duration of extreme rainfall spells was found to be stationary but associated with nonstationarity intensity and frequency (Mondal and Mujumdar 2015). Hence, a methodology was developed that is able to differentiate watersheds that have undergone significant changes in land use, urbanization, and/or hydroclimatic conditions between stationarity and nonstationarity (Sadegh et al. 2016). Since stationarity is almost always a part of the

composition of a time series (Matalas 2012), and an underlying assumption for many statistical procedures used in time series analysis, nonstationary results are often converted to stationary data in some cases (Benoit et al. 2018; Montanari and Koutsoyiannis 2015).

With environmental changes, the validity of stationarity-based water-resource planning is being questioned, while the uncertainty of nonstationary planning may be higher. Therefore, it is critical to identify the stationarity of climate variables, especially precipitation, for water-resource planning. Time series can be classified into strictly stationary and weakly stationary time series (Shumway and Stoffer 2011). A time series, wherein the probability function of all moments is constant over time is defined as strictly stationary or higher-order stationarity. A weakly stationary time series, also known as second-order stationary, is constant in regard to only mean and covariance functions. A weakly stationary test is considered sufficient to evaluate whether a time series is stationary or not and is widely used in practice (Murphy and Ellis 2014; Shumway and Stoffer 2000). This analysis is based on data from 1427 stations for continuous observation of precipitation from 1959 to 2018 over China; data from stations with longer observation are included to study the annual precipitation stationarity. In section 2, we describe the study data and methods. Section 3 reports the stationarity of the past 60 years, those for the longer period, and the variations in the past 20 years; this is followed by the conclusions of the study.

2. Data and methods

Figure 1 shows the 1473 meteorological stations that recorded precipitations daily without exception from 1959 to 2018 to analyze the stationary characteristics of annual precipitation in China. The data were obtained from meteorological stations of the China Meteorological Data Service Center (CMDC) (<http://data.cma.cn/>). The precipitation was manually observed twice (0800 and 2000 local Beijing time) a day, and the daily precipitation was determined from the accumulated observation data from 2000 to 2000 local time. Rain gauge, tilling, and siphon rain gauge were the main instruments for observing precipitation. Daily precipitation above 0.1 mm is defined as a precipitation event. All data were checked for; suspicious and incorrect data were rechecked and rectified manually (CMDC) (<http://data.cma.cn/>). To minimize the statistical deviation caused by nonuniformity of the distribution of the stations, we defined the grid cells as having a spatial resolution of $1^{\circ} \times 1^{\circ}$ and identified the effective grid cells containing at least one station; 593 effective grid cells

FIG. 1. The meteorological stations with daily data from 1959 to 2018 without exception over China and selected grid cells, containing at least one station each (spatial resolution of $1^\circ \times 1^\circ$).

were selected. For a grid containing more than one observation station, the average of the precipitation data collected from the relevant stations was used for calculation and analysis. The analysis results based on meteorological stations are also provided in the online supplemental material. Stationarity was analyzed by the mean and autocorrelation of annual precipitation time series according to the definition of weak stationarity. The method of stationarity analysis for precipitation was developed by Sun et al. (2018). Traditional statistical analyses were performed using SPSS (version 22) and Matlab (version R2015b). SigmaPlot 10 and ArcGIS 9.3 were used to perform geostatistical analyses and produce figures.

3. Results and discussion

a. Autocorrelation stationarity of annual precipitation over China (1959–2018)

We calculated the lag 1–8 autocorrelation coefficient of annual precipitation for each grid cell in 1959–2018. Figure 2 shows the autocorrelation with a 90% confidence level (CL). The 90% confidence limits for the autocorrelation $[= \pm(1.64/\sqrt{60})]$ are ± 0.212 , which are thresholds to distinguish grid cells that have lag autocorrelation indistinguishable from zero (blue cells in Fig. 2) from those showing positive (yellow) and

negative (red) lag autocorrelation. Of the grid cells for a lag 1 autocorrelation coefficient (Fig. 2a), 92.24% are within the 90% confidence interval (CI) and 93.76%–96.12% for lags 2–8. The results indicate that the autocorrelations of precipitation in China (1959–2018) are indistinguishable from 0 and their autocorrelation functions are independent of the specific time position. At the same time, the lag 1–8 autocorrelation coefficients based on meteorological stations are also provided in the supplemental material (Fig. S1). For lag 1–8 years of precipitation, 89.84%–94.39% of the stations are indistinguishable from 0 (90% CL).

b. Mean stationarity of annual precipitation over China (1959–2018)

Because 30 years is a widely used climatic time scale (Arguez et al. 2012; WMO 2019), the precipitation period of 1959–2018 is divided into two periods, 1959–88 and 1989–2018. The mean stationarity of the 90% CL for each grid cell is calculated. Figure 3 presents the results of the 30-yr mean precipitation (90% CL) for the periods 1959–88 and 1989–2018, respectively; 97.47% of the grid cells are within 90% CI. Results based on meteorological stations show that 97.97% of the stations are within 90% CL (Fig. S2). The grid cells with mean precipitation beyond the CI are primarily located in northwest China where the annual rainfall is less. The autocorrelation and 30-yr means of all grid cells with

FIG. 2. Analysis of the stationarity of precipitations for 60 years (1959–2018) over China. Autocorrelation for (a)–(h) lags 1–8 for the annual precipitation (1959–2018). Significance values (± 0.212) are for the 90% confidence level (CL), which are thresholds to distinguish grid cells that have lags with autocorrelation indistinguishable from zero (blue) from those showing positive (yellow) and negative (red) lag autocorrelation.

FIG. 3. Results of the 30-yr mean precipitation within the 90% CL during the period (a) 1959–88 and (b) 1989–2018.

mean precipitation beyond the 90% CI are further analyzed (Fig. 4 and Fig. S3). Results indicate that the 30-yr means are almost on the lines of the 90% confidence limits, and the average value beyond the limit is

± 3.78 mm. Figure 2 also shows that the grid cells with autocorrelation larger than 90% confidence limits are also mainly located in northwest China. Figure 4 and Figure S3 also show their autocorrelation coefficients of lag 1–20.

FIG. 4. The grid cells of the 30-yr mean precipitation beyond the 90% CL over the periods 1959–88 and 1989–2018. Autocorrelation of precipitation from lags 1–20 with 90% CL (dashed). Annual precipitation from 1959 to 2018 (vertical step). Averages (dotted line) over 30-yr time periods with 90% CL (dashed). The analysis of other seven grid cells in the middle are shown in Fig. S3.

FIG. 5. The significance test for annual precipitation between two 30-yr periods. A one-way ANOVA is used, and the blue dot indicates that there is no significant difference [$F_{\text{calculated_value}} < F_{\text{table_lookup_value}} = F_{0.05}(1, 56) = 4.01$, or $P > 0.05$] in annual precipitation between the two 30-yr periods.

It can be seen that the autocorrelation coefficients are indistinguishable from 0 except for several years of lag. Results show that the means of precipitation were stationary and independent over time, indicating first-order stationarity. The climate variables are considered as stationarity if the means remain constant over the climate time scale (Arguez and Vose 2011; Griggs and Noguer 2002; Knox and Kundzewicz 1997; Sun et al. 2018).

Further, the statistical analysis shows that the annual precipitation in the two 30-yr periods has the same distribution, which conforms to the normal distribution. A one-way ANOVA is used to test the significant differences in precipitation between the two 30-yr periods. The results indicate that there is no significant difference [$F_{\text{calculated_value}} < F_{\text{table_lookup_value}} = F_{0.05}(1, 56) = 4.01$, or $P > 0.05$] in annual precipitation between the two 30-yr periods at 1281 out of 1427 stations (approximately 89.77%); the statistics presented are shown in Fig. 5. Combining the autocorrelation stationarity results (section 3a), we can conclude that the annual precipitation over China has a weakly stationary behavior.

c. Stationarity of long-term precipitation in Beijing and Shanghai

Based on the annual precipitation observations of Beijing for 200 years (1819–2018) and Xujiahui station in Shanghai for 140 years (1879–2018), the stationarity

of long-term annual precipitation is analyzed. The average annual precipitation is 605.32 mm in Beijing and 1180.90 mm in Shanghai. The autocorrelation coefficients of two stations with a lag of 1–80 years are calculated. The results show that most of the autocorrelation coefficients are in the 90% CI (Figs. 6b,e). The 30-yr mean precipitations over six periods in Beijing are within the 90% CI, as are those over the four periods in Shanghai. The means are constant, and the autocorrelations are indistinguishable from 0, so the long-term annual precipitation in Beijing and Shanghai depicts stationary behavior.

d. Variations in annual precipitation over China (1999–2018)

The variations in precipitation in the past 20 years (1999–2018), compared to that in the past 60 years (1959–2018), are analyzed using the method of Sun et al. (2018). Figure 7 shows that 95.23% of precipitation variations are within the 90% CI. The average variation in precipitation over China in 30 successive years is ± 78.94 mm, which accounts for 9.55% of the mean annual precipitation. Mean stationarity between 10 successive years is also analyzed (Fig. S4). For the five consecutive 10-yr periods from 1959 to 2008, more than 91% of the mean precipitation of the grid cells are within 90% CL, with an average of 93.70%, and the average of 86% for 2009–18. The precipitation for 10 successive

FIG. 6. Annual precipitation data at the Beijing station over 200 years (1819–2018) and Shanghai station over 140 years (1879–2018). (left) Beijing station. (right) Xujiahui station in Shanghai. (a),(d) Annual precipitation. (b),(e) Autocorrelation of precipitation for lag 1–80 with 90% CL (dashed). Averages (dotted line) over (c),(f) 30-yr time periods with 90% CL (dashed).

years also exhibits a stationarity behavior, although it does not exhibit a more stable behavior than that occurring over 30 consecutive years. The average variation in precipitation between 10 successive years is ± 136.73 mm over China, which accounts for 16.53% of the mean annual precipitation. The analysis based on meteorological stations shows similar results to that based on grid cells analysis (Fig. S5).

Stationarity is predicated based on an assumption that the generating process is in equilibrium around an underlying mean and that variance remains constant over time. The stationarity is analyzed by the mean and autocorrelation of annual precipitation time series according to the definition of weak stationarity over China. From what has been analyzed above, the annual precipitation in China exhibits a stationary behavior that is indistinguishable from the stationary stochastic process. This result is consistent with many previous studies conducted on the stationarity of annual precipitation. Sun et al. (2018) found that the annual precipitation showed a stationary behavior over the global land surface and approximately 76% of it showed little or no change (90% CL) using the same method. Murphy and Ellis (2014) found stationarity of annual precipitation in watersheds of the Colorado River basin with time series analysis methods and testing criteria established per the statistical definitions of stationarity. Majority of the stationary results are based on annual precipitation;

and monthly analysis results have been obtained. Based on analysis techniques including homogeneity tests and anomalies and trend analysis, monthly precipitation series showed such stationary behavior during 1859–1997 in peninsular Spain (Llasat and Quintas 2004). Mahlstein et al. (2012) estimated the global temperature increase required for precipitation change signal of interannual variability using global climate models and found that the signal of precipitation changes during the wet season was not anticipated in the near future over a widespread region and would occur before the end of this century when the global temperature has increased by 1.4°C above 1900–29 values (Mahlstein et al. 2012). Further, grid cells within 90% CL show stationary behavior according to the definition of stationarity, while the grid cells outside of the 90% do not mean that they are nonstationary. Because a significant number of grid cells might be expected to fall outside of a 90% CI by chance alone (DelSole and Yang 2011; Ivanov et al. 2017; Renard et al. 2008), this aspect needs further analysis.

However, the signal of extreme precipitation change with temperature has been clearly detected, and the precipitation extreme is expected to increase by 7% per degree warming according to the Clausius–Clapeyron (CC) relation which states that the atmosphere can hold about 6%–7% more water vapor per degree of warming before saturation occurs (Dhakal et al. 2015; Gu et al. 2017; Jakob et al. 2011; Khari et al. 2007;

FIG. 7. Testing annual precipitation in recent 20 years (1999–2018) for significant changes compared to precipitation over the past 60 years (1959–2018). The ordinate shows ΔP , calculated as the difference between mean annual P for 1999–2018 and that for 1959–2018 as a function of the variance of the annual time series (1959–2018) for the observations.

Lewis 2018; Prosdocimi et al. 2014; Seth and Sisson 2011; She et al. 2015; Ubaldi and Lussana 2017). Extreme precipitation is expected to increase by 7% at daily time scales and 14% at subdaily time scales with 1°C increase in temperature in China (Wang et al. 2018). Many studies have reported that extreme precipitation depicts nonstationarity behavior, that is, nonstationarity in the timing of extreme precipitation over China (Gu et al. 2017), nonstationarity in intensity, duration and frequency of extreme precipitation over India (Mondal and Mujumdar 2015), nonstationarity in seasonality of extreme precipitation in the state of Maine, located in the northeastern region of the United States (Dhakal et al. 2015), and nonstationarity in annual and seasonal series of extreme precipitation in the United Kingdom (Prosdocimi et al. 2014).

Therefore, it is crucial and feasible to use the historical data of annual precipitation as the basis of water resources application in China. Moreover, the changes in extreme precipitation as well as daily and subdaily precipitation must be considered for improved planning of water-resource engineering.

4. Conclusions

Based on daily precipitation observations of 1473 meteorological stations from 1959 to 2018 over China,

the Beijing station with 200 years (1819–2018) of data and Xujiahui station in Shanghai with data of 140 years (1879–2018), the stationarity characteristics of annual precipitation are analyzed. A total of 593 efficient grid cells ($1^{\circ} \times 1^{\circ}$), containing at least one station each grid, are constructed over China to minimize the statistical deviation caused by the nonuniformity of the distribution of the meteorological station.

Stationarity is analyzed by the mean and autocorrelation of annual precipitation time series according to the definition of weak stationarity. The results of the 30-yr mean precipitation (90% CL) indicate that 97.47% of the grid cells are within the 90% CI over China. The results of precipitation autocorrelation stationarity indicate that 92.24% of the grid cells for lag 1 autocorrelation coefficient are within 90% CI, and 93.76%–96.12% for lags 2–8 over China. The means are constant and the autocorrelations are indistinguishable from 0; thus, the annual precipitation over China depicts stationary behavior. Similarly, the mean and autocorrelation of annual precipitation in Beijing for 200 years and Shanghai for 140 years also indicate clear stationary behaviors. The precipitation variations in the past 20 years, compared to those of the past 60 years, over China are analyzed, and 95.23% of precipitation variations are within the 90% CI. The average precipitation variations in 30 and 10 successive years are ± 78.94 and ± 136.73 mm, respectively.

The annual precipitation in China exhibits a stationary behavior, which shows that the historical observation data are still of significant value. Moreover the changes in extreme precipitation as well as daily and subdaily precipitation must be considered for improved planning of water-resource engineering.

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