Influence of non-stationarity and auto-correlation of climatic records on spatio-temporal trend and seasonality analysis in a region with prevailing arid and semi-arid climate, Iran Postprint

Authors: Mahsa MIRDASHTVAN, Mohsen MOHSENI SARAVI, Mahsa MIRDASHTVAN

Date: 2021-01-15T00:00:00+00:00

Abstract

Trend and stationarity analysis of climatic variables are essential for understanding climate variability and provide useful information about the vulnerability and future changes, especially in arid and semi-arid regions. In this study, various climatic zones of Iran were investigated to assess the relationship between the trend and the stationarity of the climatic variables. The Mann-Kendall test was considered to identify the trend, while the trend free pre-whitening approach was applied for eliminating serial correlation from the time-series. Meanwhile, time series stationarity was tested by Dickey-Fuller and Kwiatkowski-Phillips-Schmidt-Shin tests. The results indicated an increasing trend for mean air temperature series at most of the stations over various climatic zones, however, after eliminating the serial correlation factor, this increasing trend changes to an insignificant decreasing trend at a 95% confidence level. The seasonal mean air temperature trend suggested a significant increase in the majority of the stations. The mean air temperature increased more in northwest towards central parts of Iran that mostly located in arid and semi-arid climatic zones. Precipitation trend reveals an insignificant downward trend in most of the series over various climatic zones; furthermore, most of the stations follow a decreasing trend for seasonal precipitation. Furthermore, spatial patterns of trend and seasonality of precipitation and mean air temperature showed that the northwest parts of Iran and margin areas of the Caspian Sea are more vulnerable to the changing climate with respect to the precipitation shortfalls and warming. Stationarity analysis indicated that the stationarity of climatic series influences on their trend; so that, the series which have significant trends are not static. The findings of this investigation can help planners and policy-makers in various fields related to climatic issues, implementing better management and planning

strategies to adapt to climate change and variability over Iran.

Full Text

Preamble

Influence of Non-Stationarity and Auto-Correlation of Climatic Records on Spatio-Temporal Trend and Seasonality Analysis in a Region with Prevailing Arid and Semi-Arid Climate, Iran

Mahsa MIRDASHTVAN*, Mohsen MOHSENI SARAVI
Department of Range and Watershed Management, Faculty of Natural Resources, College of Agriculture and Natural Resources, University of Tehran, Karaj 3158777871, Iran

Abstract: Trend and stationarity analysis of climatic variables are essential for understanding climate variability and provide useful information about vulnerability and future changes, especially in arid and semi-arid regions. This study investigated various climatic zones of Iran to assess the relationship between trend and stationarity of climatic variables. The Mann-Kendall test was used to identify trends, while the trend-free pre-whitening approach was applied to eliminate serial correlation from the time series. Meanwhile, time series stationarity was tested using Dickey-Fuller and Kwiatkowski-Phillips-Schmidt-Shin tests. The results indicated an increasing trend for mean air temperature series at most stations across various climatic zones; however, after eliminating the serial correlation factor, this increasing trend changed to an insignificant decreasing trend at the 95% confidence level. The seasonal mean air temperature trend suggested a significant increase at the majority of stations, with greater warming observed from the northwest toward central parts of Iran, mostly located in arid and semi-arid climatic zones. Precipitation trend analysis revealed an insignificant downward trend in most series across various climatic zones, with most stations also following a decreasing trend for seasonal precipitation.

Spatial patterns of trend and seasonality of precipitation and mean air temperature showed that the northwestern parts of Iran and marginal areas of the Caspian Sea are more vulnerable to changing climate with respect to precipitation shortfalls and warming. Stationarity analysis indicated that the stationarity of climatic series influences their trends, such that series with significant trends are not static. These findings can help planners and policy-makers in various fields related to climatic issues implement better management and planning strategies to adapt to climate change and variability across Iran.

Keywords: climate change; trend analysis; stationarity tests; serial correlation; seasonality; arid and semi-arid regions

1 Introduction

Water resources decision-makers require analysis tools to develop appropriate strategies for efficient water resources management under changing climate conditions [?, ?]. Analyzing the trend and stationarity of climatic variables provides information for understanding climate change and future possibilities [?, ?, ?]. Methods for detecting trends in meteorological series are mainly categorized into parametric and non-parametric approaches [?]. Compared to parametric trend tests, non-parametric methods are more appropriate for naturally observed meteorological time series [?, ?]. The Mann-Kendall (M-K) test [?, ?] is one of the most popular non-parametric methods for testing trends in natural series and has been widely used in climatological and hydrological studies [?, ?, ?, ?]. Most studies have proven the M-K test as an effective and robust technique for identifying monotonic trends in natural time series. While the M-K test is efficient even when seasonal components exist in the time series [?], it is not robust against serial correlation, which can affect the test statistics [?]. Therefore, various alternatives have been suggested to eliminate the effects of auto-correlation [?, ?]. Among these approaches, trend-free pre-whitening (TFPW) is effective for removing first-order auto-regression (AR(1)) components, as de-trending prior to pre-whitening provides more accurate AR(1) estimation in serially dependent series [?, ?, ?, ?, ?, ?].

Non-stationarity is a common characteristic of climatic and hydrological time series closely related to trend. Stationarity in climatic variables means they fluctuate within an unchanging envelope of variability randomly [?], while non-stationarity indicates a gradual trend or sudden shift [?]. Few studies have examined the non-stationarity of climatic series and its effects on trends globally or in Iran [?, ?, ?, ?, ?]. Since stationarity and trend identification provide insights for better water resources management, they must be considered in climatic modeling investigations.

Iran' s natural ecosystems and resources are highly vulnerable to climate variability and change due to its location primarily in arid and semi-arid regions. Numerous researchers have studied climatic time series trends in Iran using various detection techniques [?, ?, ?, ?, ?, ?, ?]. Delju et al. (2013) reported that mean precipitation decreased by approximately 9.2% in the Urmia Lake Basin in northwestern Iran from 1964 to 2005. Using the M-K test with data from 1967 to 2006, Some' e et al. (2012) demonstrated a downward trend in annual precipitation series at 79% of stations, with significant reductions over northern Iran. Tabari et al. (2011) assessed annual precipitation trends across western, southern, and southwestern Iran from 1966 to 2005 and found no significant trends. In recent years, the frequency and persistence of dry periods have increased significantly across various climatic zones in Iran [?, ?, ?]. Combined with high population growth and inappropriate water management strategies, especially in central arid zones, these trends have placed considerable pressure on water resources, particularly groundwater. Identifying observed climatic series trends can lead to better understanding of future tendencies and consequently more effective water management strategies under changing climate.

The purposes of this research are: (1) to characterize precipitation and mean air temperature trends and seasonality across various climatic zones of Iran before and after applying a pre-whitening approach to demonstrate the effect of serial correlation on climatic series trends; and (2) to analyze the influence of climatic series stationarity on their trends and seasonality. Analyzing the stationarity of climatic records is crucial before modeling any hydrological system, as non-stationarity can manifest as a gradual trend or a sign of climate change [?]. Conducting this phase before climatic and hydrological modeling allows researchers to achieve more accurate results and adopt more efficient decisions on climate-related issues.

2.1 Study Area and Datasets

Iran is a high plateau (24°–40°N, 44°–64°E) located in arid and semi-arid regions of the Earth. Climatically, most parts of Iran are classified as arid and semi-arid [?]. Approximately 30% of precipitation occurs as snow, with the remainder as rainfall and other forms. Precipitation varies both temporally and spatially, with some regions south of the Caspian Sea receiving over 2000 mm annually while central and eastern Iran receive less than 50 mm. Most precipitation occurs during autumn and winter due to association with western Mediterranean winds [?]. Given high climate variability and the effects of climate variables on other systems, studying and analyzing trend and stationarity of climatic series based on various climatic zones is vital. Figure 1 [Figure 1: see original paper] shows the geographical location of the study region with stations in various climatic zones over Iran based on the De-Marton climate classification index (Table 1).

Detecting variability of climatic records requires reliable and integrated time series. This study selected monthly precipitation and mean monthly air temperature time series from 73 synoptic stations (1985–2014) across Iran to determine trends, seasonality, and stationarity. The nearest neighbor approach was used to rebuild missing data. The randomness and independence of the series were examined using the runs test and the non-parametric Mann-Whitney test, respectively (Fig. 2 [Figure 2: see original paper]). The characteristics of the selected stations are summarized in Table S1.

2.2 Trend and Seasonality Detection

The classic M-K test is a non-parametric approach utilized in different time series types to identify monotonic trends. Initially proposed by Mann (1945) and further developed by Kendall (1975), the method was improved by Hirsch et al. (1991, 1982) to account for seasonality. The null hypothesis (H0) indicates the series belongs to an independent and identically distributed population, while the alternative hypothesis (Ha) shows the records follow a monotonic trend. The M-K test is based on Kendall' s tau measure of association between two samples, which uses ranks within samples and assumes observations are independent [?, ?].

In this method, differences between each observation and all subsequent observations are calculated (Eq. 1):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \quad (1)$$

where S is the number of positive differences minus negative differences; n is the number of data points; and x_j and x_k are the jth and kth data points, respectively. The sgn function is calculated as Equation 2:

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (2)$$

The variance of S is calculated using Equation 3 or 4, depending on data characteristics:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \quad (3)$$

where n and m are numbers of sequences with duplicate data, and t_i indicates the frequency of tied values.

The test statistic Z is obtained from Equation 4:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (4)$$

Assuming a two-tailed test, the null hypothesis is accepted if $|Z| \leq Z_{\alpha/2}$, where α is the significance level and $Z_{\alpha/2}$ is the standard normal distribution statistic.

The seasonal M-K statistic (S_g) is defined as:

$$S_g = \sum_{i=1}^{m} \sum_{k=1}^{n_i-1} \sum_{j=k+1}^{n_i} \operatorname{sgn}(x_{ij} - x_{ik}) \quad (6)$$

The seasonal M-K statistic for entire records (S_{total}) is calculated as:

$$S_{total} = \sum_{i=1}^{m} S_i \quad (7)$$

Further details about seasonal M-K descriptions and equations can be found in Hirsch et al. (1991).

2.3 Auto-Correlation Modification

Serial correlation can complicate trend identification and produce false outcomes in M-K tests [**?**]. Several techniques exist to eliminate serial correlation, with pre-whitening being common, though investigators [**?**, **?**] noted that pre-whitening can eliminate some trends along with serial correlation. Therefore, the TFPW approach was developed.

This study applied the following steps before conducting the M-K test:

First, remove the linear trend from the raw time series using Equation 8:

$$Y_t = X_t - \beta t \quad (8)$$

where X_t, βt, and Y_t are the series value, linear regression slope, and de-trended series at time t, respectively.

Second, remove serial correlation if the lag-1 serial correlation coefficient of the de-trended series is statistically significant at the 5% confidence level:

$$Y_t' = Y_t - r_1 Y_{t-1} \quad (9)$$

where Y_t' is the de-trended and pre-whitened series (residual series).

Third, add the previously removed linear trend back to the de-trended or residual series:

$$Y_t'' = Y_t' + \beta t \quad (10)$$

where Y_t'' is the trend-free pre-whitened series.

2.4 Stationarity Analysis

A time series is considered stationary if its statistical features do not vary with time, meaning the first and second moments of the probability density function are time-independent. Detecting stationarity status is essential for identifying the origin of non-stationarity [**?**]. This study utilized Dickey-Fuller (DF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests as common stationarity tests.

2.4.1 KPSS Method

The KPSS method decomposes the series into a deterministic trend, random walk, and stationary error using the linear regression model [?]:

$$X_t = r_t + \beta t + \varepsilon_t \quad (11)$$

where X_t is the time series, r_t is a random walk, βt is a deterministic trend, and ε_t is a stationary error.

The series is stationary around a deterministic trend, with the null hypothesis being $\sigma_u^2 = 0$. Residuals e_t (t=1, 2, ···, N) come from regressing x on an intercept and time trend, where $e_t = \varepsilon_t$. The consistent estimation of σ^2 is constructed from residuals e_t by Equation 12:

$$\hat{\sigma}^2 = \frac{1}{N}\sum_{t=1}^{N} e_t^2 + \frac{2}{N}\sum_{j=1}^{p} w_j(p) \sum_{t=j+1}^{N} e_t e_{t-j} \quad (12)$$

where p is the truncation lag and $w_j(p)$ is an optional weighting function. The KPSS statistic is obtained by Equation 13:

$$\mathrm{KPSS} = \frac{1}{N^2\hat{\sigma}^2}\sum_{t=1}^{N}\left(\sum_{i=1}^{t} e_i\right)^2 \quad (13)$$

2.4.2 DF Method

The DF unit root test is a common method for determining time series stationarity, introducing a statistic with a finite distribution performed using regression models [?]:

$$\Delta y_t = \rho y_{t-1} + u_t \quad (14)$$

where t ranges from 1 to N and u_t is a random, independent series. If $|\rho| < 1$, the series y_t is stationary; if $\rho = 1$, the series is non-stationary. The value of $\hat{\rho}$ is calculated using the exponential maximal method by Equation 15:

$$\hat{\rho} = \frac{\sum_{t=2}^{N} y_{t-1} y_t}{\sum_{t=2}^{N} y_{t-1}^2} \quad (15)$$

The test statistic is calculated by Equation 16:

$$t_{\hat{\rho}} = \frac{\hat{\rho} - 1}{\mathrm{SE}(\hat{\rho})} \quad (16)$$

where $\hat{\sigma}_p$ is the standard least square error for coefficient $\hat{\rho}$. In this test, the null hypothesis $H_0 : \rho = 1$ (non-stationary) is tested against the alternative $H_a : |\rho| < 1$ (stationary). If H_a is rejected, the series is unstable; if H_0 is rejected, the series is considered stationary.

3.1.1 Mean Air Temperature

Serial correlation detection revealed significant auto-correlation in all mean air temperature series (Table 2), requiring the TFPW approach to modify M-K test results. The primary M-K test showed both positive and negative trends, though temperature followed an increasing trend at most stations (approximately 86%), which was not significant at the 95% confidence level. After removing auto-correlation, temperature records revealed a downward trend at approximately 73% of stations. Monthly mean air temperature showed a significant upward trend at Ardebil station in northwestern Iran, though this significance was removed after applying TFPW. Konarak station exhibited contrasting behavior after M-K modification: the insignificant increasing trend converted to a significant decreasing trend after removing serial correlation. The Theil-Sen slope estimator showed maximum slopes of -0.003°C and 0.009°C for negative and positive trends at Konarak and Ardebil stations, respectively. Notably, after modifying M-K results, trend slopes decreased for most series.

Figure 3 [Figure 3: see original paper] illustrates mean air temperature trend slope zoning across Iran. Results indicate that series belonging to specific climate classifications do not necessarily follow similar trends. Trend slope zoning shows greater warming in southern Iran compared to other regions, with lower upward slopes in the northeast, southwest, and southeast. While most series show an increasing trend, it remains insignificant at the 95% confidence level. Consistent warming in the study region is confirmed by other studies [?, ?, ?, ?, ?]. Researchers worldwide have linked climate variable trend analysis to significant climate change signals, with numerous studies demonstrating consistent global air temperature increases [?, ?, ?], confirmed by Intergovernmental Panel on Climate Change (IPCC) assessment reports [?, ?, ?, ?]. Contrary to temperature records, precipitation shows no consistent positive or negative trend pattern, likely due to its more complex nature compared to temperature [?, ?, ?, ?]. Air temperature increases depend on factors including global warming, greenhouse gas concentration from human activities, increased cloud cover, and urbanization [?]. Increasing temperature trends generally result in more drought conditions in the region [?].

Seasonal M-K test results indicate a significant increasing trend at most stations, though approximately 18% of series show a significant downward trend. After TFPW modification, this decreasing trend significance was eliminated from all stations except Siri Island. Some series, such as Ilam, Jask, Minab, and Sahand stations, changed from decreasing to insignificant upward trends. As Figure 4 [Figure 4: see original paper] illustrates, trend slopes increase from southeast to northwest Iran, with higher warming slopes in northwestern Iran.

Warming slopes decrease gradually toward central and southeast parts, affecting water resources system vulnerability and water availability safety. Temperature increases impact hydrological factors such as evapotranspiration and relative humidity, altering water cycle processes and causing water resources redistribution [?], contributing to serious economic, social, and political issues.

3.1.2 Precipitation

M-K test results for precipitation series show a decreasing trend at approximately 70% of selected time series across Iran' s climate zones. This significant increasing trend changes to a downward trend after removing serial correlation in some series. The Theil-Sen slope estimator shows maximum negative and positive slopes of -0.016 mm and 0.012 mm at Rasht and Ramsar stations, respectively. After removing auto-correlation, maximum negative and positive slopes appear at Rasht (-0.016 mm) and Noshahr (0.012 mm) stations, both located in the very humid climate zone (Fig. 1 [Figure 1: see original paper]).

As shown in Figure 5 [Figure 5: see original paper], observed trends vary within particular climate zones, meaning precipitation series within specific climate classifications do not follow uniform trends. However, precipitation records in the very humid climate zone along the southern Caspian Sea margins show upward trends with higher slopes, while annual precipitation decreases along the eastern and western Caspian Sea margins. The southern Urmia Lake region in northwestern Iran experiences decreasing trends with higher slopes compared to other regions.

These precipitation trend findings align with results from Tabari et al. (2011), Some' e et al. (2012), Feizi et al. (2014), and Zohrabi et al. (2014) who investigated precipitation trends across Iran. Similarly, downward precipitation trends at most stations on monthly and seasonal scales agree with studies in other basins [?, ?, ?]. Tabari and Marofi (2011) showed precipitation variability does not follow a single pattern across Iran, with both negative and positive trends at different stations and climatic zones. Zohrabi et al. (2014) confirmed decreasing rainfall trends at most Iranian meteorological stations during 1968–2008 with increasing temperatures. While rainfall might be expected to increase, precipitation series show downward trends over arid and semi-arid regions like Iran, likely due to geographical conditions. Since Iran is located in arid and semi-arid regions with low atmospheric moisture, increasing air temperature raises moisture capacity, consequently decreasing precipitation [?].

The seasonal M-K test shows a significant decreasing trend at the 95% confidence level at most stations across climatic zones. After applying TFPW to modify seasonal trend test results, the number of stations following a downward trend increases. According to Theil-Sen slope estimator results for seasonal precipitation series, the highest negative and positive trend slopes were -0.688 mm and 0.517 mm at Rasht and Ramsar stations, respectively. After modification, the highest negative and positive trends become -0.322 mm and 0.204 mm at

Rasht and Maku stations, respectively.

Seasonal precipitation trend analysis shows that decreasing trend slopes along the eastern and western Caspian Sea margins exceed those in other regions. Precipitation variables indicate different trends across Iran, even within specific climatic zones, demonstrating higher variability in precipitation trend patterns compared to air temperature (Fig. 6 [Figure 6: see original paper]).

3.2 Stationarity Analysis

DF unit root test and KPSS stationarity test results show that all precipitation series, regardless of climatic zone, follow a stationary state (Table 2). This aligns with precipitation trend test results (Section 3.1.2), which show decreasing trends at most stations that are not significant at the 95% confidence level. Since significant trends are a primary cause of time series non-stationarity, the lack of significant trends in precipitation records leads to series stationarity. The DF test determines unit root presence, and stationarity analysis outputs rejected the null hypothesis, concluding that precipitation series are stationary, meaning they can be linear with no significant trend.

As shown in Table 4 , mean air temperature series across Iran's climatic zones are stationary at the 95% confidence level, rationalized by the absence of significant trends. However, KPSS test results show the mean air temperature series at Konarak station (southern Iran) exhibits non-stationarity at the 95% confidence level. As discussed in Section 3.1.1, Konarak station' s air temperature records show a significant decreasing trend even after removing serial correlation and modifying primary trend results. Since significant trends are a major factor creating non-stationarity, Konarak station' s temperature series non-stationarity corresponds to its significant decreasing trend.

Different stationarity types exist; this study investigated trend stationarity to compare and interpret relationships between trend and stationarity. A series without a unit root but with a trend is referred to as trend stationary. The KPSS test classifies a time series as stationary based on unit root absence, meaning series can be trend stationary, as illustrated for most mean air temperature and all precipitation series in the study region. Non-stationarity can occur as gradual trends or sudden shifts, so this study emphasized trends and abrupt changes. Analyzing relationships among stationarity, trend, and seasonality of climatic variables provides useful hints for reducing uncertainty in climatic and hydrological simulations and consequently adopting better water resources management strategies across Iran' s climatic zones [**?**].

4 Conclusions

Pressure on natural resources has become a widespread problem in arid and semi-arid regions. In recent decades, this issue has intensified as climate change impacts have aggregated with high population growth rates and resource mismanagement. Analyzing stationarity and trends of climatic variables is important for adopting appropriate water resources management strategies, particularly in arid and semi-arid regions [?, ?]. This study examined the last 30-year (1985–2014) spatiotemporal behavior of climate series using monthly precipitation and mean air temperature time series from 73 climate stations across nine distinct climatic zones in Iran. Classic and seasonal M-K tests identified monotonic and seasonal trends, while the TFPW pre-whitening approach removed auto-correlation effects on trend and stationarity test results. Additionally, KPSS and DF approaches analyzed stationarity and its influence on trend detection.

The main conclusions are:

- Temperature changes reveal a warming trend since 1985, with greater warming from northwest to central Iran. This upward trend, especially in arid and semi-arid zones, has created challenges for regional populations, most problematic where precipitation decreases accompany temperature increases, particularly in central Iran with high precipitation variability that makes these areas prone to drought. Results suggest climate may continue warming if this increasing temperature trend persists.
- Precipitation series follow a downward trend at most stations across Iran' s climatic zones, though this trend is not significant at the 95% confidence level. Precipitation records show non-significant decreasing trends at seasonal scales.
- Spatial patterns of precipitation and mean air temperature trends and seasonality show that northwestern Iran and Caspian Sea marginal areas are more vulnerable to changing climate regarding precipitation shortfalls and warming.
- Climatic series stationarity impacts their trends, as non-stationarity results in significant trends. Investigation of average seasonal trends reveals decreasing precipitation and increasing temperature trends across the study region.
- This study developed the first comprehensive assessment of stationarity' s influence on climatic series trends, applying a corrective pre-processing approach for trend tests across Iran' s climatic zones. These conclusions highlight the importance of analyzing non-stationarity and auto-correlation effects on trend and seasonality, providing a comprehensive regional climate change outlook and helping improve adaptation practices. Comparing different serial correlation correction methods with TFPW-corrected results provides useful information for assessing modeling uncertainty and achieving more accurate projections.

Acknowledgements: This research was supported by the Iran National Science Foundation (9583187).

References

Abbaspour M, Sabetraftar A. 2005. Review of cycles and indices of drought and their effect on water resources, ecological, biological, agricultural, social and economical issues in Iran. *International Journal of Environmental Studies*, 62(6): 709-724.

Ahmad I, Tang D, Wang T, et al. 2015. Precipitation trends over time using Mann-Kendall and Spearman' s rho tests in Swat River Basin, Pakistan. *Advances in Meteorology*, 2015(2): 1-15.

Alijani B. 1995. *Climate of Iran*. Tehran: Piame Noor University, 21-35.

Amiri M, Eslamian S. 2010. Investigation of climate change in Iran. *Journal of Environmental Sciences and Technology*, 3: 208-216.

Aziz O I A, Burn D H. 2006. Trends and variability in the hydrological regime of the Mackenzie River Basin. *Journal of Hydrology*, 319(1-4): 282-294.

Blain G C. 2015. The influence of nonlinear trends on the power of the trend-free pre-whitening approach. *Acta Scientiarum Agronomy*, 37(1): 21-28.

Brockwell P J, Davis R A. 1991. *Time Series: Theory and Methods*. New York: Springer Science and Business Media.

Burn D H, Elnur M A H. 2002. Detection of hydrologic trends and variability. *Journal of Hydrology*, 255(1-4): 107-122.

Burn D H, Cunderlik J M, Pietroniro A. 2004. Hydrological trends and variability in the Liard River basin. *Hydrological Sciences Journal*, 49(1): 53-67.

Delju A, Ceylan A, Piguet E, et al. 2013. Observed climate variability and change in Urmia Lake Basin, Iran. *Theoretical and Applied Climatology*, 111: 285-296.

Duan W, He B, Sahu N, et al. 2017. Spatiotemporal variability of Hokkaido' s seasonal precipitation in recent decades and connection to water vapour flux. *International Journal of Climatology*, 37(9): 3660-3673.

Duan W, Hanasaki N, Shiogama H, et al. 2019. Evaluation and future projection of Chinese precipitation extremes using large ensemble high-resolution climate simulations. *Journal of Climate*, 32(8): 2169-2183.

El-Nesr M N, Abu-Zreig M M, Alazba A A. 2010. Temperature trends and distribution in the Arabian Peninsula. *American Journal of Environmental Sciences*, 6(2): 191-203.

Fathian F, Morid S, Kahya E. 2015. Identification of trends in hydrological and climatic variables in Urmia Lake basin, Iran. *Theoretical and Applied Climatology*, 119: 443-464.

Feizi V, Mollashahi M, Farajzadeh M, et al. 2014. Spatial and temporal trend analysis of temperature and precipitation in Iran. *Ecopersia*, 2: 727-742.

Field C B, Barros V R. 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Gocic M, Trajkovic S. 2013. Analysis of changes in meteorological variables using Mann-Kendall and Sen' s slope estimator statistical tests in Serbia. *Global and Planetary Change*, 100: 172–182.

Golian S, Mazdiyasni O, AghaKouchak A. 2015. Trends in meteorological and agricultural droughts in Iran. *Theoretical and Applied Climatology*, 119: 679–688.

Hamed K. 2009. Enhancing the effectiveness of prewhitening in trend analysis of hydrologic data. *Journal of Hydrology*, 368(1–4): 143–155.

Hirsch R M, Alexander R B, Smith R A. 1991. Selection of methods for the detection and estimation of trends in water quality. *Water Resources Research*, 27(5): 803–813.

Hirsch R M, Slack J R, Smith R A. 1982. Techniques of trend analysis for monthly water quality data. *Water Resources Research*, 18(1): 107–121.

Hosseinzadeh T P. 2014. Iranian rainfall series analysis by means of nonparametric tests. *Theoretical and Applied Climatology*, 116: 597–607.

Houghton J T, Albritton D L, Meira F, et al. 2001. Technical summary of working group 1. Cambridge: Cambridge University Press.

Kahya E, Kalaycı S. 2004. Trend analysis of streamflow in Turkey. *Journal of Hydrology*, 289(1–4): 128–144.

Kendall M. 1975. *Multivariate Analysis*. Charles Griffin.

Kumar S, Merwade V, Kam J, et al. 2009. Streamflow trends in Indiana: effects of long term persistence, precipitation and subsurface drains. *Journal of Hydrology*, 374(1–2): 171–183.

Kwiatkowski D, Phillips P C, Schmidt P, et al. 1992. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? *Journal of Econometrics*, 54(1–3): 159–178.

Libanda B, Zheng M, Ngonga C. 2019. Spatial and temporal patterns of drought in Zambia. *Journal of Arid Land*, 11(2): 180–194.

Mann H B. 1945. Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society*, 13: 245–259.

Masih I, Uhlenbrook S, Maskey S, et al. 2011. Streamflow trends and climate linkages in the Zagros Mountains, Iran. *Climatic Change*, 104: 317–338.

Modarres R, da Silva V. 2007. Rainfall trends in arid and semi-arid regions of Iran. *Journal of Arid Environments*, 70(2): 344–355.

Parey S, Hoang T, Dacunha-Castelle D. 2019. Future high-temperature extremes and stationarity. *Natural Hazards*, 98: 1115–1130.

Peel M C, Finlayson B L, McMahon T A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences Discussions*, 4: 439–473.

Raziei T, Arasteh P D, Saghafian B. 2005a. Annual rainfall trend in arid and semi-arid regions of central and eastern Iran. *Water and Wastewater*, 54: 73–81.

Raziei T, Arasteh P D, Saghafian B. 2005b. Annual rainfall trend in arid and semi-arid regions of Iran. In: ICID 21st European Regional Conference, 15–19.

Sahoo D, Smith P. 2009. Hydroclimatic trend detection in a rapidly urbanizing semi-arid and coastal river basin. *Journal of Hydrology*, 367(3–4): 217–227.

Samadi S, Carbone G J, Mahdavi M, et al. 2013. Statistical downscaling of river runoff in a semi-arid catchment. *Water Resources Management*, 27: 117–136.

Shadmani M, Marofi S, Roknian M. 2012. Trend analysis in reference evapotranspiration using Mann-Kendall and Spearman' s Rho tests in arid regions of Iran. *Water Resources Management*, 26: 211–224.

Shao Q, Li M. 2011. A new trend analysis for seasonal time series with consideration of data dependence. *Journal of Hydrology*, 396(1–2): 104–112.

Solomon S, Qing D, Manning M, et al. 2007. *Climate Change 2007: The Physical Science Basis*. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Some' e B S, Ezani A, Tabari H. 2012. Spatiotemporal trends and change point of precipitation in Iran. *Atmospheric Research*, 113: 1–12.

Stocker T F, Qin D, Plattner G-K, et al. 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Sun F, Roderick M L, Farquhar G D. 2018. Rainfall statistics, stationarity, and climate change. *Proceedings of the National Academy of Sciences*, 115(10): 2305–2310.

Tabari H, Marofi S. 2011. Changes of pan evaporation in the west of Iran. *Water Resources Management*, 25: 97–111.

Tabari H, Marofi S, Aeini A, et al. 2011. Trend analysis of reference evapotranspiration in the western half of Iran. *Agricultural and Forest Meteorology*, 151(2): 128–136.

Toller M, Santos T, Kern R. 2019. SAZED: parameter-free domain-agnostic season length estimation in time series data. *Data Mining and Knowledge Discovery*, 33: 1775–1798.

Um M-J, Heo J-H, Markus M, et al. 2018. Performance evaluation of four statistical tests for trend and non-stationarity and assessment of observed and projected annual maximum precipitation series in Major United States cities. *Water Resources Management*, 32: 913–933.

Unal Y S, Deniz A, Toros H, et al. 2012. Temporal and spatial patterns of precipitation variability for annual, wet, and dry seasons in Turkey. *International Journal of Climatology*, 32(3): 392–405.

Wang W, van Gelder P, Vrijling J. 2005. Trend and stationarity analysis for streamflow processes of rivers in Western Europe in the 20th century. In: Proceedings: IWA International Conference on Water Economics, Statistics, and Finance, Rethymno, Greece, 8–10.

Webb B W, Nobilis F. 2007. Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal*, 52(1): 74–85.

Wu Z, Huang N E, Long S R, et al. 2007. On the trend, detrending, and variability of nonlinear and nonstationary time series. *Proceedings of the National Academy of Sciences*, 104(38): 14889–14894.

Xu Z, Takeuchi K, Ishidaira H. 2003. Monotonic trend and step changes in Japanese precipitation. *Journal of Hydrology*, 279(1–4): 144–150.

Yue S, Pilon P, Phinney B, et al. 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes*, 16(9): 1807–1829.

Yue S, Wang C Y. 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. *Water Resources Research*, 38(6): 4-1–4-7, doi: 10.1029/2001WR000861.

Zhang Q, Liu C, Xu C Y, et al. 2006. Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River basin, China. *Journal of Hydrology*, 324(1–4): 255–265.

Zhao J, Huang Q, Chang J, et al. 2015. Analysis of temporal and spatial trends of hydro-climatic variables in the Wei River Basin. *Environmental Research*, 139: 55–64.

Zhou J, Liang Z, Liu Y, et al. 2015. Six-decade temporal change and seasonal decomposition of climate variables in Lake Dianchi watershed (China): stable trend or abrupt shift? *Theoretical and Applied Climatology*, 119: 181–191.

Zohrabi N, Bavani A M, Goodarzi E, et al. 2014. Attribution of temperature and precipitation changes to greenhouse gases in northwest Iran. *Quaternary International*, 345: 130–137.

Appendix

Table S1 Characteristics of the selected synoptic stations over Iran

Station	Longitude	Latitude	Altitude (m)	Climatic class
Ardebil	49°46 E	34°06 N	-	Semi-arid
Oroomiyyeh	48°17 E	38°15 N	-	Mediterranean
Esfahan	45°03 E	37°40 N	-	Semi-arid
Aqajari	51°40 E	32°37 N	-	Extremely arid
Omidiyyeh	49°40 E	30°46 E	-	Extremely arid
Ahwaz	49°39 E	30°46 N	-	Mediterranean
Iranshahr	48°40 E	31°20 N	-	Semi-arid
Abadan	60°42 E	27°12 N	-	Semi-arid
Abadeh	46°26 E	33°38 N	-	Humid
Abali	48°15 E	30°22 N	-	Semi-arid
Babolsar	52°40 E	31°11 N	-	Extremely arid
Bojnourd	51°53 E	35°45 N	-	Very humid
Bandar Anzali	52°39 E	36°43 N	-	Extremely arid
Bandar Abbas	57°16 E	37°28 N	-	Extremely arid
Bandar Lengeh	58°21 E	29°06 N	-	Semi-arid
Boushehr (Coastal)	49°27 E	37°29 N	-	Semi-arid
Birjand	56°22 E	27°13 N	-	Semi-arid
Moqan	54°50 E	26°32 N	-	Extremely arid
Tabriz	50°49 E	28°54 N	-	Extremely arid
Torbat Heidariyyeh	59°12 E	32°52 N	-	Extremely arid
Tehran	47°55 E	39°39 N	-	Mediterranean
Boumousa Island	46°17 E	38°05 N	-	Extremely arid
Siri Island	59°13 E	35°16 N	-	Semi-arid
kish Island	51°19 E	35°41 N	-	Semi-arid
Jolfa	57°46 E	25°38 N	-	Semi-arid
Chabahar	54°50 E	25°50 N	-	Semi-arid
Khorramabad	54°29 E	26°30 N	-	Semi-arid
Dezfoul	45°40 E	38°45 N	-	Very humid
Doushan Tappeh	60°37 E	25°17 N	-	Very humid
Dogonbadan	48°17 E	33°26 N	-	Extremely arid
Ramsar	44°58 E	38°33 N	-	Extremely arid
Rasht	48°23 E	32°24 N	-	Semi-arid
Zabol	51°20 E	33°42 N	-	Mediterranean
Zahedan	50°49 E	30°20 N	-	Mediterranean
Zanjan	50°40 E	36°54 N	-	Semi-arid
Sabzevar	49-37 E	37-19 N	-	Semi-arid

Station	Longitude	Latitude	Altitude (m)	Climatic class
Sarakhs	61°29 E	31°02 N	-	Extremely arid
Saqqez	60°53 E	29°28 N	-	Semi-arid
Semnan	48°29 E	36°41 N	-	Semi-arid
Sanandaj	57°39 E	36°12 N	-	Semi-arid
Sahand	61°10 E	36°32 N	-	Semi-arid
Sirjan	46°16 E	36°15 N	-	Semi-arid
Shahroud	53°25 E	35°35 N	-	Semi-arid
Esfahan (East)	47°00 E	35°20 N	-	Semi-arid
Shahrekord	46°07 E	37°56 N	-	Semi-arid
shiraz	55°41 E	29°28 N	-	Extremely arid
Tabas	54°57 E	36°25 N	-	Extremely arid
Ferdows	51°52 E	32°40 N	-	Very humid
Qazvin	50°21 E	32°17 N	-	Semi-arid
Qouchan	52°36 E	29°32 N	-	Extremely arid
Kashan	56°55 E	33°36 N	-	Semi-arid
Kerman	58°10 E	34°01 N	-	Semi-arid
Karaj	53°41 E	28°58 N	-	Semi-arid
Kermanshah	50°03 E	36°15 N	-	Extremely arid
Konarak	50°51 E	34°42 N	-	Semi-arid
Gorgan	58°30 E	37°04 N	-	Semi-arid
Maraqeh	51°27 E	33°59 N	-	Extremely arid
Masjed Soleiman	56°58 E	30°15 N	-	Mediterranean
Mashhad	50°54 E	35°55 N	-	Semi-arid
Mahabad	47°09 E	34°21 N	-	Semi-arid
Minab	60°22 E	25°26 N	-	Semi-arid
Nowshahr	54°24 E	36°54 N	-	Semi-arid
Hamedan	44°26 E	39°20 N	-	Semi-arid
Hamedan (Nowjeh)	46°16 E	37°24 N	-	Very humid

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.