Seasonal and annual precipitation time series trend analysis in North Carolina, United States

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ABSTRACT

The present study performs the spatial and temporal trend analysis of the annual and seasonal time-series of a set of uniformly distributed 249 stations precipitation data across the state of North Carolina, United States over the period of 1950–2009. The Mann–Kendall (MK) test, the Theil–Sen approach (TSA) and the Sequential Mann–Kendall (SQMK) test were applied to quantify the significance of trend, magnitude of trend, and the trend shift, respectively. Regional (mountain, piedmont and coastal) precipitation trends were also analyzed using the above-mentioned tests. Prior to the application of statistical tests, the pre-whitening technique was used to eliminate the effect of autocorrelation of precipitation data series. The application of the above-mentioned procedures has shown very notable statewide increasing trend for winter and decreasing trend for fall precipitation. Statewide mixed (increasing/decreasing) trend has been detected in annual, spring, and summer precipitation time series. Significant trends (confidence level ≥ 95%) were detected only in 8, 7, 4 and 10 nos. of stations (out of 249 stations) in winter, spring, summer, and fall, respectively. Magnitude of the highest increasing (decreasing) precipitation trend was found about 4 mm/season (−4.50 mm/season) in fall (summer) season. Annual precipitation trend magnitude varied between −5.50 mm/year and 9 mm/year. Regional trend analysis found increasing precipitation in mountain and coastal regions in general except during the winter. Piedmont region was found to have increasing trends in summer and fall, but decreasing trend in winter, spring and on an annual basis. The SQMK test on "trend shift analysis" identified a significant shift during 1960 − 70 in most parts of the state. Finally, the comparison between winter (summer) precipitations with the North Atlantic Oscillation (Southern Oscillation) indices concluded that the variability and trend of precipitation can be explained by the Oscillation indices for North Carolina.

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1. Introduction

Precipitation is one of the most important variables for climate and hydro-meteorology. Changes in precipitation pattern may lead to floods, droughts, loss of biodiversity and agricultural productivity. Therefore, the spatial and temporal trends of precipitation results are important for climate analyst and water resources planner.

Precipitation has changed significantly in different parts of the globe during the 20th century (New et al., 2001). Climate change studies have demonstrated that the land-surface precipitation shows an increase of 0.5–1% per decade in most of the Northern Hemisphere mid and high latitudes, and annual average of regional precipitation increased 7–12% for the areas in 30–85° N and by about 2% for the areas 0°–55° S over the 20th century (Houghton et al., 2001; Xu et. al, 2005). Over the last several decades, the total precipitation has increased across the United States (Small et al., 2006). Karl and Knight (1998) reported a 10% increase in annual precipitation across United States between 1910 and 1996. Keim and Fischer (2005) used Climate Division Database (CDD) to assess the precipitation trends in the United States and found mostly increasing through

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time. Small et al. (2006) reported the increment in the annual 7-day low flow to large increment in precipitation across the eastern United States. Generally, all trend study suggests that the precipitation over the eastern United States has increased during last several decades.

Boyles and Raman (2003) predicted precipitation and temperature trend in North Carolina on seasonal and annual time scales during the period of 1949–1998. Their study was based on the 75 precipitation measuring stations. Linear time series slopes were analyzed to investigate the spatial and temporal trends of precipitation. They found that the precipitation of last 10 years in the study period was the wettest. They also found that precipitation has increased over the past 50 years during the fall and winter seasons, but decreased during the summer.

In pursuit of detecting the trend and the shift of trend in hydro-meteorological variables, various statistical methods have been developed and used over the years (Jha and Singh, 2013; Martinez et al., 2012; Modarres and Silva, 2007; Modarres and Sarhadi, 2009; Sonali and Nagesh, 2013; Tabari et al., 2011). Of the two methods commonly used (parametric and non-parametric), non-parametric method has been favored over parametric methods (Sonali and Nagesh, 2013). The non-parametric Mann–Kendall (MK) statistical test (Mann, 1945; Kendall, 1975) has been frequently used to quantify the significance of trends in precipitation time series (Martinez et al., 2012; Modarres and Silva, 2007; Modarres and Sarhadi, 2009; Tabari et al., 2011). The MK test does not provide an estimate of the magnitude of the trend itself. For this purpose, another nonparametric method referred to as the Theil–Sen approach (TSA) is very popular by the researchers to quantify slope of the trend (magnitude). TSA is originally described by Theil (1950) and Sen (1968). This approach provides a more robust slope estimate than the least-square method because it is insensitive to outliers or extreme values and competes well against simple least squares even for normally distributed data in the time series (Hirsch et al., 1982; Jianqing and Qiwei, 2003). Both the MK test and TSA require time series to be serially independent which can be accomplished by using the pre-whitening technique (von Storch, 1995). Long term trend analysis can reveal beginning of trend year, trend changes over time, and abrupt trend detection in a time-series. An extension of the MK method, called Sequential Mann–Kendall (SQMK) test, is widely used to detect the time when trend has a shift (change in regime) (Modarres and Silva, 2007; Partal and Kahya, 2006; Some'e et al., 2012; Sonali and Nagesh, 2013). SQMK is a sequential forward (u (t)) and backward (u′ (t)) analyses of the MK test. If the two series are crossing each other, the year of crossing exhibits the year of trend change (Modarres and Silva, 2007). If the two series cross and diverge to each other for a longer period of time, the beginning diverge year exhibits the abrupt trend change (Some'e et al., 2012).

The objective of this paper is to analyze the long term (1950–2009) spatial and temporal trends of annual and seasonal precipitation in North Carolina utilizing statewide 249 gauging station data. The non-parametric MK test was applied to detect the significant trend; TSA was applied to quantify the trend magnitude; and, SQMK was applied for abrupt temporal trend shift detection. The analyses were conducted for the entire state of North Carolina as well as three physiographic regions of North Carolina (mountain, piedmont and coastal) on an annual and seasonal (winter, spring, summer and fall) basis. It is expected that the findings of this study will bring about more insights for understanding of regional hydrologic behavior over the last several decades in North Carolina.

2. Materials and methods

2.1. Study area and data availability

North Carolina lies between 34°–36° 21′ N in latitude and 75° 30′–84° 15′ W in longitude in the southeastern United States (Fig. 1). The total area of the state is approximately 52,664 mi^2 (or 136,399 km^2). Land slopes upward from eastern piedmont plateau to the western part containing southern Appalachian Mountains (Great Smokey Mountains and Blue Ridge) (Robinson, 2005). The three principal physiographic regions of North Carolina are the mountain, piedmont and coastal zone (west to east) with 89, 82, and 78 meteorological stations, respectively (Fig. 1). The station density is quite compact (1 per 548km^2) and indicative of an important component of the analyses.

According to Boyles et al. (2004), North Carolina does not represent any distinct wet and dry seasons. Average rainfall varies with seasons. Summer precipitation is normally the greatest, and July is the wettest month. Summer rainfall is also the most variable, occurring mostly as showers and thunderstorms. Fig. 2 shows the annual and seasonal precipitation conditions in North Carolina. The summer has the greatest (1568 mm) and the spring has the lowest maximum precipitation (934 mm) in 60 year period. In seasonal and annual scales, highest amount of precipitation occur in last decades in one of the stations situated in southwestern North Carolina.

2.2. Method

Precipitation datasets of 249 stations across North Carolina were analyzed for the period of 1950–2009. Daily precipitation was collected from the United States Department of Agriculture-Agriculture Research Service (USDA-ARS, 2012). This dataset facilitated by National Oceanic and Atmospheric Administration (NOAA) includes Cooperative Observer network (COOP) and Weather-Bureau-Army-Navy (WBAN) combined 249 stations from the period of 1-1-1950 to 12-31-2009. These data contain quality control information from both agencies and NOAA. Daily values were summed up to obtain seasonal and annual scale precipitation. Seasons were defined as follows: winter (January, February, March); spring (April, May, June); summer (July, August, September) and fall (October, November, December). The double-mass curve analysis (Tabari et al., 2011) and autocorrelation analysis were applied to the precipitation time series of each station to check the consistency and the homogeneity in the time-series (Costa and Soares, 2009; Peterson et al., 1998). Double-mass curve analysis is a graphical method for checking consistency of a hydrological record. It is considered to be an essential tool before taking it for further analysis. Inconsistencies in hydrological or meteorological data recording may occur due to various reasons, such as: instrumentation, changes in observation procedures, or changes in gauge location or surrounding conditions (Peterson et al., 1998).
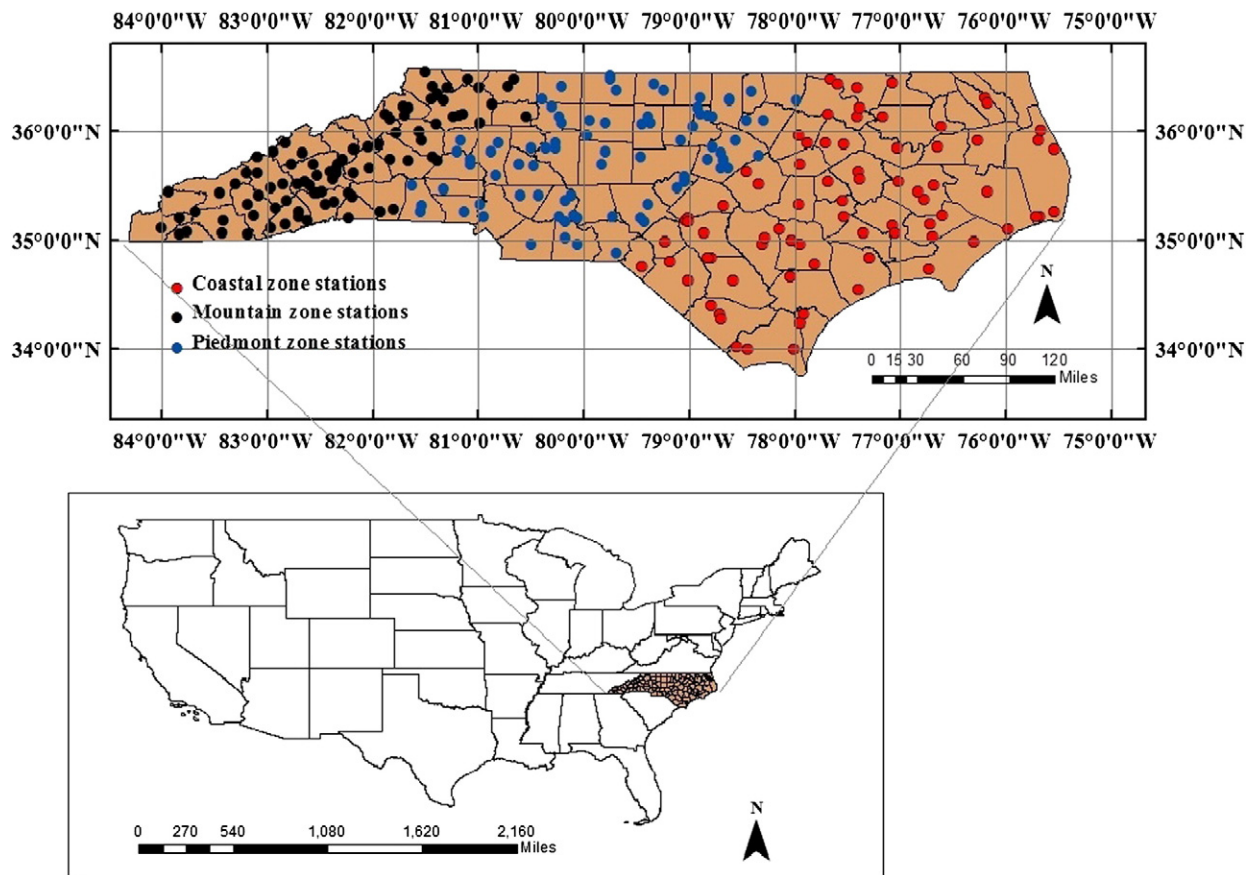
Fig. 1. Geographical position and regional distribution of the 249 meteorological stations in North Carolina.

The surface interpolation technique was used to prepare a spatial precipitation data map over North Carolina from the point precipitation measuring stations within the Arc-GIS framework. For spatial distribution of trends in maps, contours are generated using an inverse-distance-weighted (IDW) algorithm with a power of 2.0, 12 grid points, and variable radius location.
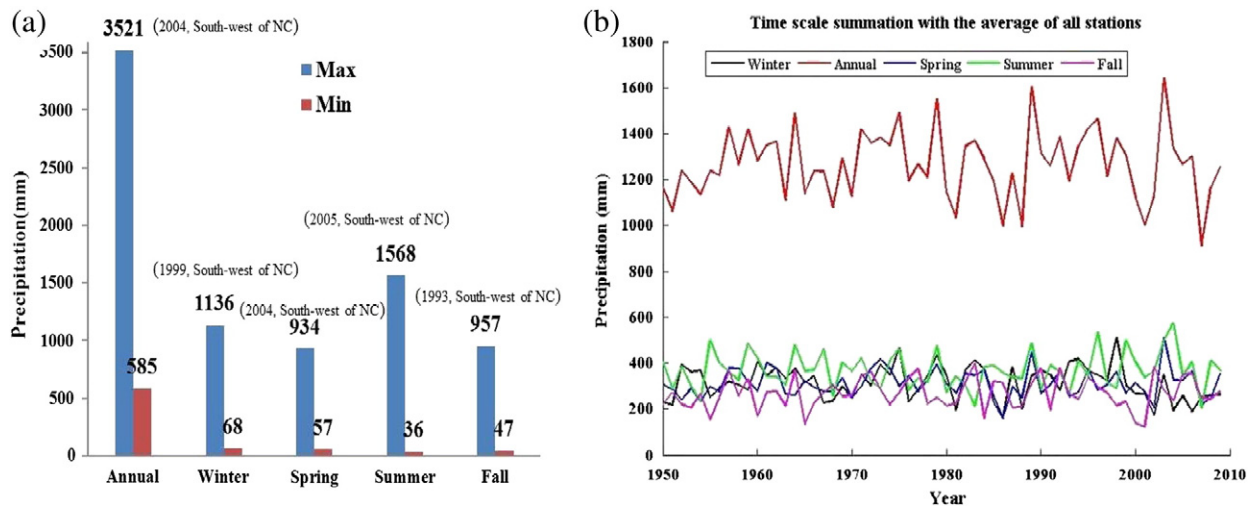

Fig. 2. (a) Amount of maximum and minimum precipitations in annual and seasonal time scale considering 1 typical station out of 249 stations within the period 1950–2009 in North Carolina, (b) average precipitation of 249 stations in annual and seasonal time scales within the period 1950–2009 in North Carolina.

2.2.1. Mann–Kendall (MK) trend test

The MK test statistic S (Mann, 1945; Kendall, 1975) is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right). \tag{1}$$

In Eq. (1), n is the number of data points, x_i and x_j are the data values in time series i and j (j > i), respectively and in Eq. (2), sgn $(x_j - x_i)$ is the sign function as

$$sgn\left(x_j - x_i\right) = \begin{cases} +1, \text{if } \left(x_j - x_i\right) > 0 \\ 0, \text{if } \left(x_j - x_i\right) = 0 \\ -1, \text{if } \left(x_j - x_i\right) < 0 \end{cases}. \tag{2}$$

The variance is computed as

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k \ (t_k - 1) \ (2t_k + 5)}{18}. \tag{3}$$

In Eq. 3, n is the number of data points, m is the number of tied groups, and t_k denotes the number of ties of extent k. A tied group is a set of sample data having the same value. In cases where the sample size n > 10, the standard normal test statistic Z_S is computed using Eq. (4):

$$Z_S = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}}, & \text{if } S < 0 \end{cases}. \tag{4}$$

Positive values of Z_S indicate increasing trends while negative Z_S values show decreasing trends. Testing trends is done at the specific α significance level. When $|Z_S| > Z_{1-\frac{\alpha}{2}}$, the null hypothesis is rejected and a significant trend exists in the time series. $Z_{1-\frac{\alpha}{2}}$ is obtained from the standard normal distribution table. In this analysis, we applied the MK test to detect if a trend in the precipitation time series is statistically significant at significance levels α = 0.01 (or 99% confidence intervals) and α = 0.05 (or 95% confidence intervals). At the 5% and 1% significance level, the null hypothesis of no trend is rejected if $|Z_S| > 1.96$ and $|Z_S| > 2.576$, respectively.

2.2.2. Theil–Sen approach (TSA)

In this study for quantifying the magnitude of the trend, following steps were adopted:

i. The interval between time series data points should be equally spaced.
ii. Data should be sorted in ascending order according to time, then apply the following formula to calculate Sen's slope (Q_k):

$$Q_k = \frac{x_j - x_i}{j - i} \text{ for } k = 1, \dots, N. \tag{5}$$

In Eq. (5), X_j and X_i are the data values at times j and i (j > i), respectively.

iii. In the Sen's vector matrix members of size $N = \frac{n(n-1)}{2}$, where n is the number of time periods. The total N values of Q_k are ranked from smallest to largest, and the median of slope or Sen's slope estimator is computed as:

$$Q_{med} = \begin{cases} Q_{[N+1]/2}, & \text{If N is odd} \\ \dfrac{Q_{[N/2]} + Q_{[N+2]/2}}{2}, & \text{if N is even}. \end{cases} \tag{6}$$

Q_{med} sign reflects data trend direction, while its value indicates the steepness of the trend.

2.2.3. Serial correlation effect

In this research the steps were adopted in the sample data $(X_1, X_2,\dots, X_n)$ are following:

1. The lag-1 serial coefficient (r_1) of sample data X_i, originally derived by Salas et al. (1980) but several recent researchers have been utilizing the same equation (Gocic and Trajkovic, 2013) to compute (r_1). It can be computed by

$$r_1 = \frac{\dfrac{1}{n-1} \sum_{i=1}^{n-1} (x_i - E(x_i)) \cdot (x_{i+1} - E(x_i))}{\dfrac{1}{n} \sum_{i=1}^{n} (x_i - E(x_i))^2} \tag{7}$$

$$E(x_i) = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{8}$$

where $E(x_i)$ is the mean of sample data and n is the number of observations in the data.

2. According to Salas et al. (1980) and most recent study Gocic and Trajkovic (2013) have used the following equation for testing the time series data sets of serial correlation.

$$\frac{-1 - 1.645 \sqrt{(n-2)}}{n-1} \leq r_1 \leq \frac{-1 + 1.645 \sqrt{(n-2)}}{n-1} \tag{9}$$

If r_1 falls inside the above interval, then the time series data sets are independent observations. In cases where r_1 is outside the above interval, the data are serially correlated.

3. If time series data sets are independent, then the MK test and the TSA can be applied to original values of time series.
4. If time series data sets are serially correlated, then the 'pre-whitened' time series may be obtained as $(x_2 - r_1 x_1, x_3 - r_1 x_2, \dots, x_n - r_1 x_{n-1})$ (Gocic and Trajkovic, 2013; Partal and Kahya, 2006).

2.2.4. Identification of precipitation shifts

The application of SQMK test has the following four steps in sequence

1. At each comparison, the number of cases $x_i > x_j$ is counted and indicated by n_i, where $x_i(i = 1,2,\dots,n)$ and $x_j(j = 1, \dots, i-1)$ are the sequential values in a series.
2. The test statistic t_i of SQMK test is calculated by Eq. (10)

$$t_i = \sum_i n_i. \tag{10}$$

3. The mean and variance of the test statistic are calculated using Eqs. (11) and (12), respectively.

$$E(t) = \frac{n(n-1)}{4} \qquad (11)$$

$$Var(t_i) = \frac{i(i-1)(2i+5)}{72} \qquad (12)$$

4. Sequential progressive value can be calculated in Eq. (13)

$$u(t) = \frac{t_i - E(t)}{\sqrt{Var(t_i)}}. \qquad (13)$$

Similarly, sequential backward $(u'(t))$ analysis of the MK test is calculated starting from the end of the time series data.

3. Results and discussion

In this study, Matlab R2012b was used to generate the algorithm of three different non-parametric methods. Arc-GIS 10.0 tool was used to create the surface interpolation and other necessary maps. No. of stations in MK test (Z-value) results of positive and negative trend and 99% confidence level station summarization are shown in Fig. 3a and b, respectively of annual and seasonal time scale precipitation data series during 1950–2009. Figs. 4 and 5 show the location of gauging stations with the significant trends (Z-value) and the interpolated trend magnitude (in mm/year), obtained by the MK test and the TSA method in annual and seasonal time scale, respectively for the period 1950–2009. The briefed details of the annual and seasonal results are presented in Figs. 3a, b, 4 and 5a–d and discussed in the following subsections.

3.1. Annual trends of precipitation

Analysis of the annual precipitation time-series using MK test found about half of the stations with a positive trend (128 of 249 stations or 51%) and rest with a negative trend (Fig. 3a). The level of significance using Z value identified 10 stations having significant trend with 95% and higher confidence level (7 stations with positive trend and 3 stations with negative trend) (Fig. 3b). Significant positive trend are found mostly in southern coastal plain and middle mountain zone, whereas, significant negative trend are found in western piedmont and western mountain zone (Fig. 4). In general, positive and negative trends were found in locations which are scattered all around in North Carolina. Fig. 4 also shows the trend magnitude of annual precipitation (mm/year); statewide mild positive and negative slopes (trends) are noticed. Specifically, some portion of western part of the mountain zone shows high
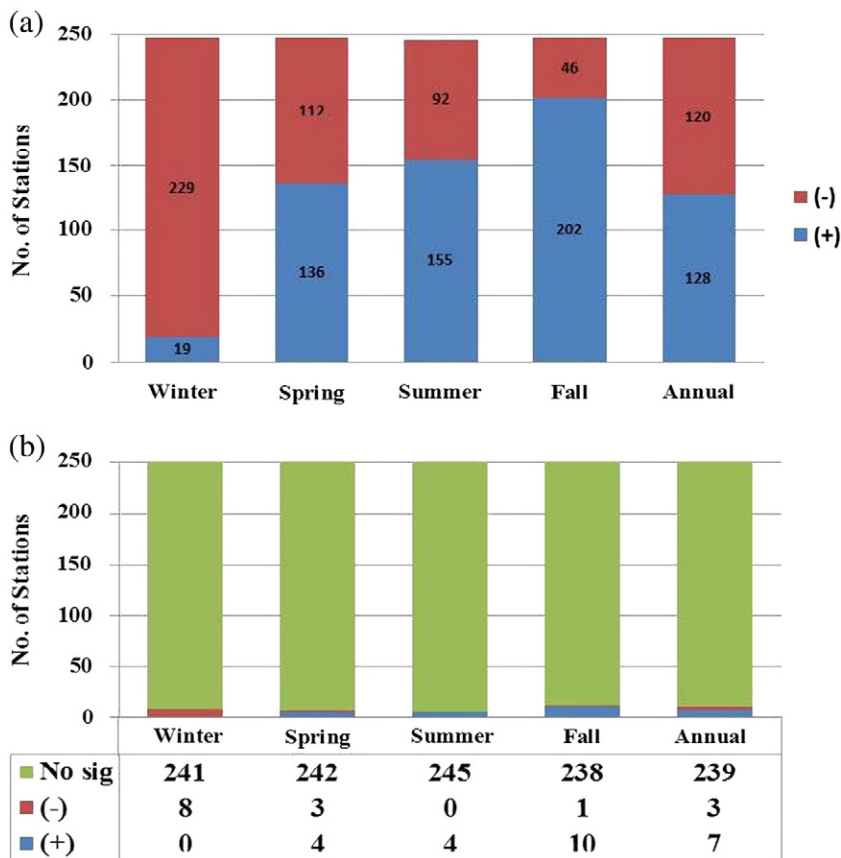

Fig. 3. No. of gauging stations of (a) overall negative and positive trends and (b) significant (confidence level ≥ 95%) negative and positive trends in annual and seasonal time scales.
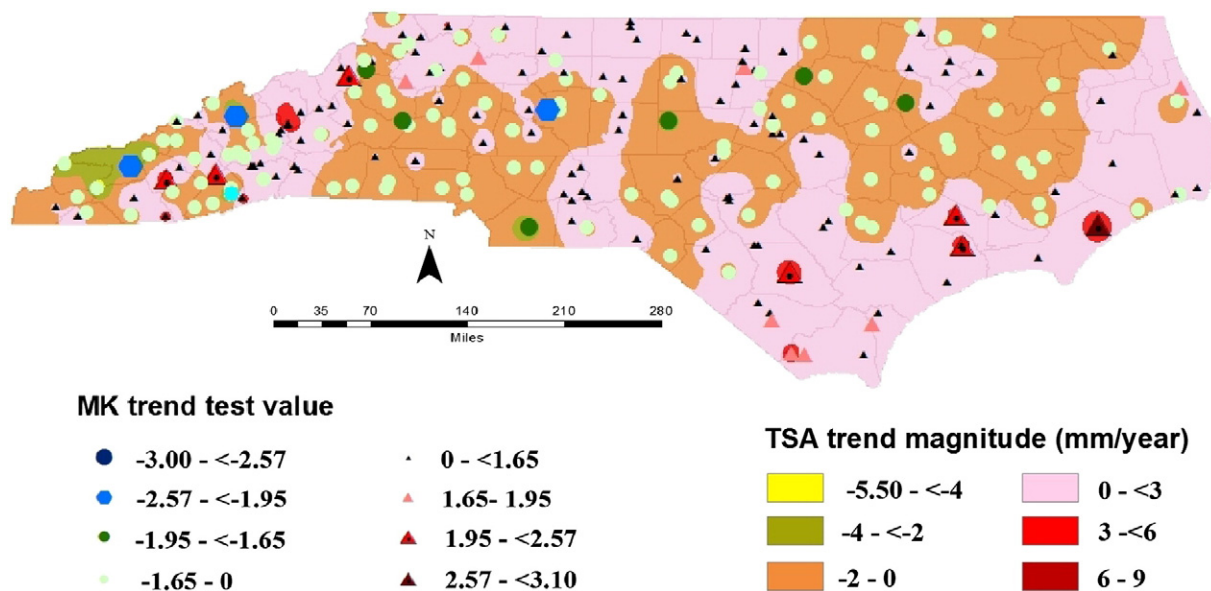
Fig. 4. Spatial distribution of stations with MK statistics and Interpolated trend (mm/year) results from TSA in annual time series data over the period 1950–2009.
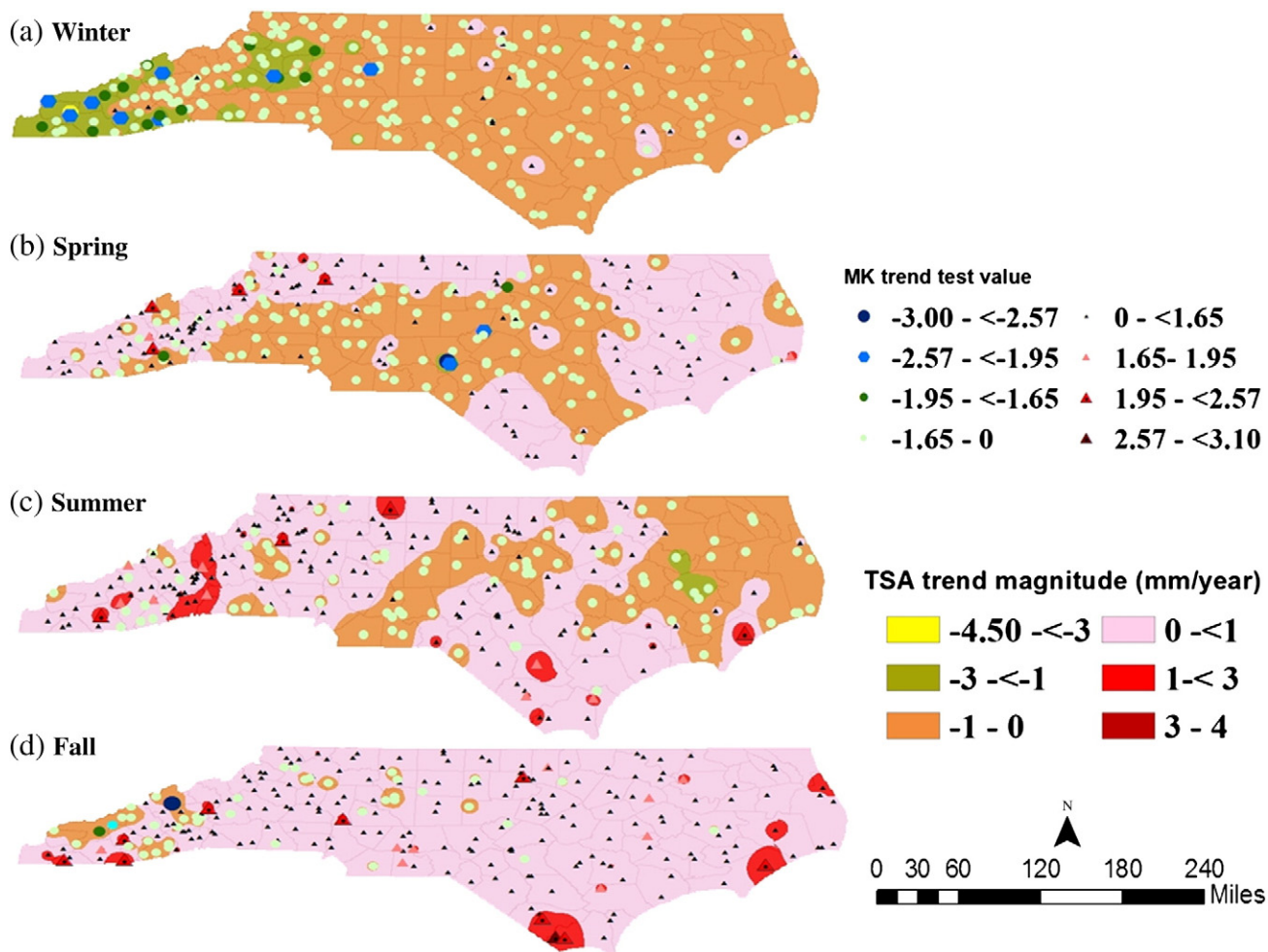

Fig. 5. Spatial distribution of stations with MK statistics and interpolated trend (mm/season per year) results from TSA in (a) winter, (b) spring, (c) summer, and (d) fall time series precipitation over the period 1950–2009.

negative slopes and some portion of southern part of the coastal zone shows high positive slopes. The magnitude of the trend varies between −5.50 mm/year and 9 mm/year. Boyles and Raman (2003) found statewide positive slopes except for the northeast corner, but in our study in addition with the northeast corner, southwest piedmont areas were also showing mild positive trend. They also found the most positive slopes in the southern coastal plain and the southern mountain which are consistent with this study.

3.2. Seasonal trends of precipitation

3.2.1. Winter

MK test found very larger nos. of stations with negative trends (229 of 249 stations, 92%) than the positive trends (Fig. 3a). However, only 8 were found to have significant negative trend (95% confidence level) and none was significant for positive trend (Fig. 3b). Significant negative trends are mostly found in western part of the mountain and piedmont zones (Fig. 5a). As can be seen in Fig. 5a, spatial distribution of winter precipitation trend magnitude shows statewide mild negative slopes except mountain zone with higher trend magnitude. The trend slope varied between −4.50 and 1 mm/season per year. In general, winter season has been found to experience statewide declining precipitation trends over the past 60 years.

3.2.2. Spring

MK test found positive trend in about half of the stations (136 of 249 stations, 55%; Fig. 3a) with significant trend in only 7 stations (4 positive trends and 3 negative trends; Fig. 3b). Significant positive trends are mostly found to exist in the mountain zone whereas significant negative trends are located in the mid-piedmont zone (Fig. 5b). Unlike the winter, mountain zone in spring season exhibits increasing precipitation trend. Most of the stations have positive trend in coastal zone and negative trend in piedmont zone. The range of trend magnitude in spring precipitation varied between −3 and 3 mm/season per year.

3.2.3. Summer

Summer precipitation trends show an opposite nature when compared with that of winter. In this case, 155 (62%) stations and 92 (37%) stations show positive and negative trends, respectively (Fig. 3a). Only 4 stations are found with significant positive trends and none with significant negative trends (Fig. 3b). Significant positive trends are mostly found in mountain zone, northern piedmont, and southern coastal zone of North Carolina (Fig. 5c). Spatial distribution shows statewide mild positive slopes except coastal zone and some portion of piedmont zone shows mild negative trend magnitude. Like spring, summer precipitation trend magnitude also varied between −3 and 3 mm/season per year. In general, it can be said that the summer season has been experiencing mild increasing precipitation trends over 60 years.

3.2.4. Fall

The fall precipitation series demonstrated an increasing trend over the study area for the majority of the stations 202 of 249 (81%) and decreasing trend in the remaining stations (Fig. 3a). Total 11 nos. of stations (10 positive and 1 negative)

were found to have significant trend (95% and more confidence level; Fig. 3b), of which 10 stations with positive trend are scattered all around the state (southern piedmont, eastern coastal and southern mountain zone) and one with negative trend is located in western mountain zone of North Carolina (Fig. 5d). Spatial distribution (Fig. 5d) shows statewide mild positive slopes for fall precipitation. The magnitude of trend varied between −1 and 4 mm/season per year (opposite of winter pattern). In general, it can be concluded that the fall season has been experiencing a mild increase in precipitation over 60 years.

Statewide increasing trend of fall precipitation is similar with the Boyles and Raman (2003) but the winter trend is opposite. State wide mild decreasing winter trend found in this study was similar with the findings by Prat and Nelson (in press) in the period 1998–2010. Mild negative trends in northern coastal plain represent the similarity with the Boyles and Raman (2003) study. Mild negative trends at the piedmont zone with no general trends in the spring season are consistent with the previous study.

3.3. Precipitation shift analysis

The shift in precipitation time-series was analyzed using Sequential Mann–Kendall (SQMK) test. The analysis was conducted only for those time-series with significant trend at the 99% confidence (i.e., MK test, Z values > 2.57). Table 1 indicates four cases with significant trend (99% confidence) including one on annual time-series, two on fall season time-series (one positive trend and one negative trend), and one spring season time-series. Fig. 6 shows graphical results of the SQMK test which clearly identified the year when the abrupt shift occurred (shift year is presented in Table 1). The identified shift year in each case represents the initiation of a positive (+) or a negative (−) trend.

The abrupt positive trend shift of annual precipitation series at one of the south-east stations began around 1970, and becomes significant in around 1985 till present time (Fig. 6a). In Fig. 6b, spring precipitation series at one of the mid-south stations' abrupt negative trend shift began around 1968, and becomes significant in around 2000. The abrupt positive (negative) trend shift of fall precipitation series at one of the south (west) stations began around 1968 (1965), and becomes significant in around 1995 (2000), (Fig. 6c and d). No significant shift was found in the case of summer and winter precipitation time series over the period 1950–2009. The abrupt trend shift provides ideas about that particular stations and surrounding positions. However, it is not a representative of the whole region. It can be generalized that

Table 1
Values of statistics Z of the MK trend test (99% confidence level) and geographic position of that trend with the abrupt change year calculated by Sequential MK (SQMK).

Time scale	Station	Z(+)	Year	Station	Z(−)	Year
Winter	–	–	–	–	–	–
Spring	–	–	–	Mid-south(1)	−2.88	1965
Summer	–	–	–	–	–	–
Fall	South (1)	2.74	1968	West(1)	−2.64	1965
Annual	South-east (1)	3.03	1970	–	–	–
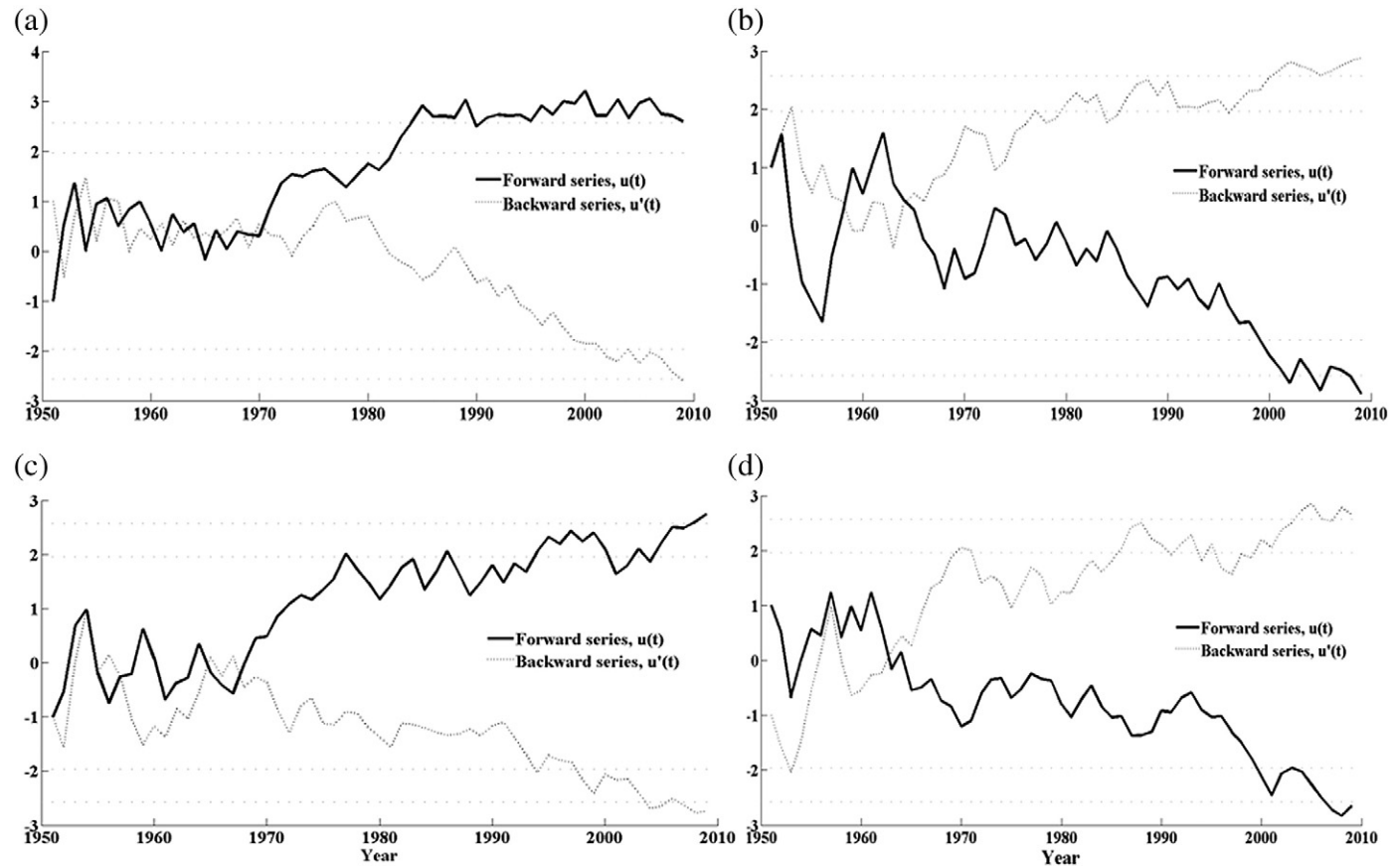
Fig. 6. Sequential Mann–Kendall (SQMK) test to predict the abrupt shift year of precipitation data series of the stations of 99% confidence level MK statistics for (a) Annual (+ve); (b) Spring (−ve); (c) Fall (+ve); and (d) Fall (−ve) scale time series over the period 1950–2009.

Table 2
Results of the statistical tests for regional (mountain, piedmont and coastal) precipitation trend of annual and seasonal time scale over the period 1950–2009.

Season/Year	Mountain		Piedmont		Coastal	
	Z	b	Z	b	Z	b
Winter	− 1.0651	− 1.1292	− 0.8228	− 0.4924	− 0.7207	− 0.5361
Spring	0.5549	0.4472	− 0.4783	− 0.1897	0.3635	0.2433
Summer	0.6952	0.4773	0.0702	0.0407	0.0191	0.0138
Fall	0.3253	0.1841	1.0141	0.4679	1.1799	0.6846
Annual	0.1212	0.2465	− 0.1594	− 0.272	0.236	0.2289

Z: Statistics of the Mann–Kendall test, b: Slope from Theil–Sen-approach (mm/season or year).

all abrupt shift in significant trend (99% confidence interval) were found around 70s.

3.4. Regional precipitation trends

Out of 249 meteorological stations studied, 3 regions of NC: mountain, piedmont, and coastal zone have 89, 82, and 78 stations, respectively. The regional trend assessment was conducted by applying the trend statistics (z-value, trend magnitude (b value), abrupt shift) on the precipitation time-series, which were the average values from stations within each region over the period 1950–2009.

It is seen in Table 2 that regional precipitation trend are not significant (confidence level ≥ 95%). In annual and seasonal time series, magnitude of precipitation trend varies from − 0.27 to + 0.23 mm/year and from − 1.13 to + 0.68 mm/season, respectively. It is found in Table 2 that winter season precipitation is decreasing in all three regions. Annual precipitation is increasing in mountain and coastal but decreasing in piedmont region over the 60 year period.

Fig. 7 shows the SQMK test results on annual and seasonal precipitation time-series for mountain, piedmont and coastal regions. Significant abrupt precipitation shifts are not detected in annual and seasonal scale precipitation, except for the coastal (mountain) region in spring (winter and summer) season. Overall, regional precipitation trend decreases statewide in annual time series. In summer, almost all 3 regions show the decreasing precipitation trend from the period of around 1960 to 2000. It seems that statewide summer precipitation trend increases in last decade. Statewide mild temporal precipitation trend increment occurs in fall season. The winter and spring seasons show no general temporal precipitation trend shift. However, statewide decreases trend detected in last decades in winter season.

3.5. Comparison of precipitation trend with NAO (North Atlantic Oscillation) index and SO (Southern Oscillation) index

The NAO and SO are the primary modes of the climate variability occurring in the northern hemisphere. NAO positive (negative) phase is associated with a stronger (weaker) north–south pressure gradient between the sub-tropical high and the Icelandic low (Durkee et al., 2008). Whereas, SO is an oscillation in surface air pressure between the tropical eastern and the western Pacific Ocean waters. The strength of the SO is measured by the Southern Oscillation Index (SOI). The SOI is computed from fluctuations in the surface air pressure difference between Tahiti and Darwin, Australia (Kurtzman and Scanlon, 2007). Previous researchers anticipated the strong relationship between precipitation and Oscillation (i.e. NAO, SO) over northern hemisphere/eastern United States/southeastern United States (Durkee et al., 2008; Hurrell, 1995; Kurtzman and Scanlon, 2007).

Here we compare winter (summer) precipitation with the NAO (SO) indices using 10-year moving average data (Fig. 8a and b). NAO and SO monthly data sets are collected from the Climate Prediction Center/National Oceanic and Atmospheric Administration (CPC, 2013). Monthly data were averaging out to generate the seasonal data series. Based on the coefficient of correlation ($R_{winter-NAO} = 0.37$ and $R_{summer-SOI} = 0.35$) and visual observation of the raw datasets of seasonal precipitation and NAO, SO indices; winter (summer) precipitation with the NAO (SO) indices was selected for the discussion in this section.

Three time periods 1972–1984, 1989–1998 and 1998–2009 (Fig. 8a) were found to have similar phase of winter average precipitation with the winter NAO indices. Durkee et al. (2008) found significant increase in the occurrence of rainfall observations during positive NAO phases in the eastern U.S. Winter average precipitation increases with the increment of positive NAO index in the period of 1989–1998. Similarly, two time periods of 1967–1979 and 1985–1998 (Fig. 8b) found similar pattern of summer average precipitation with the summer ENSO indices. Kurtzman and Scanlon (2007) found varying significance level (0.05–0.001) correlation of summer precipitation with SOI over the state of North Carolina in their southern United Sates study. This section discusses the relational pattern of winter and summer precipitation trends with the NAO and SOI. However, the predictability of precipitation pattern with the long term climate variability is still an undergoing research.

4. Summary and Conclusion

This paper analyzes the behavior of annual and seasonal precipitations in the state of North Carolina looking for trend in long historical (1950–2009) data series. Denser observation data (1 per 548km^2) totaling 249 meteorological stations were applied to the non-parametric Mann–Kendall test, the Theil–Sen approach and the Sequential Mann–Kendall test to investigate the precipitation trends. MK test, TSA method, and SQMK test were applied for significant trend detection, magnitude of trend, and precipitation trends shift analysis, respectively. Three distinct region (mountain, piedmont, and coastal) precipitation trends were also analyzed based on the above tests. A pre-whitening technique was applied to pre-process the data series prior to the application of the MK test and the TSA method, in order to reduce the serial correlation in long time series, as well as its effects on trends.
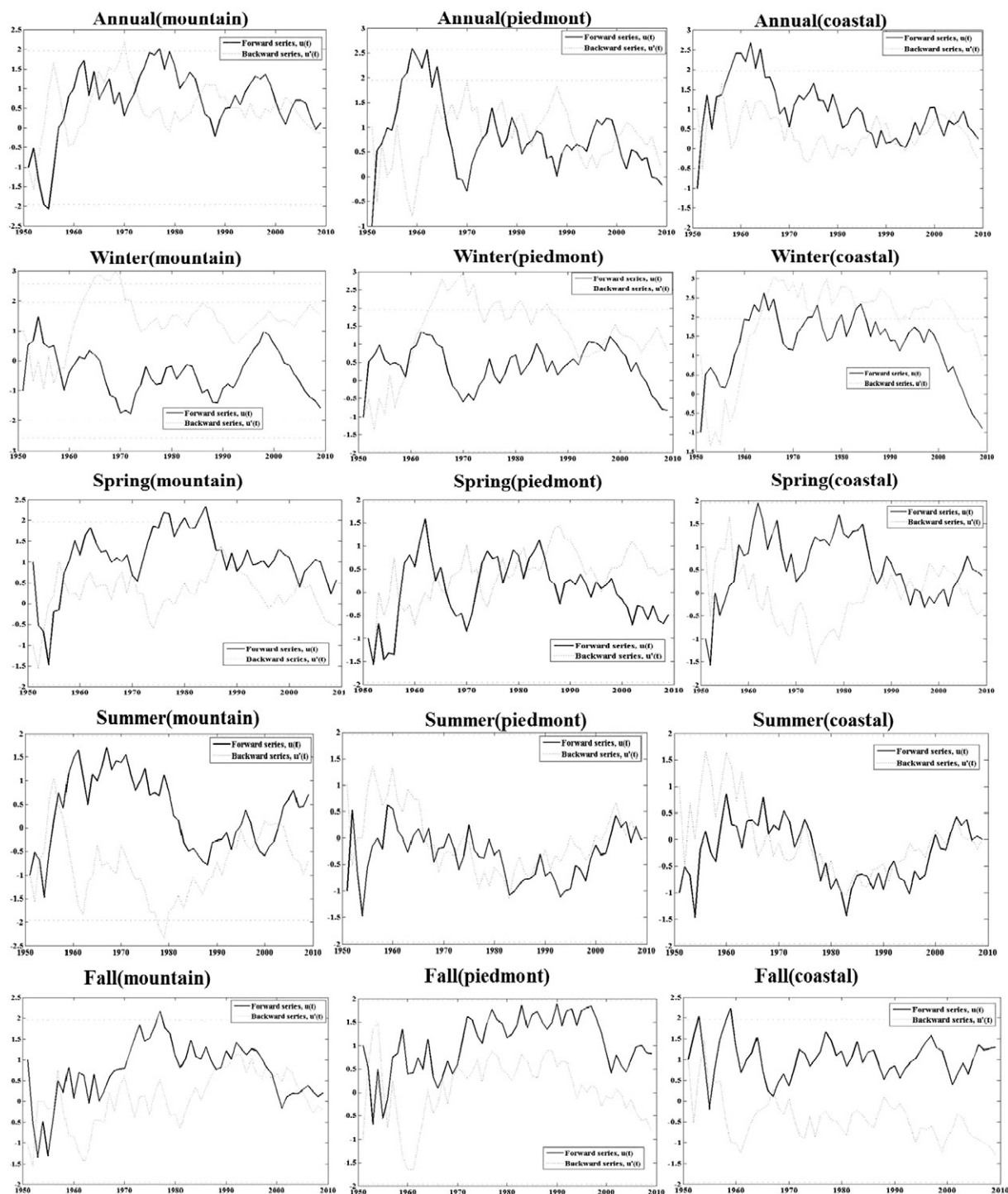
Fig. 7. Graphical representation of the forward series u (d) and the backward series u′ (d) of the Sequential Mann–Kendall (SQMK) test for annual and seasonal precipitation at the 3 regions (mountain, piedmont and coastal) of North Carolina.

Almost equal nos. of stations were showing positive and negative trends in annual time series. Among the positive (negative) trends, seven (three) significant trends were observed at the 95% and 99% confidence levels. The range of magnitude of annual precipitation trends varied from (−)

5.50 to (+) 9 mm/year. The spatial distribution of the annual precipitation trends indicated that the significant positive (negative) trends mostly happened in the south-east (mid and west) part of North Carolina. There is no single positive significant trend station found in piedmont zone. Most of
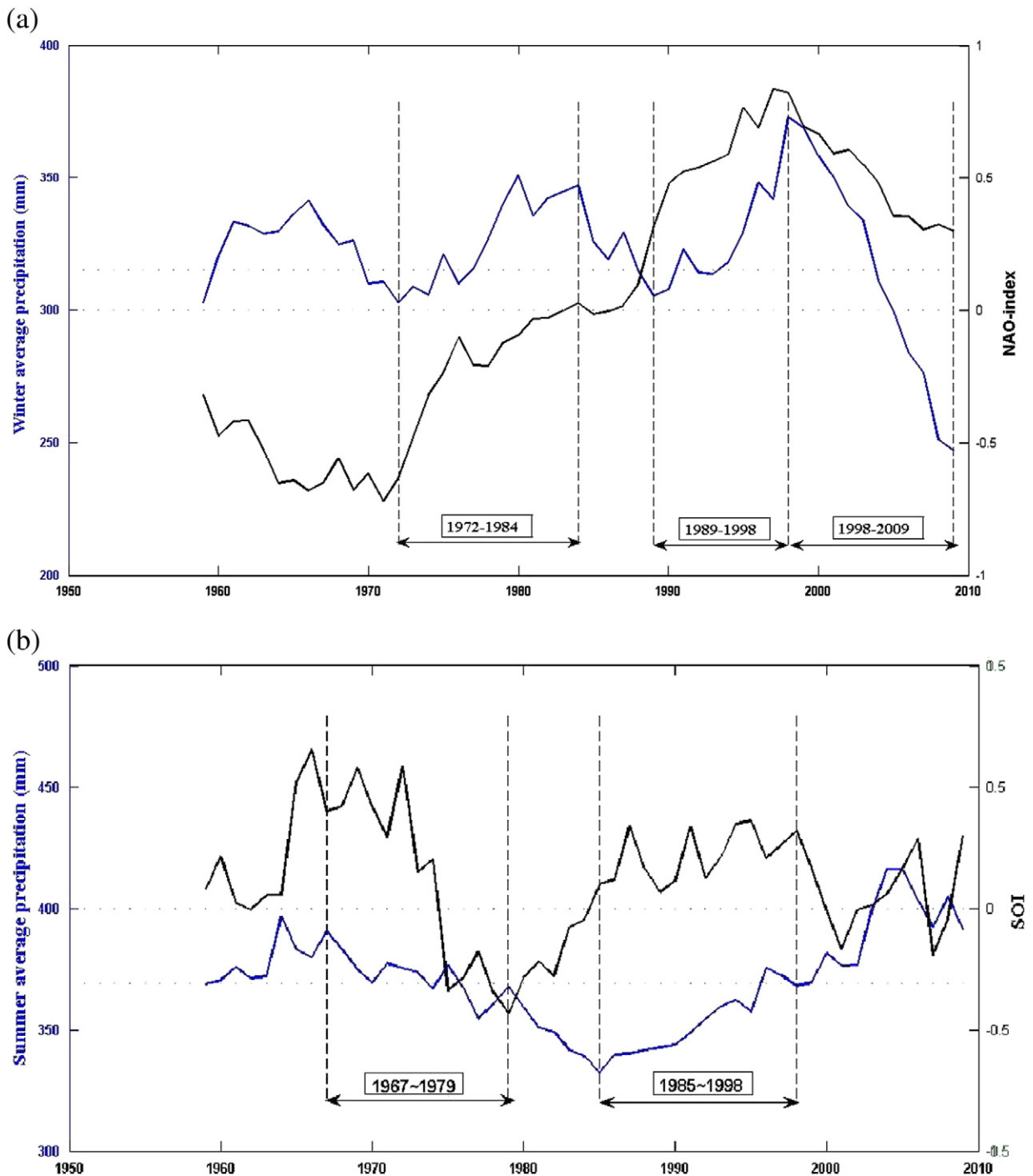
(a)

(b)

Fig. 8. (a) 10-Year moving average of winter average precipitation and winter NAO index and (b) 10-year moving average of summer average precipitation and summer SOI.

the stations precipitation shift occurred around 1970 either positive or negative. Notable significant precipitation trend shift (either increasing or decreasing) was not detected in regional trend shift analysis.

The analysis of the seasonal precipitation time series showed a mix of positive and negative trends. In winter the majority of the stations (229 out of 249) show the negative trend whereas

in fall, 202 positive trend stations found. In summer positive (negative) trends were found in (92) 155 stations.

This paper develops for the first time a full picture of recent precipitation trends with the denser gauging stations data across the state of North Carolina, which should be of interest to future agriculture and water resource management personnel. This study also found some correlations between North Atlantic

Oscillation (Southern Oscillation) indices with the winter (summer) precipitations. However, it is still unclear whether this trend change is either due to the Multi-decadal Natural Oscillation or the anthropogenic effects, such as: population change and land cover land use change or due to the greenhouse gas alteration effects, which will be the future research interests. Other different test results can also be comparable with the finding trend in this study might be an interesting inclusion with the future studies.

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References

Boyles, P.R., Raman, S., 2003. Analysis of climate trends in North Carolina (1949–1998). Environ. Int. 29, 263–275.
Boyles, R.P., Holder, C., Raman, S., 2004. North Carolina climate: a summary of climate normals and averages at 18 agricultural research stations. Technical Bulletin, 322. North Carolina Agricultural Research Service.
Costa, A.C., Soares, A., 2009. Homogenization of climate data: review and new perspectives using geostatistics. Math. Geosci. 41, 291–305.
CPC, 2013. North Atlantic Oscillation (NAO): Climate Prediction Center (CPC), National Oceanic and Atmospheric Administration (NOAA). http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml (Available online at).
Durkee, J.D., Frye, J.D., Fuhrmanny, C.M., Lacke, M.C., Jeong, H.G., Mote, T.L., 2008. Effects of the North Atlantic Oscillation on precipitation-type frequency and distribution in the eastern United States. Theor. Appl. Climatol. 94, 51–65. http://dx.doi.org/10.1007/s00704-007-0345-x.
Gocic, M., Trajkovic, S., 2013. Analysis of changes in meteorological variables using Mann–Kendall and Sen's slope estimator statistical tests in Serbia. Glob. Planet. Chang. 100, 172–182.
Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18, 107–121.
Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK/New York, USA.
Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation—regional temperatures and precipitation. Science 269, 676–679.
Jha, M.K., Singh, A.K., 2013. Trend analysis of extreme runoff events in major river basins of Peninsular Malaysia. Int. J. Water 7 (1/2), 142–158.
Jianqing, F., Qiwei, Y., 2003. Nonlinear time series: nonparametric and parametric methods. Springer Series in Statistics.0387224327.

Karl, T.R., Knight, R.W., 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bull. Am. Meteorol. Soc. 79, 231–241.
Keim, B.D., Fischer, M.R., 2005. Are there spurious precipitation trends in the United States Climate Division database? Geophys. Res. Lett. 32. http://dx.doi.org/10.1029/2004GL021985 (L04702).
Kendall, M.G., 1975. Rank Correlation Measures. Charles Griffin, London.
Kurtzman, D., Scanlon, B.R., 2007. El Niño—Southern Oscillation and Pacific Decadal Oscillation impacts on precipitation in the southern and central United States: evaluation of spatial distribution and predictions. Water Resour. Res. 43. http://dx.doi.org/10.1029/2007WR005863 (W10427).
Mann, H.B., 1945. Non-parametric tests against trend. Econometrica 13, 245–259.
Martinez, J.C., Maleski, J.J., Miller, F.M., 2012. Trends in precipitation and temperature in Florida, USA. J. Hydrol. 452–453, 259–281.
Modarres, R., Sarhadi, A., 2009. Rainfall trends analysis of Iran in the last half of the twentieth century. J. Geophys. Res. 114. http://dx.doi.org/10.1029/2008JD010707 (D03101).
Modarres, R., Silva, V., 2007. Rainfall trends in arid & semi-arid regions of Iran. J. Arid Environ. 70, 344–355.
New, M., Todd, M., Hulme, M., Jones, P., 2001. Precipitation measurements and trends in the twentieth century. Int. J. Climatol. 21, 1899–1922.
Partal, T., Kahya, E., 2006. Trend analysis in Turkish precipitation data. Hydrol. Process. 20, 2011–2026.
Peterson, T.C., Easterling, D.R., Karl, T.R., Groisman, P.Y., Nicholis, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D., Vincent, L., Heino, R., Tuomenvirta, H., Mestre, O., Szentimrey, T., Salinger, J., Førland, E., Hanssen-Bauer, I., Alexandersson, H., Jones, P., Parker, D., 1998. Homogeneity adjustments of in situ atmospheric climate data: a review. Int. J. Climatol. 18, 1493–1517.
Prat, O.P., Nelson, B.R., 2013. Characteristics of annual, seasonal, and diurnal precipitation in the Southeastern United States derived from long-term remotely sensed data. Atmos. Res. http://dx.doi.org/10.1016/j.atmosres.2013.07.022 (in press).
Robinson, P., 2005. North Carolina Weather and Climate. University of North Carolina Press in Association with the State Climate Office of North Carolina (Ryan Boyles, graphics).
Salas, J.D., Delleur, J.W., Yevjevich, V., Lane, W.L., 1980. Applied Modelling of Hydrologic Time Series. Water Resources Publications, Littleton, Colorado.
Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63 (324), 1379–1389.
Small, D., Islam, S., Vogel, R.M., 2006. Trends in precipitation and streamflow in the eastern US.: paradox or perception? Geophys. Res. Lett. 33. http://dx.doi.org/10.1029/2005GL024995 (L03403).
Some'e, B.S., Ezani, A., Tabari, H., 2012. Spatiotemporal trends and change point of precipitation in Iran. Atmos. Res. 113, 1–12.
Sonali, P., Nagesh, K.D., 2013. Review of trend detection methods and their application to detect temperature changes in India. J. Hydrol. 476, 212–227.
Tabari, H., Somee, B.S., Zadeh, M.R., 2011. Testing for long-term trends in climatic variables in Iran. Atmos. Res. 100 (1), 132–140.
Theil, H., 1950. A rank-invariant method of linear and polynomial regression analysis. Proc. K. Ned. Akad. Wet. A53, 386–392.
USDA-ARS, 2012. Agricultural Research Service, United States Department of Agriculture. http://www.ars.usda.gov/Research/docs.htm?docid=19440 (accessed November, 2012).
von Storch, H., 1995. Misuses of statistical analysis in climate research. In: Storch, H.V., Navarra, A. (Eds.), Analysis of Climate Variability: Applications of Statistical Techniques. Springer, Berlin, pp. 11–26.
Xu, Z.X., Takeuchi, K., Ishidaira, H., Li, J.Y., 2005. Long-term trend analysis for precipitation in Asia Pacific Friend river basin. Hydrol. Process. 19, 3517–3532.