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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.

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).