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Innovative trend analysis of solar radiation in China during 1962–2015

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ABSTRACT

An innovative trend analysis (ITA) with significant test was proposed for detecting the annual and seasonal variation trends of solar radiation at 48 stations in five different climatic zones across China during 1962–2015. The solar radiation generally showed a significant decreasing trend ($p < .05$ or $p < .01$) at most stations, however, some stations exhibited significant increasing trends ($p < .05$ or $p < .01$) in eastern part of temperate monsoon climatic zone, western part of subtropical monsoon climatic zone and tropical monsoon climatic zone using ITA. The ITA method was compared with two traditional trend analysis methods, i.e., linear regression analysis (LRA) and Mann-Kendall (M-K) test. The results indicated almost all significant trends ($P < .05$ or $P < .01$) that can be detected by LRA or M-K test (117 time series) can be effectively identified using ITA (116 time series). Meanwhile, many significant trends (93 time series) that cannot be effectively detected by LRA or M-K test can be identified using ITA. So ITA could detect hidden-trends that cannot be observed using traditional LRA and M-K test. The possible causes for decreasing trends at most stations in China were investigated by discussing the annual and seasonal variations of anthropogenic aerosol loadings and sunshine duration. Moreover, the differences, similarities and advantages of ITA, LRA and M-K test were compared and evaluated.

1. Introduction

Solar radiation is the fundamental energy source at the Earth's surface, which plays an important role in many fields and applications, such as solar energy technologies, agricultural productivity, terrestrial ecological ecosystem, hydrological cycle and climate prediction [1–5]. Any variations in the amount of solar radiation have great influences on our lives and surrounding environment. Global solar radiation at many stations shows a decreasing trend in recent decades, however, an increasing trend has also been observed at some sites around the world [6–9]. It is essential to make an accurate knowledge about the spatial-temporal characteristics of solar radiation in different parts of the world. However, there is still no clear knowledge about the spatial-temporal trends of solar radiation in global and regional scales, therefore, accurate determination and clear understanding of solar radiation is of great importance for understanding meteorological and hydrological processes, ecological functions, energy development and utilization [10–13].

At present, there are many methods to detect hydrological and meteorological time series trends, such as linear regression analysis, Mann-Kendall (M-K) test, Sen's T test, Spearman's Rho (SR) test and Tramo/S0eats program [14–16]. These methods have been successfully applied in different hydrological and meteorological time series around world [17–19], for example, Caloiero et al. [20] applied the M-K test and linear regression to analyze the trends in annual and seasonal precipitation in Calabria, Italy, and a decreasing trend in annual and autumn-winter precipitation and an increasing trend in summer precipitation were observed. Tabari et al. [21] analyzed the trends of water quality parameters on seasonal and annual time scales at four stations along the Maroon River during 1989–2008 using M-K test, Sen' slope and linear regression, and the significant trends were obtained in calcium,

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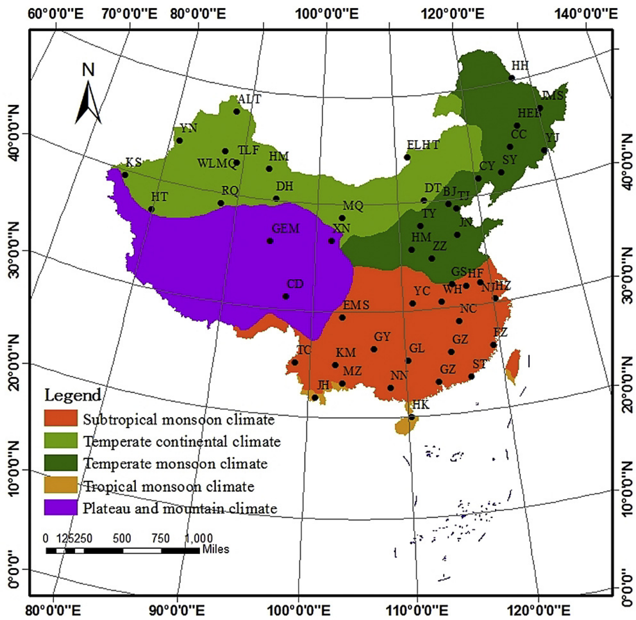

Fig. 1. The distributions of solar radiation stations in China.

magnesium, sodium absorption ratio, pH, and turbidity series at some stations. Chowdhury et al. [22] analyzed more than 100 years of rainfall data in South Australia using M-K test, linear regression and Spearman's rho test. They found decreasing trends in the southern and south-east parts of South Australia, and overall positive trends in spring and summer rainfall, but negative trends in autumn and winter.

Great achievements have been made using different statistical methods in literature, however, above mentioned methods have some disadvantages, for instance, linear regression requires data to be independent and normally distributed, which is in contradiction with the patterns of meteorological and hydrological time series (generally positively or negatively skewed data); the M-K and SR test are suitable for cases where the trend may be assumed as a monotonic and normal distribution [23,24], so there are still some negative aspects for applying these traditional methods to detect variation trends for meteorological and hydrological time series. Recently, ITA method was developed by Sen [23,25] and applied to different types of time series [26,27]. Kisi [27] analyzed the trends of monthly pan evaporation at six different locations using M-K test, Spreaman Rho test and ITA, the results indicated that above methods provided similar trends at three stations. Meanwhile, some increasing and decreasing trends for low, medium and peak pan evaporation values at other stations that cannot been detected using M-K and Spearman Rho tests can be identified easily by ITA, however, there is no necessary statistical equations to measure the trends qualitatively. Wu and Qian [26] put forward to an algorithm to measure annual and seasonal rainfall variation trends at 14 stations in Shaanxi Province, China using ITA, but the test results did not pass a significant test. Meanwhile, previous studies focused on the hydrological and meteorological time series, and most studies focusing on estimating solar radiation using different modeling techniques [28–30], for example, Wang et al. [30]predicted daily solar radiation using artificial neural network (ANN) methods, multilayer perceptron (MLP), generalized regression neural network (GRNN) and radial basis neural network (RBNN). Very few studies analyzed the trends of solar radiation around the world. A clear and accurate knowledge about trend detection of solar radiation in regional and global scales using different methods is particularly important due to its widespread application in climate prediction and energy research [13,31].

It is reported that there are different variation trends of solar radiation in different areas of China, for example, Liu et al. [32] analyzed the variations of solar radiation at 6 stations in Haihe River basin during 1957–2008 using M-K test, significant decreasing trends were obtained at above all stations. Zheng et al. [33] analyzed the spatiotemporal characteristics of solar radiation in Beijing-Tianjin-Hebei region during 1960–2005, the results showed that solar radiation increased in the eastern part, and significantly decreased in the western part. Qi et al. [34] investigated the spatiotemporal characteristics of solar radiation using linear regression across China and significant decreasing trends were observed at most stations, however, significant increasing trends were also detected at some stations. Li et al. [35] investigated the spatiotemporal characteristics of solar radiation in South-China during 1961–2008 and significant decreasing trends were observed at most stations, however, the significant increasing trends were also detected at some stations. There is still no clear knowledge about the spatial-temporal trends of solar radiation in China [36], which necessitated this study for innovative trend analysis of global solar radiation in China during 1962–2015.

The main objectives of this study are: (1) to apply three different trend analysis methods to study the variation trends of solar radiation across China; (2) to analyze the long-term variation trends of solar radiation in China and discuss its possible reasons; (3) to compare and evaluate the differences, similarities and advantages of LRA, M-K test and ITA, respectively.

2. Data and methodology

2.1. Study area and data

There are various methods to classify climatic types of China [37,38]. For this research, China temperature-precipitation method is recommended [39], including subtropical monsoon climate (SMC), temperate continental climate (TCC), temperate monsoon climate (TMC), tropical monsoon climate (TRMC) and plateau and mountain climate (PMC). Fig. 1 shows the geographical distributions of radiation stations in China and the associated climatic zones. There were obvious differences in different climatic zones, for example, Changchun (CC) is characterized by temperate monsoon climate, the annual rainfall is about 522–615 mm, and monthly average air temperature ranges from −19 °C in winter to 23 °C in summer. Wuhan (WH) is located at the subtropical monsoon climate, the hottest month is July (29.3 °C) and coldest month is January (3 °C). Urumqi belongs to temperate continental climate, the annual rainfall is about 286 mm, and the monthly average air temperature varies from 15.2 °C in January to 23 °C in July. Geermu (GEM) is located at the Plateau and mountain climate zone, which is characterized by extremely cold winter, the annual mean air temperature (T_a), maximum air temperature (T_M) and minimum air temperature (T_m) at GEM is about 5.26 °C, 13.01 °C and −1.39 °C, respectively. The Haikou (HK) station is located at Hainan Peninsula, the annual T_a and rainfall (25.22 °C and 1664 mm) are the highest among all stations in China.

There are totally 756 meteorological stations in China, only 122 of them have records of global solar radiation. The radiation