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Journal of Hydro-environment Research 9 (2015) 368–380

Journal of Hydro-environment Research

www.elsevier.com/locate/jher

Research paper

Detecting distributional changes of annual rainfall indices in Taiwan using quantile regression

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Received 27 August 2013; revised 7 July 2014; accepted 29 July 2014
Available online 19 December 2014

Abstract

It is commonly recognized that hydrologic cycle has been intensified by climate change, which may lead to changes in mean, variability, and extremes of climate and hydrologic variables. This study aims to explore possible distributional changes of rainfall characteristics over time in Taiwan using quantile regression. A simplified nine-category distributional-change scheme, with focusing on changes of scale and location of empirical probability density function, is proposed in this study to examine distributional changes of rainfall characteristics. A total of 23 daily rainfall series in Taiwan over the period of 1947–2000 is selected for detecting distributional changes of annual rainfall, annual rain days, and annual 1-day maximum rainfall. Inconsistent variation patterns are observed since distributional changes of these three annual rainfall indices are respectively classified into 7, 6, and 7 categories. The prevalent distributional change is only noted for annual rain days because 14 out of 23 stations (60.9%) are classified as the Category VII (leftward and sharpened distribution). Considerable spatial diversity is also observed in Taiwan except that the distributional change of annual rain days classified as Category VII is clustered in North and South regions.

Keywords: Climate change; Trend analysis; Quantile regression; Annual rainfall index

1. Introduction

There is an increasing concern about impacts of climate change on water-resources system as well as ecosystem worldwide over recent years. Hydrologic-cycle intensification induced by global warming would alter frequency, intensity, and magnitude of rainfall and other climate variables (Ziegler et al., 2003). Many studies have demonstrated strong evidence of climate change on rainfall characteristics. For example, the Intergovernmental Panel on Climate Change (IPCC) (2007) concluded that precipitation increased significantly in eastern parts of North and South America, northern Europe, and northern and central Asia according to observed data from 1900 to 2005. Alterations of rainfall characteristics would affect current operations and future design criteria of water-resources systems and thus render necessity of exploring trends of rainfall processes.

Within evaluation framework of trend analysis, linear regression and non-parametric Mann–Kendall test are traditional and widely used approaches to identify possible trends of hydrologic and climate series. A vast literature is devoted to studying trends of temperature (Sajjad et al., 2009; Zhang et al., 2009; Sansigolo and Kayano, 2010; Toros, 2012), rainfall (Matti et al., 2009; Del Rio et al., 2011; Jung et al., 2011; Dravitzki and McGregot, 2011; Rana et al., 2012), evaporation (Tabari et al., 2012), streamflow (Wilson et al., 2010; Gautam and Acharya, 2012), drought (Wu et al., 2008; Abarghouei et al., 2011; Zhang et al., 2012), water quality (Bouza-Deaño et al., 2008; Yenilmez et al., 2011), and

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http://dx.doi.org/10.1016/j.jher.2014.07.006
1570-6443/

ozone (Antón et al., 2011). Although these two approaches exhibit computational efficiency in trend assessments, many limitations such as sensitive to outliers and conditional mean estimations have been indicated by previous studies (e.g., Muhlbauer et al., 2009; Timofeev and Sterin, 2010). Besides, noticeable changes in the extremes and variability of hydrologic and climate variables are undetectable through these two trend-detection approaches.

Quantile regression, initiated by Koenker and Basset (1987), is capable of identifying changes over time of any percentile values of hydrologic and climate variables. Widespread applications of this method have been observed in economics, biology, ecology, and finances (Yu et al., 2003). However, only a few, but recently emerged, studies apply quantile regression in environmental researches. For example, Koenker and Schorfheide (1994) used the quantile regression to reanalyze the global surface air temperature and found that a break existed in the general upward sloping trend during the period of 1940–1965. Baur et al. (2004) and Sousa et al. (2009) predicted ozone concentration based on several meteorological variables using quantile regression. Chamaille-Jammes et al. (2007) and Mazvimavi (2010) employed the quantile regression to detect changes of annual rainfall over time in Zimbabwe. Barbosa (2008) identified the long-term sea-level variability at Baltic Sea using quantile regression and concluded that the slopes in maxima exhibit greater trends. Jagger and Elsner (2009) modeled the wind speed of tropical cyclones in USA with four climate variables based on quantile regression. Luce and Holden (2009) tested for trend in distribution of annual runoff using quantile regression in the Pacific Northwest United States and indicated that 72% of the stations showed significant declined in the 25th percentile annual flow. Timofeev and Sterin (2010) used quantile regression to analyze changes in surface climate and free atmosphere climate series in Moscow. Villarini et al. (2011) used the quantile regression associated with other methods to investigate temporal and spatial variation of rainfall in the Midwest of the United States. Hirschi et al. (2011) identified the relationship between soil-moisture and two temperature indices in southeastern Europe by quantile regression. Barbosa et al. (2011) examined the changes in daily mean air temperature over Central Europe using quantile regression and found that considerable spatial diversity over such region. Monteiro et al. (2012) analyzed the ozone concentrations in the Iberian Peninsula by means of quantile regression and summarized the spatial distribution using classical clustering procedure. Wang et al. (2013) employed quantile regression associated with stationary and change-point analyses to examine possible change of monthly precipitation in southeastern USA.

The above quantile regression-based studies focus on detecting changes of variables for specific quantiles such as 0.9 or 0.1 only. Such separate collections of changes of a variable at some specific quantiles do not reveal changes in entire distribution of that variable. A novel approach based on quantile regression model for detecting distributional changes of hydrologic and climate variables is proposed in this study. This study hypothesizes that changes of rainfall regime may not equally affect all the percentile values of rainfall characteristics. It is thus necessary to examine the changes in various quantile of rainfall characteristics using quantile regression and integrate into a distributional change. Taiwan is inadequately represented in global rainfall studies such as Dai et al. (1997) and Alexander et al. (2006). In addition, climate change and other factors (Chu et al., 2012, 2014) may alter rainfall characteristics in Taiwan. This study aims to develop a quantile regression-based approach for detecting distributional changes of rainfall characteristics and applied to three annual rainfall indices at 23 rainfall gauge stations with 54-year daily rainfall records in Taiwan.

The remainder of this paper is organized as follows. Section 2 presents an introduction of quantile regression model and the approach for detecting distributional change. Section 3 summarizes the annual rainfall indices at 23 stations located in Taiwan during the mid- and late 20th century (1947–2000). Results and discussions are given in the Section 4, which is followed by the Section 5 of conclusions.

2. Methodology

2.1. Quantile regression model

It is convenient to introduce quantile regression model by firstly stating the traditional linear regression model, which is given by

$$y = a + bx + \varepsilon \quad (1)$$

where y and x are dependent and independent variables, respectively; a and b are regression coefficients and represent intercept and linear slope, respectively; ε is the random error term associated with the regression.

Within the classical linear regression framework, the regression coefficients a and b are estimated by the method of least squares. Considering n pairs of observed data x_i and y_i, this method minimizes the sum of squared errors, i.e.,

$$\min \sum_{i=1}^{n} (y_i - a - bx_i)^2 \quad (2)$$

The obtained $\hat{y}_i = \hat{a} + \hat{b}x_i$, where $\hat{a}$ and $\hat{b}$ denoted the estimated coefficients, is the conditional mean of a given known x_i. If the regression coefficients a and b are estimated by minimizing the sum of absolute deviations which is given by

$$\min \sum_{i=1}^{n} |y_i - a - bx_i| \quad (3)$$

The obtained $\hat{y}_i$ then becomes the conditional median. Actually, Equation (3) is a special case of the quantile regression with quantile equaling to 0.5. The linear quantile regression model is analogy to Equation (1) except that the regression coefficients are quantile-dependent. That is,

$$y_q = a_q + b_q x + \varepsilon_q \quad (4)$$

where q is quantile and ranges between 0 and 1; a_q and b_q are regression coefficients which depend on the selected quantile q