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Changes in aridity index and reference evapotranspiration over the central and eastern Tibetan Plateau in China during 1960–2012

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ABSTRACT

Based on climate data from 68 meteorological stations over the Tibetan Plateau (TP) observed by the China Meteorological Administration in 1960–2012, temporal and spatial variations in aridity index (AI) and reference evapotranspiration (ET_0) were comprehensively investigated. The abrupt change and the period in AI and ET_0 were characterized using a comprehensive time series analysis conducted with Mann–Kendall test and Morlet wavelet. The results indicated that the regionally averaged value of AI significantly decreased by 0.04/decade during 1960–2012 period, with the maximum observed in 1972. Similarly, the regional trend for ET_0 was at the rate of −9.6 mm/decade with statistically significant at the 0.01 level. Most of these stations with positive value for AI were primarily distributed at the northern southwestern TP. Moreover, a majority of stations with low values of ET_0 were substantially distributed at the central and eastern TP, and amounts of the stations with high values of ET_0 were mainly located at a lower elevation. Abrupt changes of both AI and ET_0 primarily happened in 1980s. The major cycles of AI and ET_0 were 15 y and 17 y scale over the study period with apparent periodic oscillation characteristics, respectively, and together with other different scale cycles co-existing. The significant correlations between AI and East Asian Summer Monsoon Index (EASMI) indicated that AI over the TP was related to the EASMI.

1. Introduction

Climate changes and human activities have leaded to dramatic changes in ecohydrological patterns in recent decades, which in turn have resulted in the changes of hydrological processes in many basins around the world, and have already caused a series of water resources problems in some regions (Li et al., 2007; McVicar et al., 2007). It was much warmer in the most recent three decades than in any other decades after 1850 (IPCC, in press), which was expected to lead to higher evaporation rates and to enable the atmosphere to transport higher amounts of water vapour. Reference evapotranspiration (ET_0), defined as the potential evapotranspiration of a hypothetical surface of green grass of uniform height, actively growing and adequately watered, was one of the most important hydrological variables for scheduling irrigation systems, preparing input data to hydrological water-balance models, and calculating actual evapotranspiration for a region or a basin (Blaney and Criddle, 1950; Xu and Li, 2003; Xu and Singh, 2005). Consequently, understanding of the temporal variations of reference evapotranspiration is a vital component in regional hydrological research.

Extensive research efforts have examined the potential impact of climate change on ET_0 in recent decades and achieved fruitful results. Thomas (2000) reached the conclusion that ET_0 had decreased in all seasons especially in northwest and southeast China. Mo et al. (2004) simulated evapotranspiration and found that the spatial pattern of annual evapotranspiration and its components corresponded to the precipitation and leaf area index patterns over the Lushi basin. For the upper and mid-lower Yangtze River basin, trends of ET_0 were substantially decreasing (Wang et al., 2007), similarly, the declining tends of ET_0 were obtained in north China (Song et al., 2009) and Taoer River basin (Liang et al., 2010). The previous studies showed that ET_0 in China presented substantially a decreasing trend. As for Tibetan Plateau (TP), significant warming trends were detected during the last several decades (Liu et al., 2006). However, most precipitation indices

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exhibited increasing trends over the southern and northern TP (You et al., 2008) "Three-River Headwaters" region (Cao and Pan, 2014). Linear trend rates for meteorological variables affecting potential evapotranspiration rates were investigated (Chen et al., 2006), significant for further understanding the mechanism of potential evapotranspiration variation. Zhang et al. (2009) analyzed the Spearman's rank correlation coefficients between March and October mean 500 hPa zonal wind speed and the time variable during 1971–2004. Additionally, Zhang et al. (2007) took catchments as research objects over the TP and found that the annual reference evapotranspiration averaged from all the observatories significantly decreased ($P < 0.05$), while actual annual evapotranspiration averaged from all the catchments increased ($P < 0.1$). However, it was found that the aridity index (AI) can be applied to predict model scenarios which estimated that drought would persist in critical agricultural areas. AI had not been widely employed except for the northwest China (Huo et al., 2013). The AI and ET_0 over such a wide plateau is spatially diverse, and more detailed analysis for the central and eastern TP is required. Thus, in order to research the changes of AI and ET_0 over the central and eastern TP from 1960 to 2012, the long-term daily meteorological data available was collected. This paper will improve our understanding of climate change and the accompanying effect on hydrology and climatic aridity, and provide a scientific basis for evaluation of water resources, as well as promote regional sustainable social and economic development.

2. Materials and methods

2.1. Study area and data description

The Tibetan Plateau is located in western China, 26° 00′ 24″–39° 46′ 50″ N, 73° 18′ 52″–104° 46′ 59″ E (Fig. 1), including the Tibet Autonomous Region, Qinghai province, as well as smaller portions of the western Sichuan province, southwestern Gansu province, northern Yunnan province and Xinjiang Autonomous Region in Western China. In addition, the TP is known as the "Third Pole" or the "Roof of the World" with an area of approximately 2.57×10^6 km^2 (Zhang et al., 2002), and has an average altitude of about 4000 m above sea level (Shen et al., 2011). There are mountain ranges around the TP, such as the Kunlun, Qilian, Hengduan, and Karakoram ranges of northern Kashmir (Yang et al., 2012). Several rivers including Yangtze, Ganges, Brahmaputra, Indus, and Yellow Rivers are fed from the TP and adjacent mountain ranges (Immerzeel et al., 2010). The study area, with annual temperature ranges from 5 to 12 °C, is a typical plateau continental monsoon region, which is primarily controlled by southeasterly and westerly winds. Precipitation primarily falls between May and September, and the mean annual precipitation decreases from more than 800 mm in the southeast to 200 mm in the northwest (Pan et al., 2013). The biodiversity and soil of the area are remarkable and typical especially for the southern TP, which can be attributed to the monsoonal climate and the large vertical gradient.

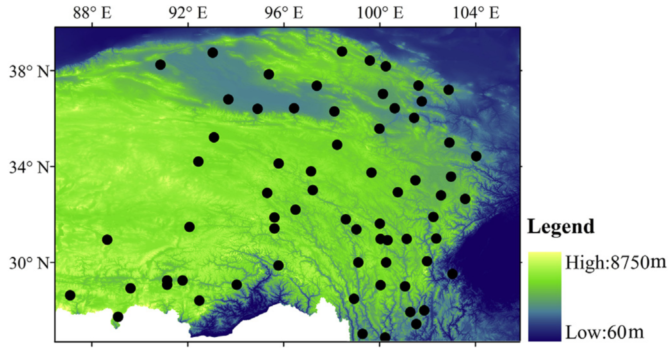

Fig. 1. Locations of meteorological stations on central and eastern TP.

The data of daily, sunshine duration, temperature (mean, maximum, and minimum temperature), daily mean relative humidity, and daily mean wind speed from 68 meteorological stations in the TP during the 1960–2012 period were obtained from the Chin Meteorological Administration (available at http://www.nmic.gov.cn). The Arctic Oscillation Index (AOI), Southern Oscillation Index (SOI), Indian Summer Monsoon Index (ISMI), Western North Pacific Monsoon Index (WNPMI), East Asian Summer Monsoon Index (EASMI) and South Asian Summer Monsoon Index (SASMI) were obtained from the National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences (available at http://www.cdc.noaa).

2.2. Reference evapotranspiration (ET_0) and aridity index (AI)

ET_0 calculator version 3.1 determined using the ET_0 Calculator Version 3.1 software (FAO, 2009). The ET_0 Calculator was issued in 2009 and employs the FAO Penman–Monteith method for the ET_0 calculating. A modified Penman–Monteith model (Thornthwaite, 1951; Jensen et al., 1990; Liu et al., 2006) (Revision in 1998, Food and Agriculture Organization of the United Nations) was adapted to calculate the ET_0 as.

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

where R_n is the net radiation at the surface (MJ/(m^2·d)); γ is the psychrometric constant (kPa/°C); G is soil heat flux (MJ/(m^2·d)); T is the average air temperature at 2 m Height (°C); Δ is the slope of the saturated water-vapor pressure curve (kPa/°C); U_2 is the wind speed at 2 m height (m/s); e_s is the saturation vapor pressure (kPa); e_a is actual vapor pressure (kPa).

AI was as expressed dividing the difference between precipitation and potential evapotranspiration by potential evapotranspiration (Thornthwaite, 1948). This definition can express the arid degree in arid area or season. In this paper, the AI was likewise calculated using the following equation:

$$\mathrm{AI} = (\mathrm{ET}_0 - \mathrm{P})/\mathrm{ET}_0 \tag{2}$$

where P is the monthly or yearly total precipitation, and ET_0 is the monthly or yearly reference evaporation.

2.3. Mann–Kendall (M–K) test and abrupt change analysis

The M–K test or Kendall's tau test (Mann, 1945; Kendall, 1975), is a rank based non-parametric test for estimating the significant tendency, and it have been widely applied in various fields. The null hypothesis H_0 is that a sample of data $\{x_i, i = 1, 2, \ldots, n\}$, x_i is independent and identically distributed. The alternative hypothesis H_1 is that a monotonic trend exists in X. The statistic S of Kendall's tau was defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{3}$$

where the x_j are the sequential data values, n is the length of the data set, and