Quaternary International 321 (2014) 116–124

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Changes in extreme wet events in Southwestern China in 1960–2011

Liguo Cao [a], Shaoming Pan [a,*], Qiang Wang [b], Yun Wang [c], Wei Xu [a]

[a] School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210023, China
[b] Lanzhou Branch of the National Science Library, Chinese Academy of Sciences, Lanzhou 730000, China
[c] College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, China

ARTICLE INFO

Article history:
Available online 4 December 2013

ABSTRACT

Based on climate data from 108 meteorological stations in Southwestern China and the spatial and temporal distributions of extreme wet events during the 1960–2011 period, the summer monsoon and winter monsoon periods are analyzed by calculating the monthly and yearly surface humid indexes, as well as the frequency of extreme wet events. The abrupt change and the period in the extreme wet events data sets are characterized using a comprehensive time series analysis conducted with a moving *t*-test and Morlet wavelet. The results indicate that the regionally averaged frequency of extreme wet events has slightly increased by 0.001 times/y over the study period. The frequency of extreme wet events tended to decrease in the 1960s, 1970s, 1980s, and 2000s, whereas in the 1990s, the frequency of extreme wet events (0.47 times/y) exhibited an increasing trend that is significantly larger than the average level in the study area. During the summer monsoon period, extreme wet events exhibit a slight decreasing trend with fluctuations. Nevertheless, the extreme wet events demonstrate an increasing trend at the rate of 0.007 times/y during the winter monsoon period, especially in Sichuan province. The spatial distribution of extreme wet events exhibits a rough uniformity. Overall, the frequency of extreme wet events decreases from west to east, except for several discrepancies in southwestern Yunnan province and southeastern Guangxi province during certain periods. The increasing number of regions that experience extreme wet events is likewise primarily distributed in the higher altitude areas. The abrupt changes obtained in 2002 and 1988 occur during the summer monsoon and winter monsoon period, respectively. The annual frequency variation is a superposition of abrupt changes during the summer monsoon and winter monsoon periods. The major cycle of extreme wet events in these two periods changes according to 26 y and 12 y over the study period.

1. Introduction

Changes in climate extremes have attracted substantial attention all over the world in recent years because extreme climate events are becoming more significant and damaging to natural and human systems (Katz and Brown, 1992; Zhang and Wei, 2009). Numerous studies demonstrate that climate extremes could result in considerable economic losses (Changnon et al., 2000; Easterling et al., 2000; Houghton et al., 2001). For instance, the National Climate Center (1998) reported an economic loss of approximately $36 billion and more than 3000 deaths owing to the severe floods that occurred in the Yangtze River and Nenjiang–Songhuajiang valley in China in summer 1998. Lately, temperature and precipitation extremes have been widely discussed in various regions around the world, such as the United States (Vincent et al., 2005; Haylock et al., 2006), Asia (You et al., 2011; Li et al., 2012), and Africa (New et al., 2006; Tramblay et al., 2012). Changes in extreme events exhibit large regional variations because of the different effects of climate changes on geographically diverse regions (Wang et al., 2013a). The results have indicated that significant widespread changes in temperature extremes are associated with warming. Moreover, precipitation extremes are less spatially coherent at many weather stations. China is often affected by a variety of extreme weather and climate events due to its vast territory and the strong influence of the East Asian monsoon (Zhou et al., 2008). Cold waves frequently break out over northern China during the winter, whereas hot days and heat waves are commonly experienced in southern China during the summer (Xu et al., 2011). For China, precipitation increased by 2% and the frequency of precipitation events decreased by 10% from 1960 to 2000 (B.H. Liu et al., 2005; S.Q. Liu et al., 2005). Southwestern China (SC), which is controlled by the South Asia monsoon but likewise influenced by the East Asia monsoon, is a typical monsoonal climate region. Previous studies (Yan et al., 2004; You et al., 2008; Li

* Corresponding author.
E-mail addresses: lgcaonju@126.com (L. Cao), span@nju.edu.cn (S. Pan).

1040-6182/$ – see front matter © 2013 Elsevier Ltd and INQUA. All rights reserved.
http://dx.doi.org/10.1016/j.quaint.2013.11.014

et al., 2012; Wang et al., 2013b) primarily focused on the long-term trends of annual and seasonal changes in temperature, precipitation, temperature extremes, and precipitation extremes. However, the variability in spatial and temporal extreme wet events across the different regions over SC has not been extensively investigated.

Therefore, based on data regarding daily temperature, precipitation, sunshine duration, mean relative humidity, and daily mean wind speed from 108 meteorological observation stations distributed in the SC, the temporal and spatial variations in extreme wet events are analyzed in this paper. The paper mainly investigates climate change as exhibited by extreme wet events during the 1960–2011 period, and outlines the climate differences in the various regions of the SC. The analysis of variations in extreme wet events is expected to enhance the understanding of the causes of the temporal and spatial characteristics of extreme wet events in inter-annual, inter-decadal, summer monsoon, and winter monsoon periods under the global warming scenario.

2. Regional setting

2.1. Study area

The study area is located at 20° 24′–34° 19′ N, 97° 21′–112° 04′ E in China, covers an area of 1,371,100 km^2, and consists of a series of mountain ranges and rivers (Fig. 1). The topography declines from north to south and from west to east. The SC in this study includes five regions, namely, Sichuan province (SCP), Yunnan province (YNP), Guangxi province (GXP), Guizhou province (GZP), and Chongqing Municipality (CQC). Four geomorphic units exist: the Hengduan Mountains, consisting of a series of north–south-oriented mountain ranges with altitudes of 4000 m to 5000 m and major rivers; the Yunnan–Guizhou Plateau, with altitudes of 1800 m to 1900 m; the Sichuan basin, with an elevation range of 300 m–700 m; and the Chuanxi Plateau with altitudes of 4000 m to 4500 m (Zhao and Chen, 1999). The region is a typical monsoonal climate region and is controlled not only by the southwest monsoon from the Bengal Bay and Indian Ocean, but also by the southeast monsoon from the Pacific Ocean (Wang et al., 2013b). The region is likewise strongly influenced by the Tibetan Plateau monsoon and westerly circulation (Li and Su, 1996). The soil and biodiversity of the area are attributed to the monsoonal climate and the large vertical gradient.

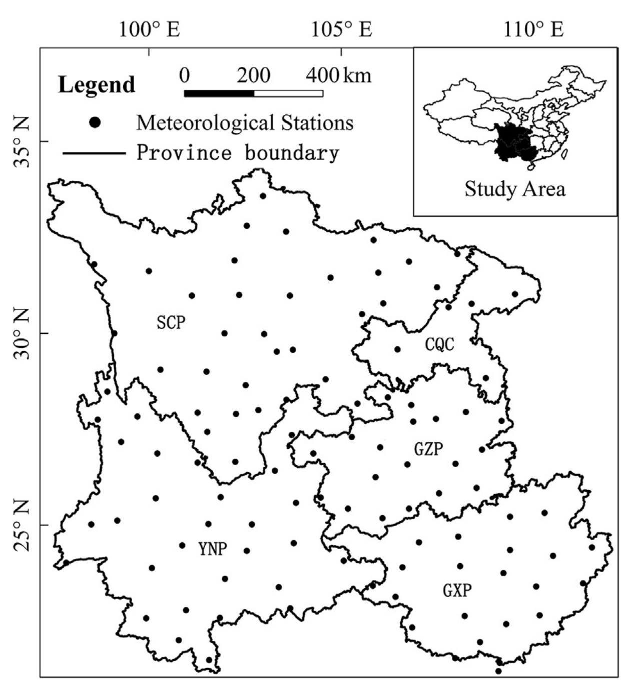

Fig. 1. Distribution of meteorological stations in the SC.

3. Material and methods

The data of daily temperature (mean, maximum, and minimum temperature), sunshine duration, daily mean relative humidity, and daily mean wind speed from 108 meteorological stations in the SC during the 1960–2011 period were obtained from the China Meteorological Administration (available at http://www.nmic.gov.cn). The Arctic Oscillation Index (AOI), Western North Pacific Monsoon Index (WNPMI), Southern Oscillation Index (SOI), 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).

An extreme wet event is defined as a standardized variable of monthly surface humid index (H) of more than or equal to 0.5 (Ma et al., 2003). Monthly surface humid indexes are calculated as:

$$H = \frac{P}{ET_0}, \tag{1}$$

where P is the monthly total precipitation, and ET_0 is the monthly potential evaporation. The standardized variable of the monthly humidity index can be expressed as follows.

$$D_{H_{ij}} = \frac{H_{ij} - \overline{H_i}}{\sigma_i}, \tag{2}$$

where $D_{H_{ij}}$ is the standardized variable of humidity index of the *i-th* month in *j-th* year; H_{ij} is the monthly surface humid index of the *i-th* month in *j-th* year; $\overline{H_i}$ is the mean surface humid index of the *i-th* month in the previous 52 years; and σ_i is the standard deviation of the humidity index of the *i-th* month. A modified Penman–Monteith model (Thornthwaite, 1951; Jensen et al., 1990; B.H. Liu et al., 2005; S.Q. Liu et al., 2005) (Revision in 1998 of the Food and Agriculture Organization of the United Nations) is adapted to calculate the ET_0 and ET_0 using the following equation:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\ U_2)}, \tag{3}$$

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 a height of 2 m (°C); Δ is the slope of the saturated water-vapor pressure curve (kPa/°C); U_2 is the wind speed at a height of 2 m (m/s); e_s is the saturation vapor pressure (kPa); and e_a is the actual vapor pressure (kPa).

The spatial distributions of extreme wet events in different periods are drawn using inverse distance weighted interpolation in ArcGIS 9 to analyze their spatial variation. The moving t-test technique is adopted to examine abrupt changes in extreme wet events. The Morlet wavelet has been widely used to reveal the periodic features of extreme wet events and detect periodic variations in different time scales. Therefore, variation periods are analyzed using the real part of the Morlet wavelet and wavelet variances. The summer monsoon period is ordinarily from May to October. Thus, the winter monsoon period includes the remaining months (from November to April) in a year. Correlation analysis was conducted to analyze the relationship between AOI, SOI,