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Variability of onset and retreat of the rainy season in mainland China and associations with atmospheric circulation and sea surface temperature

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ABSTRACT

Precipitation plays an important role in both environment and human society and is a significant factor in many scientific researches such as water resources, agriculture and climate impact studies. The onset and retreat of rainy season are useful features to understand the variability of precipitation under the influence of climate change. In this study, the characteristics of onset and retreat in mainland China are investigated. The multi-scale moving *t*-test was applied to determine rainy season and K-means cluster analysis was used to divide China into sub-regions to better investigate rainy season features. The possible linkage of changing characteristics of onset and retreat to climate factors were also explored. Results show that: (1) the onset started from middle March in the southeast of China to early June in the northwest and rainy season ended earliest in the northwest and southeast while the central China had the latest retreat; (2) Delayed onset and advanced retreat over time were observed in many parts of China, together with overall stable or increased rainy-season precipitation, would likely lead to higher probability of flooding; (3) The onset (retreat) was associated with the increased (decreased) number of cyclones in eastern China and anticyclone near the South China Sea. Delayed onset, and advanced retreat were likely related to cold and warm sea surface temperature (SST) in the conventional El Niño-Southern Oscillation (ENSO) regions, respectively. These results suggest that predictability of rainy season can be improved through the atmospheric circulation and SST, and help water resources management and agricultural planning.

1. Introduction

Precipitation is one of the most important variable responding to climate change, which has attracted urgent attention worldwide. Various aspects of precipitation have been investigated, such as seasonality and extremes (Ashok et al., 2009; Feng et al., 2011; Ratnam et al., 2011; Su et al., 2005; Taschetto and England, 2009; Tedeschi et al., 2013; Wang et al., 2013; Zhang et al., 2016). Unfortunately, characteristics of rainy season are less considered but are of vital significance to influence socio-economy. Reliable prediction of the onset of rainy season will reduce the risk of improper planting/sowing time, and assist on-time preparation of farmlands (Liebmann and Marengo, 2001; Marteau et al., 2011; Omotosho et al., 2000). A good knowledge of the retreat of rainy season is useful for the selection of crop varieties and has significant impact to ecosystem (Liebmann et al., 2007). Rainy-season precipitation will also provide certain predictability for flood occurrence and be helpful to flood monitoring. The variability of onset and retreat of rainy season and the total precipitation amount during rainy season are also direct indications for climate change and provide good scientific support to socio-economic development and climate change research.

For a large region, like China as a whole, rainy season varies substantially in both space and time. Previous researches have been limited to the analysis of the total precipitation during rainy season and ignored the onset and retreat. Many works were focused on regional scales (e.g., northwestern China, the Yangtze river basin and the coastal areas) (Chen et al., 2007; Gemmer

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et al., 2011; Su et al., 2005; Wang et al., 2013; Zhang et al., 2009), without the consideration of spatial heterogeneity, which is an important factor for the continental scale. Hence, the investigation of rainy season features variability, such as the onset and retreat, is necessary in China at the continental scale, in order to gain insight of rainfall characteristics.

There has not been a consensus agreement regarding to the determination of rainy season, due to irregularities in rainfall distribution in both space and time. In literature, the determination of rainy season can be based on rainfall data, temperature, deep convection, monsoon or combination of several indices (Cook and Heerdegen, 2001; Gan et al., 2004, 2005; Goswami and Xavier, 2005; Janowiak and Xie, 2003; Liebmann et al., 2007; Qian and Lee, 2000; Reason et al., 2005). The majority of research used threshold values of a given index (or indices) to determine the onset and retreat, which is somewhat subjective. Therefore, a data originated objective method, called the multi-scale moving *t*-test, was used in this study to detect rainy season. The onset and retreat defined by this method does not require an ad-hoc threshold as in most traditional definitions. There are also some other statistically based methods used to detect the rainy season, such as the optimal segmentation method of ordered sample, which can further divide the rainy season into several sub-periods. Nonetheless, this paper is just focused on the onset and retreat rather than the detailed types of rainy season. Therefore, the multi-scale moving *t*-test is better for this research over others based on literature.

In order to understand the driving factors or the causes of the change in rainy season, the correlations with monsoon and sea surface temperature (SST) are evaluated as they are the main factors influencing rainy season characteristics of China (Deng and Wang, 2002; Ding and Chan, 2005; Liu and Ding, 2008; Lu, 2005; Wang and LinHo, 2002; Wang et al., 2004, 2002; Yang and Lau, 2004; Zhao et al., 2010). From a meteorological perspective, the onset and retreat reflect the changes in an atmospheric heat source, whose addition or subtraction can alter large-scale and regional circulation (Figueroa et al., 1995; Lenters and Cook, 1997). SST is important for developing and maintaining atmospheric circulations (Fan et al., 2013). Previous research have found that rainy-season precipitation in China shows good relation to SST (e.g., Deng and Wang (2002)). As a consequence, it is meaningful to investigate signals of rainy season characteristics through monsoon and lag period SST.

In this paper, we will explore features of rainy season in mainland China at the continental scale. The homogeneous regions will be determined based on rainy season characteristics including the onset, retreat and rainy-season precipitation. The interannual variability of rainy season within individual homogeneous regions will be further investigated. We will also explore the possible correlation of the onset and retreat with monsoon and SST to understand the signals of variability of the onset and retreat. This study is of importance for helping us to provide a certain predictability to flooding occurrence and of great significance to understand hydrological cycle and water resource management under climate change in China.

The paper is organized as below. The study area and data are described in Section 2, followed by the methodology in Section 3. Results and discussion regarding interannual features of rainy season and their underlying correlation to monsoon and SST are presented in Section 4. The paper is concluded by a summary of the findings in Section 5.

2. Study area and data

China (Fig. 1), located in middle latitude in the Northern Hemisphere, has variable climate (i.e., the monsoon climate, the continental climate, the mountain plateau climate). China is prone to flood and drought occurrence in different regions and climate change is taken as one of the leading drivers for precipitation changes in the country.

Daily precipitation data from 1960 to 2015 at 536 meteorological stations in mainland China were used in this study. The data were obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html) and data quality were controlled based on national standards. Meteorological stations, which have at least 50 years complete data, were selected to describe rainy season characteristics. Locations of precipitation stations used in this study are presented in Fig. 1, with more observation stations in southeastern China as compared to northwestern regions. Therefore, we applied kriging interpolation method to induce a resolution of $0.2° \times 0.2°$.

NCEP-NCAR reanalysis data (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html) were used to explore relationship of rainy season and monsoon, where 850hpa vector winds data were selected (Kalnay et al., 1996). NOAA extended reconstructed SST data (https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v4) were used to consider correlation between rainy season and SST (Smith and Reynolds, 2004).

3. Methodology

The methods used in this paper includes the multi-scale moving *t*-test (Section 3.1) to determine the onsets and retreats of rainy season, K-means cluster analysis method (Section 3.2) to divide the mainland China into several obtain homogeneous sub-regions according to rainy season features (i.e., the onset, retreat and precipitation), trend analysis and Pettitt test for abrupt point analysis (Section 3.3) of rainy season characteristics in individual sub-regions, and Pearson coefficient correlations (Section 3.4) to explain the underlying relationship between rainy season characteristics and SST.

3.1. Determination of onset and retreat

The multi-scale moving *t*-test method was applied to determine the onset and retreat by detecting the most significant change between two subsamples before and after the abruption point with equal sample sizes n, where n is the length of the subsample, (n = 30, 31,..., 182 or 183). Here 182 or 183 corresponds to half the value of length of one year 365 or 366). Theoretically, the length of subsamples ranged from 1 to 182/183. Nonetheless, for the onset or retreat of rainy season, it is not reasonable if the length of the subsample is just one day or several days when the mutation point is prominent. Hence, the length of the subsample is limited from 30 to 182/183. The multi-scale abruption points can be detected as (Fraedrich et al., 1997):

$$t(n,i) = (\bar{x}_{i2} - \bar{x}_{i1})n^{1/2}(s_{i2}^2 + s_{i1}^2)^{-1/2}, \quad (1)$$

where $\bar{x}_{i1}$ and $\bar{x}_{i2}$ defined as:

$$\bar{x}_{i1} = \sum_{j=i-n}^{i-1} x_j/n; s_{i1}^2 = \sum_{j=i-n}^{i-1} (x_j - \bar{x}_{i1})^2/(n-1), \quad (2)$$

$$\bar{x}_{i2} = \sum_{j=i}^{i+n-1} x_j/n; s_{i2}^2 = \sum_{j=i}^{i+n-1} (x_j - \bar{x}_{i2})^2/(n-1), \quad (3)$$

and x_i is daily precipitation for Julian day i for one station within one year. $\bar{x}_{i1}$ and $\bar{x}_{i2}$ are averaged values of subsamples before and after the Julian day i, respectively.