Atmospheric Research 205 (2018) 80–92

Contents lists available at ScienceDirect

Atmospheric Research

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

A three-stage hybrid model for regionalization, trends and sensitivity analyses of temperature anomalies in China from 1966 to 2015

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ARTICLE INFO

Keywords:
Three-stage hybrid model
Regionalization
K-means clustering
Rotated empirical orthogonal function
Temperature
China

ABSTRACT

Temperature anomalies have received increasing attention due to their potentially severe impacts on ecosystems, economy and human health. To facilitate objective regionalization and examine regional temperature anomalies, a three-stage hybrid model with stages of regionalization, trends and sensitivity analyses was developed. Annual mean and extreme temperatures were analyzed using the daily data collected from 537 stations in China from 1966 to 2015, including the annual mean, minimum and maximum temperatures (Tm, TNm and TXm) as well as the extreme minimum and maximum temperatures (TNe and TXe). The results showed the following: (1) subregions with coherent temperature changes were identified using the rotated empirical orthogonal function analysis and K-means clustering algorithm. The numbers of subregions were 6, 7, 8, 9 and 8 for Tm, TNm, TXm, TNe and TXe, respectively. (2) Significant increases in temperature were observed in most regions of China from 1966 to 2015, although warming slowed down over the last decade. This warming primarily featured a remarkable increase in its minimum temperature. For Tm and TNm, 95% of the stations showed a significant upward trend at the 99% confidence level. TNe increased the fastest, at a rate of 0.56 °C/decade, whereas 21% of the stations in TXe showed a downward trend. (3) The mean temperatures (Tm, TNm and TXm) in the high-latitude regions increased more quickly than those in the low-latitude regions. The maximum temperature increased significantly at high elevations, whereas the minimum temperature increased greatly at middle-low elevations. The most pronounced warming occurred in eastern China in TNe and northwestern China in TXe, with mean elevations of 51 m and 2098 m, respectively. A cooling trend in TXe was observed at the northwestern end of China. The warming rate in TNe varied the most among the subregions (0.63 °C/decade).

1. Introduction

Changes in temperature are the customary parameters used to estimate recent climatic change (Robeson, 2004; Iqbal et al., 2016; Liuzzo et al., 2017). The global average temperature increased significantly after 1970, at a rate of 0.15 °C/decade. Additionally, this temperature is projected to rise by approximately 2.0–5.4 °C by 2100, depending on the region (IPCC, 2013). A general tendency towards more warm extremes and fewer cold extremes was found, while changes in temperature extremes showed apparent regional differences (Seneviratne et al., 2012; Gao et al., 2015). Temperature anomalies, especially temperature extremes, have received increasing attention due to their potentially severe impacts on ecosystems, economy and human health (Aguilar et al., 2009; Ma et al., 2011; Hijioka et al., 2014; Peng et al., 2017). The impacts of historical and potential future temperature anomalies are regionally and even locally specific (Perdinan and Winkler, 2015). In this context, it is critical to investigate temperature anomalies on a regional scale, which could improve our understanding of temperature anomalies and help us prepare for their consequences (Z.L. Wang et al., 2017).

Many regional studies have analyzed historical trends or projections of temperature anomalies. Some studies used geographic markers to define different regions (Carvalho et al., 2016). For example, Meehl et al. (2009) studied the maximum and minimum temperatures in the eastern and western USA as divided by the 100°W meridian. Deng et al. (2014) analyzed regional variations in temperature extremes in northwestern China among subregions including northern Xinjiang, southern Xinjiang and the Hexi Corridor. Dong et al. (2015) illuminated the relationship between altitude and the temperature trends in three subregions divided by their latitudes. Schoof and Robeson (2016) projected temperatures in six regions, namely, the Northwest, Southwest, Great Plains, Midwest, Southeast and Northeast parts of the United States. To improve the objectivity of the regionalization methodology described above, some methods, such as the rotated empirical orthogonal function (REOF) analysis and the K-means clustering algorithm, have been used to identify spatial patterns in temperature anomalies. For example,

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https://doi.org/10.1016/j.atmosres.2018.02.008
Received 7 August 2017; Received in revised form 13 February 2018; Accepted 14 February 2018
Available online 16 February 2018

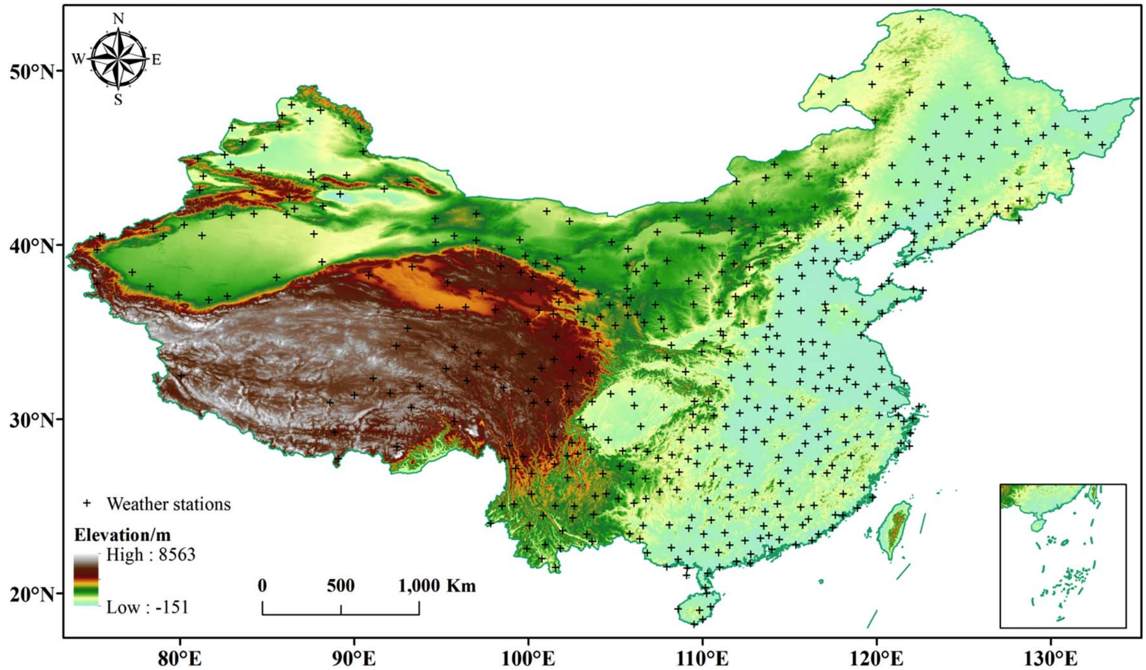

Fig. 1. Topography of China and distribution of 537 meteorological stations used in this study.

Wang et al. (2014) investigated the regional temperature variations in the Lancang River Basin using REOF analysis. Carvalho et al. (2016) divided the European domain into regions with similar temperature changes using the K-means clustering method. Generally, REOF analysis and K-means clustering algorithm are efficient for the regionalization of temperature anomalies with respect to different aspects. Specifically, REOF analysis can effectively reduce the data space, extract dominant spatial modes and identify sensitive centers based on the observed datasets (Horel, 1981; Jolliffe, 2002; Z.L. Wang et al., 2017). The K-means clustering algorithm is one of the simplest unsupervised learning algorithms that can partition data into K non-overlapping regions (MacQueen, 1967). However, regarding this regionalization, uncertainties remain due to the limitations of the methods mentioned above. For example, there are some overlapping areas or unlapped areas when using REOF analysis, and the partition results using K-means clustering are greatly influenced by the challenges in setting the cluster numbers and initial clustering centers objectively. Thus, these methods need to be applied comprehensively to reduce uncertainty and facilitate objectivity during regionalization.

China is one of the world's most vulnerable countries to climate change, and its increasing temperature trend is greater than the global trend and that of the Northern Hemisphere (Ding et al., 2007; Wang et al., 2010). Warm extremes have increased in frequency and magnitude, which has amplified local droughts, resulting in enormous economic losses and affecting more than half a billion people (Sun et al., 2014; Song et al., 2015). The spatial and temporal characteristics of temperature anomalies in China have been analyzed widely. For example, Du et al. (2014) revealed that northwestern China experienced a rapid temperature increase of 0.26 °C/decade during the past 50 years, which was higher than the national rate (0.14 °C/decade). Dong et al. (2015) investigated the regional characteristics of the temperature trends and the dependence of temperature changes on altitude in China from 1963 to 2012. Qiu et al. (2016) studied the changes in and the cause of the minimum air temperature in the Songnen Plain of China. Zhong et al. (2017) analyzed the dynamic changes in temperature extremes and their associations with atmospheric circulation patterns in the Songhua River Basin of China. Zhang et al. (2017) illuminated the spatiotemporal variability in the extreme temperature frequency and amplitude in China. However, most of the previous studies of temperature changes focused on either the mean temperature or a few extreme temperature indices and a relatively small number of meteorological stations (Deng et al., 2014; Ruml et al., 2017). A comprehensive analysis of changes in the mean and extreme temperatures for China is still lacking. Given the nation's vast territory, varied topography and diverse climates, the temperature anomalies in China have distinct regional features. Therefore, it is feasible and necessary to consider its regionalization before drawing conclusions about the trends and sensitivity of temperatures anomalies, which will be helpful for identifying sensitive areas that could be greatly affected by temperature anomalies and providing indicators of what caused regional temperature anomalies.

Therefore, a three-stage hybrid model, which consisted of stages of spatial regionalization, temporal trends and regional sensitivity analyses, was developed to analyze regional temperature anomalies. A climatologic data series was collected from 537 stations in China between 1966 and 2015 and analyzed in this study. The objectives of this study are as follows: (1) to identify subregions with coherent temperature changes derived from historical daily data; (2) to analyze temporal trends in temperature anomalies in subregions as well as in all of China; and (3) to discover sensitive areas for temperature indices and sensitive indices in specific subregions. The results of this study will contribute to our understanding of regional characteristics about temperature anomalies in China.

2. Data and methods

2.1. Study area

China covers a land area of 9.6 million square kilometers, with a wide latitudinal gradient, varied topography and diverse climates. The terrain of China is low-lying from west to east, with mountainous areas accounting for approximately 2/3 of its total area (Fig. 1). China contains five temperature zones, ranging from tropical to cold-temperate within its borders. Its northeastern region has a temperate monsoon climate as the dominant climate, and its northwestern region has a temperate continental climate. Its southern region features a subtropical monsoon climate while its southernmost corner is controlled by a tropical monsoon climate. Its Tibetan Plateau is dominated by an