Atmospheric Research 195 (2017) 20–30

Contents lists available at ScienceDirect

Atmospheric Research

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

# Long-term trend in ground-based air temperature and its responses to atmospheric circulation and anthropogenic activity in the Yangtze River Delta, China

Xia Peng[a,c], Qiannan She[b,c], Lingbo Long[b,c], Min Liu[b,c,*], Qian Xu[b], Jiaxin Zhang[b], Weining Xiang[c,d]

[a] School of Geography Sciences, East China Normal University, Shanghai 200241, PR China
[b] School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, PR China
[c] Shanghai Key Lab for Urban Ecological Processes and Eco-restoration, East China Normal University, Shanghai 200241, PR China
[d] Center for Ecological Wisdom and Practice Research, College of Architecture and Urban Planning, Tongji University, Shanghai 200092, PR China

ARTICLE INFO

*Keywords:*
Temperature change
Trend analysis
Atmospheric circulation
Anthropogenic activity
Yangtze River Delta

ABSTRACT

The Yangtze River Delta (YRD), including Shanghai City, Jiangsu and Zhejiang Provinces, is the largest metropolitan region in China. In the past decades, the region has experienced massive urbanization and detrimentally affected the environment in the region. Identifying the spatio-temporal variations of climate change and its influencing mechanism in the YRD is an important task for assessing their impacts on the local society and ecosystem. Based on long-term (1958–2014) observation data of meteorological stations, three temperature indices, i.e. extreme maximum temperature (TXx), extreme minimum temperature (TNn), and mean temperature (TMm), were selected and spatialized with climatological calculations and spatial techniques. Evolution and spatial heterogeneity of three temperature indices over YRD as well as their links to atmospheric circulation and anthropogenic activity were investigated. In the whole YRD, a statistically significant overall uptrend could be detected in three temperature indices with the Mann-Kendall (M-K) trend test method. The linear increasing trend for TMm was 0.31 °C/10 a, which was higher than the global average (0.12 °C/10 a during 1951–2012). For TXx and TNn, the increasing rates were 0.41 °C/10 a and 0.52 °C/10 a. Partial correlation analysis indicated that TMm was more related with TXx ($r_p$ = 0.68, $p$ < 0.001) than TNn ($r_p$ = 0.48, $p$ < 0.001). Furthermore, it was detected with M-K analysis at pixel scale that 62.17%, 96.75% and 97.05% of the areas in the YRD showed significant increasing trends for TXx, TNn and TMm, respectively. The increasing trend was more obvious in the southern mountainous areas than the northern plains areas. Further analysis indicated that the variation of TXx over YRD was mainly influenced by anthropogenic activities (e.g. economic development), while TNn was more affected by atmospheric circulations (e.g., the Eurasian zonal circulation index (EAZ) and the cold air activity index (CA)). For TMm, it was a result of comprehensive effects of both atmospheric circulations and anthropogenic activities. On the whole, the northern plain areas was mainly dominated by atmospheric circulations, while the southern mountain areas of YRD was more affected by anthropogenic activities. The findings of this study might help to build a better understanding of the mechanics of temperature variations, and assess the potentially influencing factors on temperature changes.

## 1. Introduction

The global and regional climate has been undergoing significant changes. According to the observed temperature records over the last several decades, the averaged surface air temperature at the global scale increased by 0.85 °C during 1880–2012 (IPCC, 2013). Climate change with the notable temperature variations has great impacts on natural processes (i.e. global climatic and hydrologic processes). It also directly impacts human activities, such as agriculture, energy consumption, and human health (Kadioğlu et al., 2001). The occurrence of extreme temperatures is one of the important aspects of long-term temperature trends. The results from Seneviratne et al. (2012) indicate an overall decrease in clod extremes and increase in warm extremes since 1950s. For instance, the famous summer heatwaves of 2003 and

* Corresponding author at: Shanghai Key Laboratory for Urban Ecological Processes and Eco-Restoration, School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, PR China.
*E-mail address:* mliu@re.ecnu.edu.cn (M. Liu).

http://dx.doi.org/10.1016/j.atmosres.2017.05.013
Received 17 January 2017; Accepted 21 May 2017
Available online 22 May 2017
0169-8095/ 

2007 had significant influences on ecosystems, economies and societies in Europe (Gönençgil and Deniz, 2016). Especially in 2003, a record-breaking heat wave resulted in an excess of over 70,000 heat-related deaths in Western Europe (Robine et al., 2008). As global warming continues, there is an increasing evidence that the extreme heat events are becoming more frequent, more intense and longer lasting (Gao et al., 2015). The extreme weather and climate events also occurred over China in 2003, 2006, 2007, and 2013 (Chen and Fan, 2007; Peng, 2014). Because of tremendous influences of temperature changes on ecological environment, economic and social development worldwide, particularly the temperature extremes, the changing properties of temperature have aroused heated discussions and became an important global issue among international communities and academic researchers in recent few decades (Arnell, 1999; Jones, 2005; Seneviratne et al., 2012).

A large amount of studies have concentrated on the topic of trends in temperature variations over regional or national scales (Jones, 2005; Ruml et al., 2017) and the global scale (Alexander et al., 2006; Donat et al., 2013a) in the past few years. The study objects shifted from average temperatures (Papakostas et al., 2007) to extreme temperatures (Ballester et al., 2010), mostly based on the temperature indices derived by the Expert Team on Climate Change Detection and Indices (ETCCD) (Karl et al., 1999), World Meteorological Organization Commission for Climatology (CCl), and World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR). According to Allen et al. (2015), most people throughout the world have been experiencing the relatively small range of projected temperatures (1.5 to 4 °C) on the daily, weekly, and seasonally scale, and many areas of the world experience far greater shorter term variability. However, the changing properties of temperature extremes are different from place to place, and large regional differences in the temperature trend patterns are existed on different scales (Bonsal et al., 2001). For example, the global conclusions performed by Alexander et al. (2006) are not the representative of Europe according to Moberg et al. (2006). Reversely, Moberg et al. (2006) and Jones (2005) both find a warming in the daily minimum temperature and the daily maximum temperature. Temperature variations are influenced by many complex factors (Jansen et al., 2007). There are substantial temperature variations caused by atmospheric circulations and sea surface temperature, such as the Arctic Oscillation (AO), the Western Pacific subtropical high (WPSH) and El Nino Southern Oscillation (ENSO) (Yu and Xie, 2013; Iqbal et al., 2016; Sun et al., 2016). In addition, the regional variations of temperature trends are also driven by land use/land cover (LUCC) changes (Yang et al., 2009), population growth (Balling et al., 2016), and urbanization (Stone et al., 2010). Although there are many studies available addressing the temperature variations, the conclusions about regional temperature variability in different study areas have not only common consensus, but also differences due to their diverse climatic systems and human activities.

The Yangtze River Delta (YRD), one of the largest metropolitan region in China has experienced an unprecedented process of rapid and massive urbanization, which dramatically altered the landscape with high population density (Xie et al., 2010). Some studies have been conducted in or near the YRD on the changes of temperature. For example, Zhang et al. (2010) tried to build the model of the impact of urbanization on the local and regional climate in the YRD. Du et al. (2007) and Xie et al. (2010) analyzed the influence of urbanization on regional climatic trend of temperature in the YRD based on non-radiance-calibrated DMSP/OLS nighttime light imagery. Wang et al. (2014) studied the temporal and spatial variation of the 16 extreme temperature indices in the Yangtze River Basin during the nearly 50 years. Sang (2012) investigated the variability of daily temperature and the urbanization impacts in the YRD during 1958–2007. Shi et al. (2009) and Jiang and Sun (2012) took into consideration urbanization, air-sea interaction and atmospheric circulations in cause analysis. However, most of the present studies on the temperature variations in the YRD were based on the data observed over several meteorological stations. Limited by the number and location of meteorological stations, it is difficult to accurately analyze the spatial variability of temperature. Moreover, most researches mainly considered the influence of anthropogenic signals on temperature variations, while there was a lack of study taking account of the comprehensive effects of atmospheric circulations and human activities.

In this investigation, this paper aims to investigate the spatio-temporal variation characteristics of temperature at the regional scale and reveal their responses to natural atmospheric circulation and human activities in the YRD region. Based on the long-term ground observations of meteorological stations, we calculated and produced three regional temperature indices (i.e. extreme maximum, minimum and mean temperature) from 1958 to 2014, using climatological calculation methods and specialization techniques. The temporal dynamic trends and spatial evolution patterns of three temperature indices at the pixel scale throughout the YRD in recent 60 years were analyzed with Mann-Kendall trend analysis. Moreover, the potential roles of atmospheric circulations and local anthropogenic activities on the long-term trends of temperature variations were also evaluated.

## 2. Study area

The Yangtze River Delta (YRD) (116°29′-123°45′E, 27°14′-35°33′N) is situated in eastern coastal areas of China and includes Jiangsu province, Zhejiang province, and Shanghai municipality, with 25 cities in total (Fig. 1).It covers an area of 210,700 $km^2$, which represents 2.1% of the national land area (China Statistical Yearbook, 2015). The YRD is significantly influenced by the humid subtropical monsoon climate, with four distinct seasons, plenty of sunshine and good rainfall. The northern areas of the YRD are plain, while the rest of the territory has a complex topography comprised of hills, as well as low and medium-high mountains. In addition, the YRD is one of the most developed economic belts in China and still keeps a fast-growth speed presently. The region's population has increased from 75.73 million in 1958 to 103.86 million in 2014, with urbanization ratio (the proportion of urban population to total population) increased from 23.35% to 75.95% during the same period. In 2014, its gross domestic product (GDP) reached CNY 12.88 trillion (USD 1866.6 billion), creating 20.2% the country's gross domestic product (GDP) (China Statistical Yearbook, 2015). Its complex natural environment and rapid urbanization dramatically altered the landscape and detrimentally affected the climate characteristics in the region (Shi et al., 2009; Xie et al., 2010).

## 3. Data and methods

### 3.1. Meteorological data and spatialization method

Meteorological and elevation data were used in this study to calculate and spatialize temperature variables in the YRD. Meteorological data was supplied by the National Climate Center of the China Meteorological Administration (CMA) with 56 meteorological stations over the YRD (Fig. 1, detailed information was provided in Appendix 1). Before publishing the meteorological data, CMA has strictly controlled the data quality, including checking for the mis-written codes and doubtful records, and homogeneity-adjusted. There are few missing values for CMA stations during their observation years. Climate change is manifested not only by changes in average conditions, but also by changes in the occurrence of climate extremes (IPCC, 2013). Therefore, three temperature indices (Table 1), i.e. extreme maximum temperature (TXx), extreme minimum temperature (TNn), and mean temperature (TMm), referred to climate indices of ETCCDI (Karl et al., 1999) and the research of Zhang et al. (2011), were used to describe the temperature variations in the YRD during 1958–2014. Digital Elevation Model (DEM) data with a spatial resolution of 1 km × 1 km, provided by Institute of the Geographic Sciences and