Spatiotemporal evolution and non-stationary characteristics of surface temperature in China from 1959 to 2018

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Abstract

Since the 20th century, global warming has become a major climate change problem, which significantly affects the sustainable development of the world, China holds the unenviable position of greatly contributing to global warming. Based on the data of 1728 national surface meteorological stations in China from 1959 to 2018, this paper explores the temporal and spatial evolution and non-stationary characteristics of surface temperature in 612 effective grids, and conducts an empirical analysis of Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta Urban Agglomeration (BTHUA, YRDUA, PRDUA). Several key conclusions are reached: (1) The annual average surface temperature rose at wave type, with an increase of 0.995 and a warming rate of 0.166 per decade in China from 1959 to 2018-global warming has become increasingly serious in the last 30 years, the areas of highest warming are mainly concentrated in North, East, Northwest and Northeast China. (2) The surface air temperature has strong auto-correlation, the auto-correlation coefficients of 49.35%-96.08% grids have significant positive correlation at the level of 0.05 in 13 lag periods. (3) The auto-correlation coefficient of 96.08% grids annual average temperature lag 1 period exceeds the critical value of the significance level, the auto-correlation coefficient showed a gradual decreasing trend with increasing lag period, indicating the temperature data had non-stationary characteristics. (4) The surface temperature showed a wave-like upward trend in BTHUA, YRDUA and PRDUA from 1959 to 2018, with temperature increases of 1.124, 1.029and 1.048 respectively, the warming rates were 0.187, 0.171 and 0.175 per decade respectively.

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Abstract

Since the 20th century, global warming has become a major climate change problem, which significantly affects the sustainable development of the world, China holds the unenviable position of greatly contributing to global warming. Based on the data of 1728 national surface meteorological stations in China from 1959 to 2018, this paper explores the temporal and spatial evolution and non-stationary characteristics of surface temperature in 612 effective grids, and conducts an empirical analysis of Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta Urban Agglomeration (BTHUA, YRDUA, PRDUA). Several key conclusions are reached: (1) The annual average surface temperature rose at wave type, with an increase of 0.995 ℃ and a warming rate of 0.166 ℃ per decade in China from 1959 to 2018—global warming has become increasingly serious in the last 30 years, the areas of highest warming are mainly concentrated in North, East, Northwest and Northeast China. (2) The surface air temperature has strong auto-correlation, the auto-correlation coefficients of 49.35%–96.08% grids have significant positive correlation at the level of 0.05 in 13 lag periods. (3) The auto-correlation coefficient of 96.08% grids annual average temperature lag 1 period exceeds the critical value of the significance level, the auto-correlation coefficient showed a gradual decreasing trend with increasing lag period, indicating the temperature data had non-stationary characteristics. (4) The surface temperature showed a wave-like upward trend in BTHUA, YRDUA and PRDUA from 1959 to 2018, with temperature increases of 1.124℃, 1.029℃ and 1.048℃ respectively, the warming rates were 0.187℃, 0.171℃ and 0.175℃ per decade respectively.

1 Introduction

Climate change affects the global natural-economic-social complex ecosystem and has created great concern in academic circles, political circles, business circles, and in the general public all over the world (IPCC, 2001). Temperature increase is an important manifestation of climate change, which has caused a series of major ecological and environmental problems, such as sea-level rise, cryosphere retreat, ecological damage (Grimm et al., 2008), and biodiversity reduction (Williams et al., 2013). The fifth assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013) shows that the rising rate of global average surface temperature increase (0.12 ℃ per decade) from 1951 to 2012 is twice that since 1880 (Qin et al, 2014). The record breaking phenomenon of global high temperature is increasing, and global climate will continue to warm in the future (King, 2017). Major research projects (or agreements), such as the IPCC (Forster et al., 2006), International Geosphere Biosphere Program (Zhou et al., 1999), Future Earth Resilience Alliance (Holling et al., 2001), Paris Climate Change Agreement, and China's Special Action on Climate Change, all focus on global warming. China's surface temperature has experienced a rapid fluctuation rising process in recent decades, faster than the global average (Gao et al., 2012), and China's surface temperature exhibits significant regional heterogeneity due to topography and monsoons (Wang et al., 2014). Which has been highly valued by the Chinese government, academics, and other parties. China's surface temperature research has become a hot topic in meteorology, geography, ecology, environmental science, and economics (Ge et al., 2016).

At present, there are more and more research achievements on the topic of surface temperature based on multidisciplinary theory, complex technical model and inter organizational cooperation. From the perspective of research topics, it mainly includes the characteristics of surface temperature stability (Xu et al., 2013), evolution trends (Zhao et al., 2014), scientific simulation (Chen et al., 2014), accurate prediction (Zhang et al., 2012), climate warming control modes (Bulkeley, 2010) and response practice (Wamsler et al., 2013), the impact of urbanization (Wang et al., 2015), land use types (Li et al., 2018) and wind power plants (Roy & Traiteur, 2010) on temperature, and the impact of climate warming on fishery economy (Sumaila et al., 2011), air quality (Jacob & Winner, 2009) and metabolism (Dillon et al., 2010). From the perspective of research scale, which mainly includes countries (Du et al., 2018), urban agglomerations (Lin et al., 2016), provinces (Wang et al., 2013), and cities (Cao et al., 2015). From the point of view of research methods, which mainly includes point-by-point regions (Feng et al., 2012), ensemble empirical mode decomposition (Wu & Qian, 2015), geographically weighted regions (Su et al., 2012), quantitative matching algorithms (Vincent et al., 2012) and discrete wavelet transforms (Nalley et al., 2013). China's research areas of great interest include BTHUA (Wang et al., 2013), YRDUA (Zhong et al., 2017), PRDUA (Zhang et al., 2016) and the Tibetan Plateau (Guo et al., 2012).

With regard to global warming, Papalexiu et al (2018) found that the warming rate was 0.19 ℃ per decade from 1965 to 2015 and 0.25 ℃ per decade from 1985 to 2015 based on the highest-temperature data of about 9000 stations across the world. With regard to China's climate warming, Wen et al (2019) found that the annual average temperature increased by 1.248℃ and the warming trend was obvious in Northeast China, based on the data of 763 meteorological stations in China from 1961 to 2015. Han et al (2013) found that the fastest warming rate (0.30℃ per decade) was in Northeast China and the slowest (0.13℃ per decade) in South China, based on the daily temperature observation data of 623 stations in China from 1951 to 2010. Zhang et al (Zhang & Ji, 2019) calculated a warming rate of 0.36 ℃ per decade using the data of 24 meteorological stations in Liaoning Province from 1960 to 2016. Using long-term historical temperature data, Zhu et al (Zhu et al., 2017) constructed the Providing Regional Climates for Impacts Studies (PRECIS) model and predicted that the annual average temperature will rise by 6 ℃ in China by the end of the 21st century. The abundance of research literature on temperature at home and abroad provides a scientific basis for temperature control and carbon emission reduction in the world. The existing literature is mainly focused on regional analysis; less uses the data from 1728 effective meteorological stations in China as basic data and a 10 × 10 grid as the research unit, mainly on a short time scale; less discuss law of the long time scale in China in 60 years and analyze the characteristics of temperature heterogeneity between the two 30 years in the study period.

The average temperature difference value is the difference between the temperature at a certain point in time and the annual mean temperature for the period that contains this point in time; which is often used to reflect the temperature evolution law on a long time scale (Chelani & Rao, 2013). Auto-correlation refers to the correlation of elements at two different time points in a long time series, which is the ratio of auto-correlation to variance (Miftahuddin & Ilhamsyah, 2018). Usually, the level of auto-correlation is judged based on the significance level of the correlation coefficient of the temperature lag period (Sun et al., 2014). Stationary means that the curve obtained from the time series of research elements can continue the existing shape in a period of time in the future (Koutsoyiannis & Montanari, 2015). If the probability function of all time changes is constant with time change, a column of time series data comprises strong stationary data (Roberth & Davids, 2009); if only the mean and variance are time independent constants, then the time series data are weak stationary data (Murphy & Ellis, 2014). If the auto-correlation coefficient of lag phase 1 exceeds the critical value of the significance level of 0.05, the auto-correlation coefficient has a significant downward trend as a function of lag period; if the data show a significant upward or downward trend over time, then the data are non-stationary data. Non-stationary temperature data hinder data prediction (Montanari & Koutsoyiannis, 2014). On the one hand, it is very important to find a suitable way to scientifically formulate climate change response planning (Milly et al., 2015), and on the other hand, non-stationary data can be converted to stationary data through technical processing in some cases (Benoit et al., 2018). Therefore, with respect to global warming, there is significant research value in analyzing the temporal and spatial evolution characteristics of the mean surface temperature in China and whether these characteristics are stationary on a long time scale.

Based on the above, this paper rasterizes map data of China with a spatial resolution of 1°× 1°, selects 1959–2018 as the research period, and calculates the average difference value of the annual average surface temperature in China from 1959 to 2018 using an average temperature difference model, to analyze it's temporal and spatial evolution trends. An auto-regressive model is used to analyze the non-stationary of the auto-correlation coefficient of China's surface annual average temperature in 1959–2018, the non-stationary characteristics of mean surface air temperature in 1959-1988 and 1989-2018 by confidence interval method, and three urban agglomerations (BTHUA, YRDUA, PRDUA) are analyzed in China. Generally, there are three innovations in this paper. Firstly, the accuracy of the research results was improved by selecting 1728 temperature stations across China from 1959 to 2018 and dividing China into 612 effective spatial grids of 1 °× 1 °. Secondly, the paper divided 1959–2018 into two 30-year time periods to compare the heterogeneity of temperature change in the two time periods. Thirdly, the non-stationary characteristics of climate change in China from 1959 to 2018 were analyzed using the change characteristics of the auto-correlation coefficient and the heterogeneity of the two 30-year mean values, providing a scientific basis for future temperature prediction.

2 Data and methods

2.1 Research data

Data from 2419 national surface meteorological station stations were collected from the China Meteorological Data Center (http:// data.cma.cn/). This study carried on the quality control of statistical mean temperature in China with a period of 1959–2018. (1) Data from stations that had over 4 hours of missing data for a given day of interest were excluded when calculating the daily mean temperature. (2) Data from stations that had over 4 days of missing data for a given month of interest were excluded when calculating the monthly mean temperature. (3) Data from stations that had over a month of missing data for a given year of interest were excluded when calculating the yearly mean temperature. (4) Stations with over a year of cumulative missing data were eliminated from our analyses. To minimize statistical deviation due to uneven spatial distribution, China's map data were rasterized with a spatial resolution of 1°×1° into 1135 grid cells. Compared with the interpolation method based on station data, the gridding method obtains more accurate element values of boundaries between the data and the non-data area. There are 612 valid cells, so that some cells have no station (Fig. 1). For the grid cell containing only one station, the surface air temperature value comprises the data for this station; for the grid cell containing more than two stations, the surface air temperature value is the temperature mean of these stations.

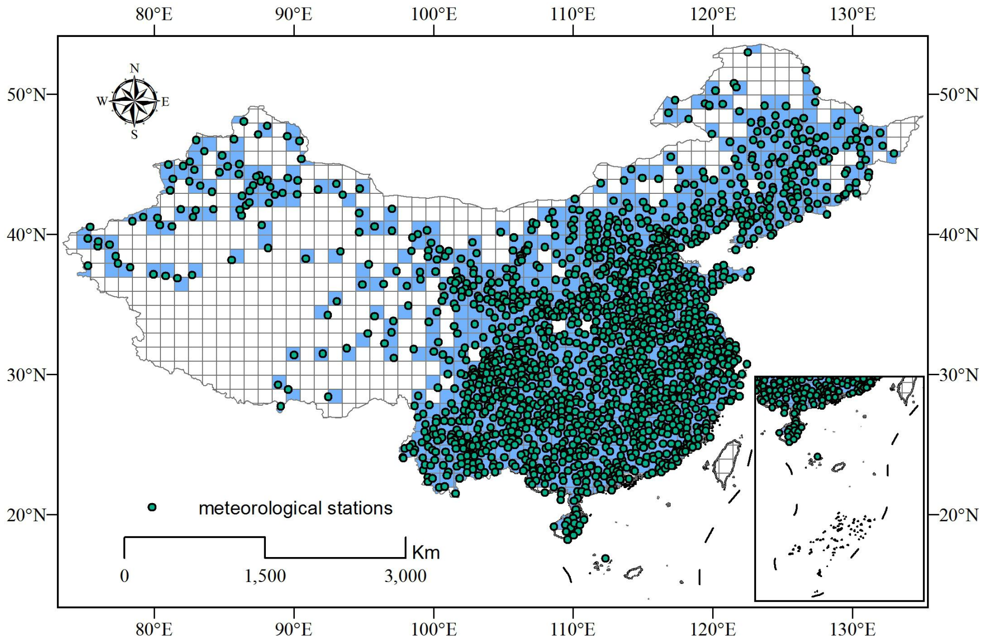

Figure 1. Meteorological station spatial distribution of valid temperature data and selected network units from 1959 to 2018. Each network unit contains at least one weather station (with 1 °× 1 ° spatial resolution).

2.2 Research methodology

2.2.1 Average temperature difference model

The average difference value is the difference between one of a series values and their mean classified as a positive average difference and a negative average difference (Wei, 1999). In this study, the average temperature difference model was used to measure differences between the data of China's annual mean surface temperature in 1959–2018 and the mean temperature of the 60-year period. The average difference function is given by

$$x'_{ij} = x_{ij} - \bar{x}_i = x_{ij} - \sum_{j=1}^{n=60} x_{ij} \Big/ 60 \tag{1}$$

where, x'_{ij} is the average temperature difference of year j in cell i (1959 is the first year), which is the difference value between annual average temperature x_{ij} of year j in cell i and the mean for a period of 1959–2018 in cell i.

2.2.2 Auto-regressive model

The auto-regressive model (AR) is one of three basic models for time series analysis and prediction and was first proposed by statisticians E. Slutsky and G. U. Yule. This model is usually applied to explore the stationary characteristics of geographic or climatic features (Wang & Sun, 2020). Our auto-regressive model of surface temperature is given by

$$y_t = c + \phi_1 y_{t-1} + \phi_2 y_{t-2} + \ldots + \phi_p y_{t-p} + e_t \tag{2}$$

where, p is the lag period, y_t denotes the surface temperature at time t in a time series, namely the dependent variable, $y_{t-1}, y_{t-2}, \ldots, y_{t-p}$ is the lag series of y_t, e_t is random error, and $c, \phi_1, \phi_2, \ldots \phi_p$ are the autoregressive parameters to be estimated. The model is calculated using the SPSS software.

3 Results

3.1 Temporal and spatial evolution characteristics of surface annual average temperature difference in China from 1959 to 2018

Using the average air temperature difference model, this paper calculates the average difference value of the annual average surface air temperature of each grid unit in China from 1959 to 2018 and draws their temporal and spatial distribution patterns (Figs. 2 and 3).

3.1.1 Time series law

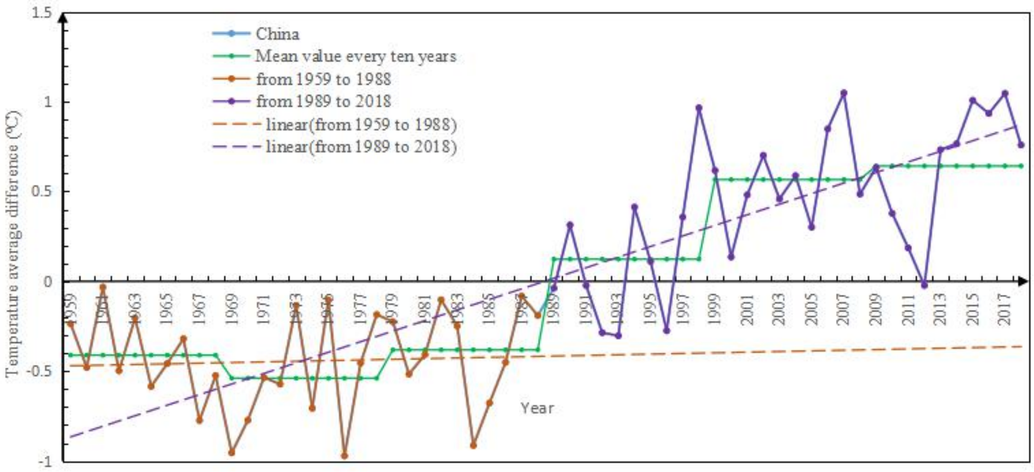

Figure 2. Temporal sequence law of annual average temperature in China from 1959 to 2018.

The annual average surface temperature showed a significant upward trend with obvious fluctuation characteristics in China from 1959 to 2018, the annual average surface temperature increased by 0.995℃, and the warming rate was 0.166℃ per decade in during the study period (Fig. 2). The average difference values of average annual surface temperature were negative from 1959 to 1988, and those values were mostly positive from 1989 to 2018; this indicated that the temperatures in 1989–2018 were significantly higher than those in 1959–1988, and that climate warming has become increasingly pronounced in the recent 30 years(1989-2018). From the average values of every decade, the annual average surface temperature initially has a decreasing trend and then an increasing trend, and the temperature rising rate increases significantly during recent 30 years. Using the average surface air temperature difference value, the linear trend lines of air temperature change in 1959–1988 and 1989–2018 are acquired. The slope of the linear trend line (0.029) for 1989–2018 is significantly higher than that (0.002) for 1959–1988, indicating that the temperature rise rate in 1989–2018 is faster than that in 1959–1988, and that the climate warming rate continues to increase during the past 30 years. The Paris Agreement requires that the global temperature rise should be controlled to within 1.5℃ above the pre-industrial level in this century; however, it is difficult to control the temperature rise, so it is necessary to strictly control carbon dioxide emissions.

3.1.2 Spatial distribution pattern

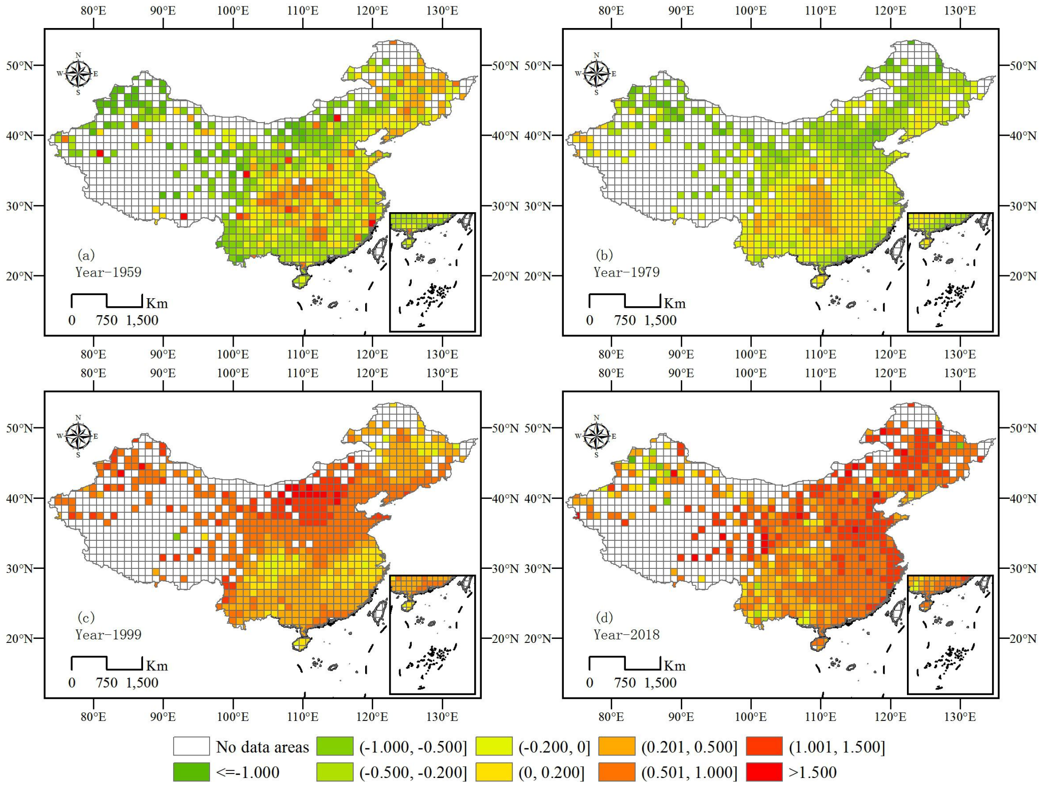

Figure 3. Spatial distribution pattern of the average temperature differencevalues of the annual average temperature in China from 1959 to 2018.

The grid surface temperature shows obvious fluctuation characteristics in China in 1959–2018, and the warming effect is significant in 1999–2018, especially in North China, East China, Northwest China, and Northeast China (Fig. 3). Compared with 1959, in 1979, the grid number of surface temperature rise and fall all accounted for 50% in, among them, 14.22% grid air temperature decreased by more than 0.5 ℃, mainly distributed in Northeast, North and East China, and 12.91% grid air temperature increased by more than 0.5 ℃, mainly distributed in central, southwest and Northwest China (Figs. 3a and 3b). 86.27% grid surface temperature rose in 1999 compared with 1959, of which 61.60% increased by more than 0.5℃, 34.15% increased by more than 1.0℃, 16.99% increased by more than 1.5℃, and 7.03% increased by more than 2.0℃. Areas with warming above 1.0℃ were mainly concentrated in North China and Northwest China (Figs. 3a and 3c). 92.49% grid surface temperature rose in 2018 compared with 1959, of which 74.84% increased by more than 0.5℃, 42.65% increased by more than 1.0℃, 16.67% increased by more than 1.5℃, and 6.86% increased by more than 2.0℃. Areas with warming above 1.0℃ were mainly concentrated in North China, East China, Northeast China, and Northwest China (Figs. 3a and 3d).

3.2 Non-stationary characteristics of surface annual average temperature in China from 1959 to 2018

3.2.1 Non-stationary characteristics of auto-correlation coefficient in different lag periods

According to the principle of auto-correlation analysis, this paper uses SPSS software to calculate the auto-correlation coefficient of the annual average temperature of each grid in China from 1959 to 2018. In statistics, the significance level is usually determined as 0.05; therefore, the significance interval of the auto-correlation coefficient [$= \pm\frac{1.96}{\sqrt{60}}$] calculated in this paper is ± 0.253. An auto-correlation coefficient > 0.253 indicates a significant positive correlation at the level of 0.05, and an auto-correlation coefficient < -0.253 indicates a significant negative correlation at the level of 0.05; an auto-correlation coefficient located in the interval [-0.253, 0.253] indicates no correlation at the level of 0.05. Figure 4 shows the proportions of the three types of grids in different lag periods, and Figure 5 shows the spatial distribution patterns of the three types of grids in different lag periods.

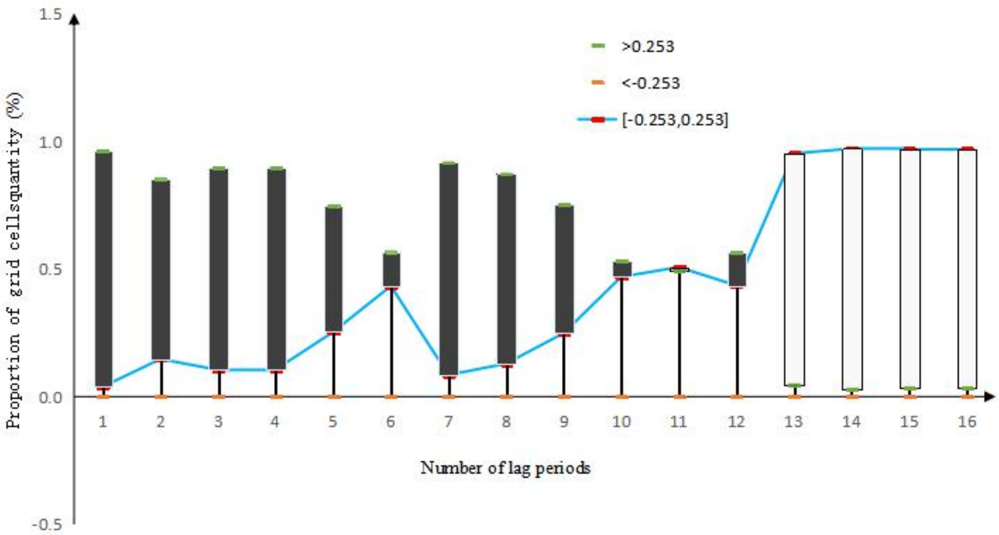

Figure 4. Share price chart of average temperature auto-correlation coefficient in China from 1959 to 2018.

China’s surface temperature has a strong auto-correlation from 1959 to 2018. The grids with an auto-correlation coefficient of 49.35%–96.08% have a significant positive correlation at the 0.05 level in the 13 lag periods (Fig. 4). After 13 lag periods, the grid with an auto-correlation coefficient of more than 95% is not significant at the 0.05 level. At the same time, there is no negative correlation in the auto-correlation coefficient of the air temperature in the 16 lag periods in China from 1959 to 2018. In theory, the temperature in any year of the study period is significantly affected by the temperature in the previous 13 years, and the relevant prevention and control measures of climate warming should be strictly implemented to avoid the impact of a sudden temperature increase in a short time during long-term climate warming.

By comparing the auto-correlation coefficient of the grid surface air temperature in different lag periods, the auto-correlation coefficients of 96.08% grid annual average temperature in the lag 1 period exceed the critical value (0.253) of a 0.05 significance level, and the auto-correlation coefficient shows a slow downward trend (Figs. 4 and 5). Therefore, China’s annual average surface air temperature shows non-stationary characteristics from 1959 to 2018. In terms of space, the auto-correlation coefficients have a significant positive correlation at the level of 0.05 in East China, South China, North China, East Central China, and North China, while the auto-correlation coefficients of other regions exhibit a downward trend in volatility. Significant positive correlation regions are mainly distributed in the eastern and southern coastal areas of China, which are the core areas of China’s economic development. The rapid development of industrialization

(Kothawale et al., 2016) and urbanization (Zhou et al., 2016; Chen et al., 2017) accelerated the rise of regional temperature, to a certain extent, but also generated a long-term auto-correlation effect with respect to regional temperature.

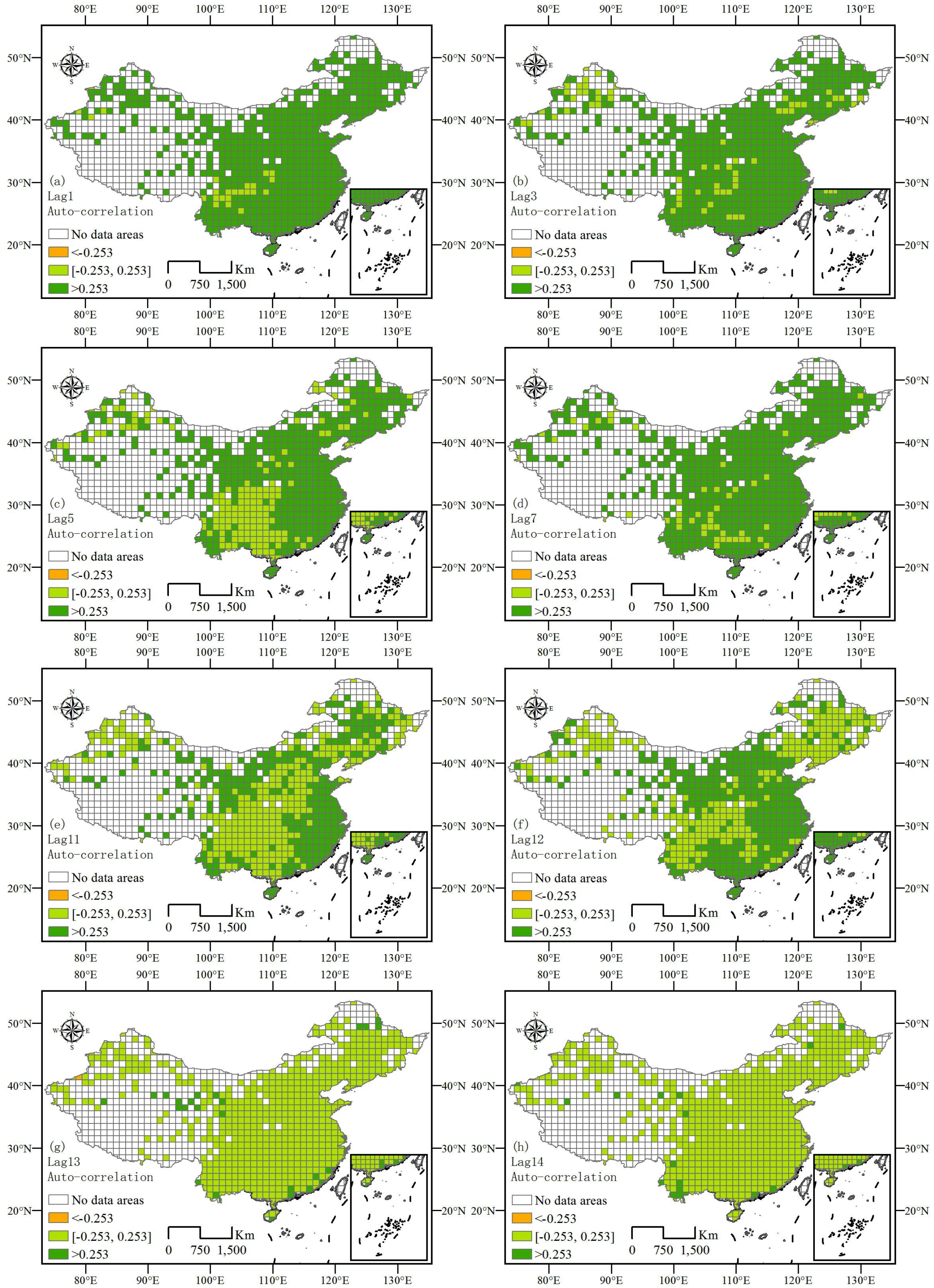

Figure 5. Annual average temperature stability analysis in China from 1959 to 2018.

3.2.2 Non-stationary characteristics of annual average value in different time periods

Thirty years is a widely accepted scale with regard to climate events in academia (Arguez et al., 2011; Sun et al., 2018). Therefore, this paper divides 1959–2018 into two periods: 1959–1988 and 1989–2018. In order to analyze the average stationary characteristics of the annual average temperature, this section judges whether the mean value of the China grid temperature from 1959–1988 and 1989–2018 is within the 90% confidence interval of temperature from 1959 to 2018. Because there are only two grids in the 95% confidence interval, the comparability is low, it is not selected.

On the whole, there are significant differences in the temperatures between 1959–1989 and 1989–2018 (Fig. 6). The annual average temperature in 1989–2018 is significantly higher than that in 1959-1988, which verifies the non-stationary characteristics of China's surface annual average temperature from 1959 to 2018. In the 612 effective grids, the 30-year mean temperature (in 1959–1988 or 1989–2018) of the 1.96% grids (12 grids in total) is within a 90% confidence interval of 60 years (1959–2018) mean temperature, which mainly distributed in Sichuan, Yunnan, Chongqing, and Hubei. The 98.04% grid is beyond the 90% confidence interval, and the annual average temperature of 600 grids in 1989–2018 is significantly higher than that in 1959–1988—the problem of climate warming in China is becoming increasingly serious.

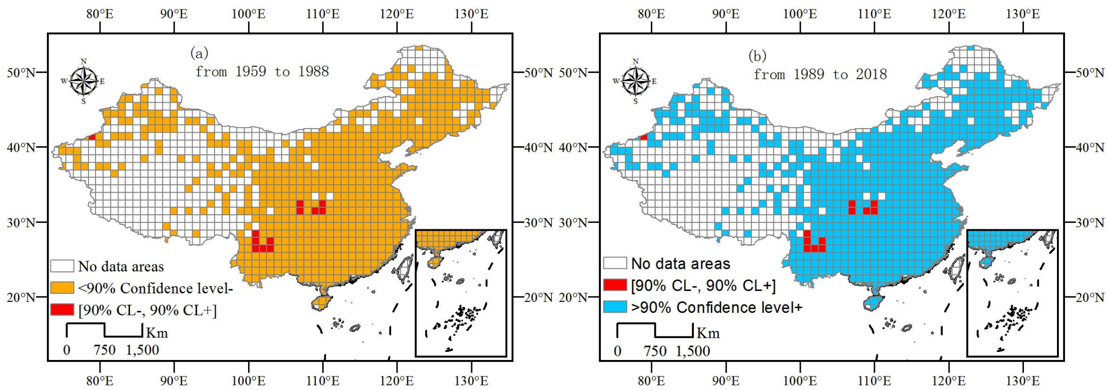

Figure 6. Spatial distribution pattern of temperature correlation test in China grid during 1959–1988 and 1989–2018.

3.3 Case study of annual average temperature in three urban agglomerations from 1959 to 2018

3.3.1 Comparative analysis of time series laws

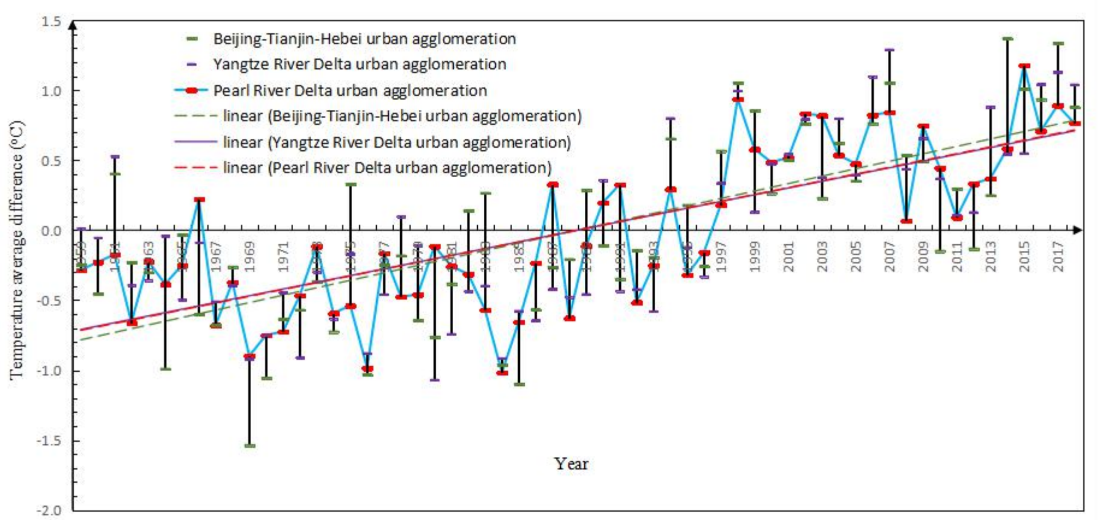

Figure 7. Line chart of annual average temperature average difference value in BTHUA, YRDUA, PRDUA from 1959 to 2018.

The annual average surface temperature showed an overall upward trend with strong inter-annual variability in BTHUA, YRDUA, and PRDUA from 1959 to 2018. During the study period, the annual average surface temperature increased by 1.124℃, 1.029℃, and 1.048℃ in the three urban agglomerations, respectively, with warming rates of 0.187℃, 0.171℃, and 0.175℃ per decade (Fig.7). The order of the annual average temperature rise of the three urban agglomerations is as follows: BTHUA > PRDUA > YRDUA. Using the surface air temperature average difference value, the linear trend lines of the three urban agglomerations from 1959 to 2018 were obtained. The slope of the linear trend line of the three urban agglomerations rank as follows: BTHUA > PRDUA > YRDUA. The results show that the warming effect in BTHUA from 1959 to 2018 is significantly higher than that of PRDUA and YRDUA, the phenomenon is related to the geographical location, natural environment, and the rapid development of heavy industry.

3.3.2 Comparative analysis of auto-correlation coefficient

The average annual surface temperatures were 11.55 ℃, 16.16 ℃, and 21.90 ℃ in BTHUA, YRDUA, PRDUA respectively from 1959 to 2018, showing an obvious fluctuation upward trend; the warming effect is more significant in recent 30 years (1989-2018) (Fig. 8). The auto-correlation coefficients have a significant positive correlation at the level of 0.05 in 12 lag periods in BTHUA and YRDUA, and a significant positive correlation at the level of 0.05 in 13 lag periods in PRDUA. The results show that there is a strong auto-correlation among the three urban agglomerations. The auto-correlation coefficient of the annual average surface temperature in the 1 lag period exceeds the critical value (0.253) of 0.05 significance level in the three urban agglomerations and shows a slow downward trend with non-stationary characteristics. The auto-correlation coefficients have a significant negative correlation at the 0.05 level after 21, 19, and 20 lag periods in BTHUA, YRDUA, and PRDUA, respectively.

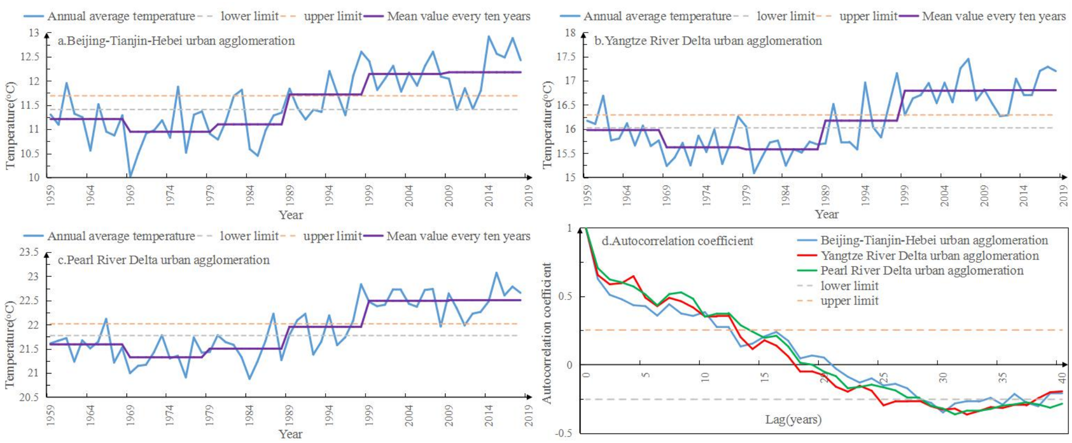

Figure 8. Annual average surface temperature non-stability of the three urban agglomerations from 1959 to 2018. Chart a-c is the line chart of annual average temperature, mean temperature per decade, and the 90% confidence interval. Chart d is the temperature auto-correlation coefficient of the three urban agglomerations and the significant coefficient interval line chart at 0.05% level.

4 Conclusions and discussion

4.1 Conclusions

Climate warming has become a significant feature of global climate change, creating a great challenge to human survival and economic and social development. Rapid industrialization and urbanization further aggravate the speed of climate warming. China is one of the countries most sensitive to climate warming, with many significantly affected areas. Since the middle of the 20th century, the warming rate has become dramatically higher than the world average for the same period. This study applied average temperature difference and auto-regressive models to explore the temporal and spatial evolution and non-stationary characteristics of China's surface temperature from 1959 to 2018.

(1) From 1959 to 2018, the annual average surface temperature in China shows a significant upward trend with obvious fluctuation characteristics, increasing by 0.995℃ overall, at a warming rate of 0.166℃ per decade. From 1989 to 2018, the slope of the linear trend line of the annual average surface temperature average difference is greater than that in 1959–2018. In the past 30 years, the climate warming problem has become increasingly serious in China, and the areas with greatest warming are mainly concentrated in North and East China, and Northwest and Northeast China. Compared with 1959, 92.49% of grids are warmer in 2018, the temperatures of the 74.84%, 42.65%, 16.67%, and 6.86% grids increase by 0.5℃, 1.0℃, 1.5℃, and 2℃, respectively.

(2) From 1959 to 2018, China's surface temperature exhibits strong auto-correlation, and 49.35%–96.08% the grids' auto-correlation coefficient has a significant positive correlation at the 0.05 confidence level in 13 lag periods. From 1959 to 2018, the auto-correlation coefficient of 96.08% grids annual average temperature in the lag 1 period exceeds a critical value of 0.253 at the 0.05 significance level; the auto-correlation coefficient decreases slowly with increasing lag period. The annual average surface temperature in 1989–2018 is higher than that in 1959–1988, and the surface temperature is non-stationary in China during the study period.

(3) From 1959 to 2018, the surface temperature shows a wave-like upward trend in BTHUA, YRDUA, and PRDUA, with warming rates of 0.187 ℃, 0.171 ℃, and 0.175 ℃ per decade, respectively. From 1959 to 2018, the slope of the linear trend line of the annual average surface temperature average difference in the three urban agglomerations is ranked as follows: BTHUA > PRDUA > YRDUA—the warming effect in BTHUA is greater than in the other two urban agglomerations. During the study period, the average surface temperatures are 11.55℃, 16.16℃, and 21.90 ℃ in BTHUA, YRDUA, and PRDUA, respectively. The warming effect is more significant in the recent 30 years(1989-2018), showing strong auto-correlation and non-stationary characteristics.

4.2 Discussion

(1) From 1959 to 2018, the annual average surface temperature increases by 0.995 ℃ in China, with a pronounced warming effect. China's government is keenly aware of the serious challenges posed by climate warming to the economic and social development and to the human living space, and has actively taken systematic measures to prevent and control it. China regards the global cooperation required to mitigate climate change as an important element in building a global community, to strengthen the strategic cooperation with other countries in climate change prevention and control. China has vast territories, complex terrain, and remarkable regional differences in surface temperature. Therefore the scientific prevention and control measures should be formulated, according to specific regional development, natural geographical characteristics, and people's well-being demand.

(2) From 1959 to 2018, the annual average surface temperature is non-stationary in. Using a long time-scale historical database of surface temperatures to predict future temperatures is not reliable enough, as the data need to be transformed into stationary time series by difference, logarithm, and ratio methods. Under global warming, the increasing tendency of surface temperature is more remarkable in China. The past 20 years have been the warmest period in

China since the 20th century. In the future, to efficiently meet the challenges of global warming, the use of disciplines, such as meteorology, human geography, geographic information systems, and economics, will prove necessary. New models, technology, software, and theory will be required, aimed at the evolution characteristics of temperature data on long time scales for the effective prediction, scientific warning, and risk response inherent to controlling the impact of climate warming on the economy and society.

(3) From 1959 to 2018, the rising value and warming rate of surface temperature in BTHUA is greater than in YRDUA and PRDUA. Urban agglomeration is the core region of industrialization and rapid urbanization, and also the area seriously affected by climate warming. The heat island effect in cities leads to an increase in the intensity and duration of heat waves, which acutely affects the quality of life for urban residents, and also poses a great challenge to city operation. It is urgent that urban agglomeration planners formulate medium and long-term planning and decision-making support mechanisms to adapt to climate warming and to enhance the climate protection capability of infrastructure. The climate problem is more acute in BTHUA than in the other two urban agglomerations, and is affected by comprehensive factors, like location, natural environment, and the rapid development of heavy industry. In the future, it will be necessary to further quantitatively explore the impact of different natural and human factors on climate warming in urban agglomerations.

(4) This study selected 1728 valid meteorological stations from 2419 meteorological stations of the China Meteorological Administration, according to the quality control principles, and calculated the annual average temperature and spatial mean of these stations, based on a spatial grid of 1 °× 1 °. Compared with interpolation methods, this method produces more accurate results. Because the periods and regions selected in this study are different from those selected in other studies, the results are distinctive. Notably, since the paper deleted some stations with missing data and averaged the data in grids, it weakens the characteristics of climate change in typical areas (e.g., Beijing, Shanghai), so the range of temperature change may be lower than the actual situation in some typical areas.

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