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Asymmetric changes of maximum and minimum temperatures in the Dabie Mountains, China

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Abstract. This study used high-quality daily temperature data from 1960–2019, recorded at five observing stations (Huoqiu, Huoshan, Jinzhai, Lu'an, and Shucheng) in Lu'an City (China), to construct annual and seasonal maximum and minimum temperature series. Annual and seasonal trends in the maximum and minimum temperature series were analyzed and the climatic tendency rates at each station were calculated. The spatial laws of the annual and seasonal variations of maximum and minimum temperature in Lu'an City were analyzed, Yamamoto and sliding t-tests were performed to identify mutations in both series, and wavelet analysis was adopted to analyze the cycles of change. The results showed that changes in annual maximum and minimum temperatures over the studied 60 years were asymmetric; the average climatic trend rate of minimum temperature was 0.262 °C/10a, while that of maximum temperature was 0.198 °C/10a, i.e., the temperature increase of the former was approximately 1.3 times that of the latter. Asymmetric changes of maximum and minimum temperatures were evident in winter, summer, and autumn throughout the entire 60-year period and in spring for the first 45 years. The spatial distribution of the asymmetric changes was uneven with decrease both from high latitudes to low latitudes and from high elevations to low elevations. High-elevation high-latitude areas such as Jinzhai, Lu'an, and Huoqiu exhibited the most significant asymmetric changes seasonally and annually. Abrupt changes in the trends of maximum and minimum temperatures occurred in 1994. Three periodicities were found in the maximum temperature series, i.e., 15–18, 32, and 4–6 years, and four periodicities were found in the minimum temperature series, i.e., 9–10, 32, 20–22, and 4 years. The 4–6-year periodicity of maximum temperature and the 4-year periodicity of minimum temperature (which passed the 95% significance test) should be associated with El Niño.

1 Introduction

Global warming (Houghton et al., 1995; Parry et al., 2007) has become recognized as indisputable fact. Further studies have found that the effect of global warming is reflected mainly at night, i.e., the increase of daily minimum temperature is much larger than that of daily maximum temperature, and the change is asymmetric. A study of most land surfaces in the Northern Hemisphere revealed that the average increase in minimum temperature during 1951–1990 was 0.84 °C, while the average

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increase in maximum temperature was 0.28 °C, i.e., the increase was asymmetric with the former 3 times greater than the latter (Karl et al., 1993). Similarly, asymmetric increase in both maximum and minimum land surface temperatures has been found globally (Jones, 1995). Karl et al. (1991) showed that the trend of minimum temperature in the United States and the former Soviet Union increased during 1951–1990, while the trend of maximum temperature showed little or no obvious increase. Horton (1995) analyzed maximum and minimum temperatures and the diurnal range over all land surfaces during the same period, and identified that the diurnal range over most of the world decreased substantially during 1981–1990 in comparison with that during 1951–1980, especially in Asia (Houghton et al., 1992). During 1951–1990, the maximum temperature in China generally increased to the west of 95°E and in the area north of the Yellow River and decreased in the area south of the Yellow River in the east. Nationally, the minimum temperature in China has generally increased and the diurnal temperature range has decreased (Zhai et al., 1997; Easterling et al., 1997; Frich et al., 2002). Cao et al. (1992) highlighted that the decrease in diurnal temperature range was due to increase in atmospheric CO_2 concentration.

The city of Lu'an is located in western Anhui Province, commonly known as "West Anhui" (31°01'–32°40'N, 115°20'–117°14'E), which is an area typical of the Dabie Mountains. The terrain is high in the southwest and low in the northeast, and mountains and hills account for 65% of the total area. The region is a traditional agricultural area, for which research on the regional climate is very limited and there has been almost no investigation of local temperature extremes. In the context of global warming, it is important to determine the magnitude and spatiotemporal variation of the asymmetric changes of the regional maximum and minimum temperatures, and to establish the effects of the typical underlying surface of the Dabie Mountain region on the observed asymmetric changes. In this study, in combination with consideration of previous research results, temperature data from the city of Lu'an recorded over the past 60 years were used to perform in-depth research on the asymmetric changes of maximum and minimum temperatures to determine the local response to global warming, and to provide decision-making support for the development of strategies designed to mitigate the effects of climate change and guide future local agricultural production.

2 Data and Processing

2.1 Data selection

This study selected accurate and continuous records of surface air temperature from five representative national meteorological stations in Lu'an City, which comprised two national fundamental stations: Lu'an (31°45'N, 116°30'E) and Huoshan (31°24'N, 116°19'E), and three national general stations: Huoqiu (32°14'N, 116°17'E), Jinzhai (31°41'N, 115°53'E), and Shucheng (31°22'N, 116°57'E) (Fig. 1). Prior to January 1, 2002, the maximum and minimum thermometers were read manually at the national fundamental stations of Lu'an and Huoshan, and prior to January 1, 2006, the maximum and minimum thermometers were read manually at the national general stations of Huoqiu, Jinzhai, and Shucheng. Backup readings were obtained using 24-h automatic instruments. Subsequently, platinum resistance temperature sensors and automatic data transmission were used as additional backup. The artificial observation records were pre-examined and checked manually. The

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thermometer and temperature sensor data were analyzed and calibrated after two years. The quality of the automatic transmission data was controlled by the Anhui Meteorological Observation Quality Management System.

The daily maximum and minimum temperature data recorded at these five meteorological stations during 1960–2019 were used in this study.

2.2 Establishment of sequences

Sequences of daily maximum temperature (T_{max}) and daily minimum temperature (T_{min}) for each year (January–December) and each season (March to May: spring, June to August: summer, September to November: autumn, and December to February of the following year: winter) at each of the five observing stations were established.

3 Study Methods

The climatic trend rate was estimated using the following linear regression equation: $x' = a_0 + a_1 t$, where x refers to the maximum or minimum temperature, and $a_1 \times 10$ refers to the climate trend rate, which reflects the change trend of the maximum and minimum temperatures every 10 years (Zhai et al., 1997; Sun et al., 2020).

Tests for abrupt changes in the sequences were conducted using the Yamamoto Test (Yamamoto et al., 1985, 1986) and the moving t-test technique. For the Yamamoto Test, we divided a continuous random variable X into two subsets: X_1 and X_2, for which u_1, s_1, and n_1 and u_2, s_2, and n_2 represent the mean, variance, and sample number of subset X_1 and X_2, respectively. The values of n_1 and n_2 are set as required.

We defined the noise ratio as follows: $\frac{S}{N} = \frac{\left|\overline{x_1} - \overline{x_2}\right|}{S_1 + S_2}$, and when $\frac{S}{N} > 1.0$, it was defined as a mutation. When n1 = n2 = 10 and $\frac{S}{N} > 1.0$, the reliability level was >95%; when n1 = n2 = 14 and $\frac{S}{N} > 1.0$, the reliability level was >99.95%.

In the moving t-test technique, the underlying principle is the same as that of the Yamamoto Test.

We defined the statistic: $t_0 = \frac{\overline{x_1} - \overline{x_2}}{S_p^2(\frac{1}{n_1} + \frac{1}{n_2})^{\frac{1}{2}}}$, where the symbols are the same as in the Yamamoto Test, and where S_P^2 is the variance of the joint sample: $S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$, which is an unbiased estimate of σ^2. Obviously, the distribution of t_0–$t(n_1 + n_2 - 2)$ and the critical value t_α can be obtained for the given reliability α. When $|t_0| \geq t_\alpha$, it was defined as a mutation; otherwise, there was no mutation.

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The periodicities of the T_{max} and T_{min} were analyzed using wavelet analysis.

4 Results

4.1 Annual and seasonal change characteristics of the time series of maximum and minimum temperatures

The change trends of the time series of annual average T_{max} and T_{min} in the city of Lu'an over the past 60 years are shown in Fig. 2a and 2b, respectively. The thick curve denotes the measured values, the dotted curve represents the univariate regression trend, and the thin curve indicates the polynomial fitting. During 1960–2019, the annual change trends of T_{max} and T_{min} were consistent with the polynomial fitting curve, with both showing curvilinear increase. Both T_{max} and T_{min} showed a trend of decrease from 1960–1984, reached a minimum value at around 1984, and increased from 1984–2019. However, the rates of increase of T_{max} and T_{min} were different, i.e., the climatic trend rate of T_{max} was 0.198°C/10a and that of T_{min} was 0.262°C/10a (both passed the 99% significance test). Overall, the magnitude of the increase in $T_{min}$was greater than that of T_{max} and the diurnal range decreased. The above shows that the asymmetric growth of T_{max} and T_{min} in the city of Lu'an over the past 60 years was consistent with the conclusions of Karl et al. (1993) and Horton (1995), i.e., the increase of T_{min} was greater than that of T_{max}, but the difference in the increase between the two was small (1.3 times).
As shown in Table 1, the trend of change of both T_{max} and T_{min} in all four seasons was mostly positive, indicating that T_{max} and T_{min} increased in all seasons. Specifically, the trend of change of T_{max} in spring and autumn, and the trend of change of T_{min} in all four seasons passed the 99% significance test. In winter, summer, and autumn for the entire 60-year period and in spring for the first 45 years, the increase in T_{min} was larger than that in T_{max} and the increase was asymmetric. The variation trend of T_{max} and T_{min} in all four seasons was consistent with the asymmetric variation trend of T_{max} and T_{min} mentioned above.
The decrease in the diurnal range between T_{max} and T_{min} was most significant in winter and summer, followed by autumn; it was smallest in spring. In winter and summer, the daily range decreased markedly, indicating locally warmer winters and cooler summers conducive to more comfortable living conditions. Additionally, the significant increase of T_{min} in winter was beneficial to agricultural production.

4.2 Spatial distribution and seasonal characteristics of increase in maximum and minimum temperatures

The distributions of seasonal climatic trend rates of maximum and minimum temperatures in the city of Lu'an from 1960–2019 are presented in Fig. 3a–d and 3e–h, respectively. It can be seen that the climatic trend rates of maximum and minimum temperatures in each season throughout the entire region were mostly positive. Moreover, 70% of the climatic trend rates passed the 99% significance test, indicating that both T_{max} and T_{min} generally showed increase in each season throughout the entire region. However, there were regional and seasonal differences between the increases in T_{max} and T_{min}.

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The regional distribution of the T_{max} warming trend in the four seasons was not completely consistent. In spring and autumn, it increased from the south to the north, and there was an obvious area of warming in eastern parts of the north; the central value of the climatic trend rate was 0.55 and 0.25 °C/10a, respectively. The trend decreased from the south to the north in both summer and winter, and it decreased to a cooling trend in the north in summer. In winter, it decreased toward western parts in the north, and there was an area of significant warming in eastern parts of the north; the central value of the climatic trend rate was 0.15 °C/10a.

There were differences in the distribution of the warming trend of T_{min} in the four seasons. In spring and winter, it increased from the south to the north, and there was an obvious area of warming in eastern parts of the north. In spring and winter, the central value of the climatic tendency rate was 0.4 and 0.45 °C/10a, respectively. In summer and autumn, the trend decreased from the east to the west, and the warming was strongest in the southwest; the central value of the climatic trend rate was 0.3 and 0.4 °C/10a, respectively. The T_{min} warming trend was weakest in summer and strongest in winter.

The climatic trend rate of the five observing stations was between 0 and 0.25 °C/10a for T_{max} and between 0.15 and 0.45 °C/10a for T_{min} in winter; between −0.05 and 0.1 °C/10a for T_{max} and between 0 and 0.3 °C/10a for T_{min} in summer; and between 0.1 and 0.25 °C/10a for T_{max} and between 0.15 and 0.4 °C/10a for T_{min} in autumn. The climatic trend rate of T_{min} throughout the entire region in summer, autumn, and winter, was greater than that of T_{max} in corresponding seasons, indicating that the increase in T_{min} was greater than that in T_{max} and that the increase was asymmetric. Asymmetric increases were found in spring for all five observing stations in the early part of the study period, and the change points were 2004, 2003, 2010, 2005, and 1978 for Huoqiu, Huoshan, Jinzhai, Lu'an, and Shucheng, respectively (Table S1). Asymmetric variation was stronger in winter and summer and weaker in autumn and spring. The climatic trend rate of T_{max} and T_{min} for the five observing stations in all four seasons was consistent with the asymmetric variation trend of T_{max} and T_{min} mentioned above.

In the recent 60 years, T_{max} and T_{min} in the city of Lu'an increased over different ranges, i.e., the daily range decreased and the asymmetric increase exhibited regional characteristics (see Table 2 and Table S2). The relationship of the increase in the climatic trend rate of T_{max} at the five observing stations was as follows: Jinzhai < Huoshan < Lu'an < Huoqiu < Shucheng, reflecting decrease both from low latitudes to high latitudes and from low elevations to high elevations. The relationship of the increase in the climate trend rate of T_{min} at the five observing stations was as follows: Shucheng < Huoshan < Huoqiu < Lu'an < Jinzhai, reflecting decrease both from high latitudes to low latitudes and from high elevations to low elevations. The relationship of the decrease in the climate trend rate of the diurnal range at the five observing stations was as follows: Shucheng < Huoshan < Huoqiu < Lu'an < Jinzhai, reflecting decrease both from high latitudes to low latitudes and from high elevations to low elevations. It can be seen that the asymmetric change in T_{max} and T_{min} in the city of Lu'an was most notable at high elevations and high latitudes. Consequently, high-elevation and high-latitude areas such as Jinzhai, Lu'an, and Huoqiu were the regions with the most significant asymmetric change seasonally and annually (Zhao et al., 2018).

In the context of global warming, the asymmetric change of T_{max} and T_{min} in the city of Lu'an is consistent with that elsewhere in China and globally, indicating that the greenhouse effect due to increased atmospheric CO_2 concentration (Houghton et al., 2001) is also the main cause of the climate warming in the city of Lu'an. However, this asymmetric change exhibits

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characteristics that reflect the regional topography of the Dabie Mountains and other underlying surface conditions, the specific reasons for which are beyond the scope of this study.

4.3 Abrupt change test of maximum and minimum temperatures

In this study, tests for abrupt changes in the T_{max} and T_{min} series for the city of Lu'an from 1960–2019 were conducted using the Yamamoto Test and the moving t-test technique. Both methods revealed abrupt change in the T_{max} and T_{min} series in 1994 (see Fig. 4). The change point of T_{min} also passed the Mann–Kendall Test (figure omitted), whereas that of T_{max} did not, indicating that the abrupt change of T_{min} was stronger than that of T_{max}.

As shown in Table 3, the mean annual and seasonal temperatures in the later period (1994–2019) were higher than those in the earlier period (1960–1994), indicating that 1994 represents a time of abrupt change in warming. Further investigation (Table 4) revealed that the seasonal and annual climatic trend rates in the later period (1994–2019) were higher than those in the earlier period (1960–1994), indicating that the increase in temperature after the abrupt change was greater, and that the increase in T_{min} was significantly higher than that in T_{max}, consistent with the asymmetric change trend mentioned above. It is suggested that this abrupt change in warming was a regional response synchronized with global warming (Gao et al., 2001).

4.4 Analysis of maximum temperature and minimum temperature periodicity

As can be seen from Fig. 5a and 5b, T_{max} in the city of Lu'an exhibited three periodicities: 15–18, 32, and 4–6 years (which passed the 95% significance test). It can be seen from Fig. 5c and 5d that T_{min} had four periodicities: 9–10, 32, 20–22, and 4 years (which passed the 95% significance test). The 4–6-year periodicity of T_{max} and the 4-year periodicity of T_{min} should be associated with El Niño.

5 Conclusions and Discussion

In this study, analysis of T_{max} and T_{min} data series for the city of Lu'an from 1960–2019, in combination with consideration of results from previous studies on the regional climate of Lu'an (Zhao et al., 2018), allowed the following conclusions to be drawn.

1) Over the 60-year study period, the increase of T_{min} in Lu'an was greater than that of T_{max}, and the two showed asymmetric changes. Asymmetric changes of T_{max} and T_{min}, which were strong in winter and summer and weak in autumn and spring, were found in winter, summer, and autumn for the entire 60-year period and in spring for the first 45 years.

2) The climatic trend rate of T_{max} reflected decrease both from low latitudes to high latitudes and from low elevations to high elevations. The climatic trend rate of T_{min} showed decrease both from high latitudes to low latitudes and from high elevations to low elevations. The climatic trend rate of the diurnal range showed decrease both from high latitudes to low latitudes and

from high elevations to low elevations. Consequently, high-elevation high-latitude areas such as Jinzhai, Lu'an, and Huoqiu were the regions with the most significant asymmetric changes seasonally and annually.

3) In 1994, T_{max} and T_{min} both experienced abrupt change in their rate of increase. In the city of Lu'an, T_{max} exhibited three periodicities of 15–18, 32, and 4–6 years (which passed the 95% significance test); T_{min} exhibited four periodicities of 9–10, 32, 20–22, and 4 years (which passed the 95% significance test). The 4–6-year periodicity of T_{max} and the 4-year periodicity of T_{min} should be associated with El Niño.

4) Table 5 shows the monthly maximum and minimum climatic tendency rate of Lu'an during 1960–2019. The warming trend of T_{min} in each month was significantly larger than that of T_{max}. The annual, seasonal, and monthly changes in T_{max} and T_{min} in Lu'an were asymmetric, consistent with the conclusions of previous studies (Karla et al., 1984).

The trend of the asymmetric change at different elevations in Lu'an City reflects the regional characteristics of climate warming (Durre et al., 2001). Some studies have shown that urbanization, land use, and industrial development have substantial impact on such asymmetric change in addition to the effect of climate (Wang et al., 1990; Cooter et al., 1995), and the specific causes of local asymmetric change characteristics deserve further discussion.

Author Contributions YMZ processed the data, performed the dataanalysis and drafted the manuscript. LYT, CMZ, YL, and FZ all made substantial and ongoing contributions toward the interpretation and discussion of the observations, in addition to the writing of the article

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Competing Interests The contact author has declared that neither they nor their co-authors have any competing interests.

The authors declare that they have no conflict of interest.

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Figure

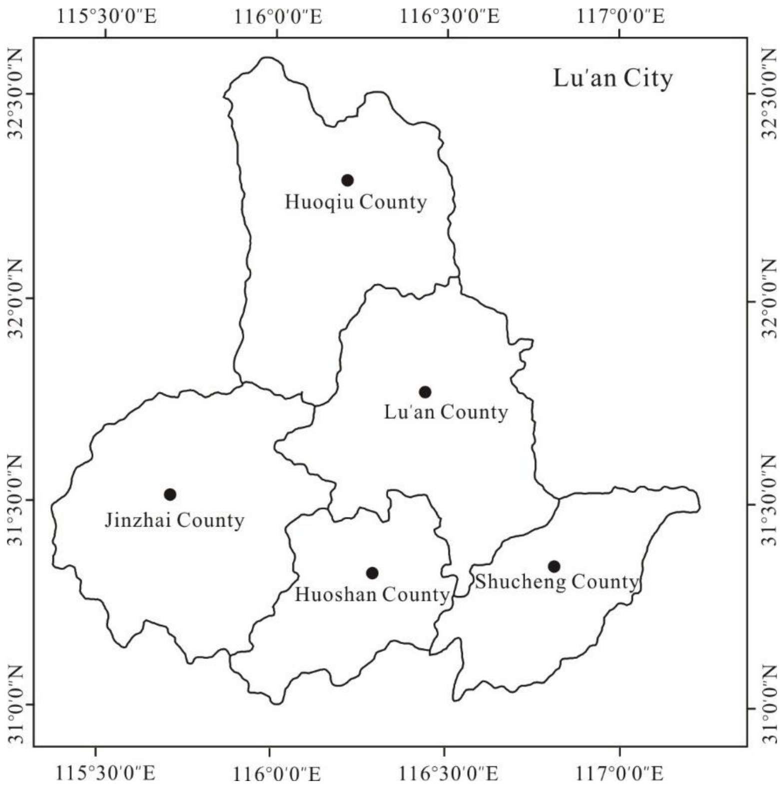

Figure 1: Regional division of the study area and locations of the five observing stations (black dots: Huoqiu, Huoshan, Jinzhai, Lu'an, and Shucheng).

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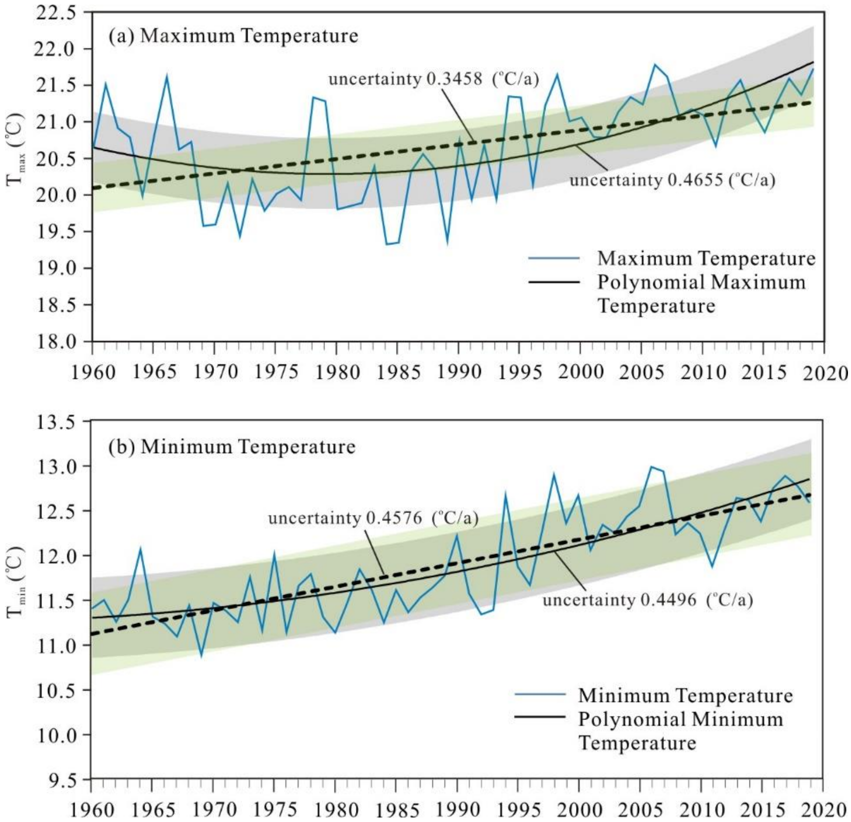

Figure 2: Change in annual (a) maximum and (b) minimum temperature in the city of Lu'an from 1960–2019. Annual maximum or minimum temperature in the city of Lu'an is the mean of the maximum or minimum temperature at the five stations: Huoqiu, Huoshan, Jinzhai, Lu'an, and Shucheng. Solid curve denotes the measured values, dotted curve represents the univariate regression trend (green shading shows uncertainty range), thin curve shows the polynomial fitting (gray shading shows uncertainty range).

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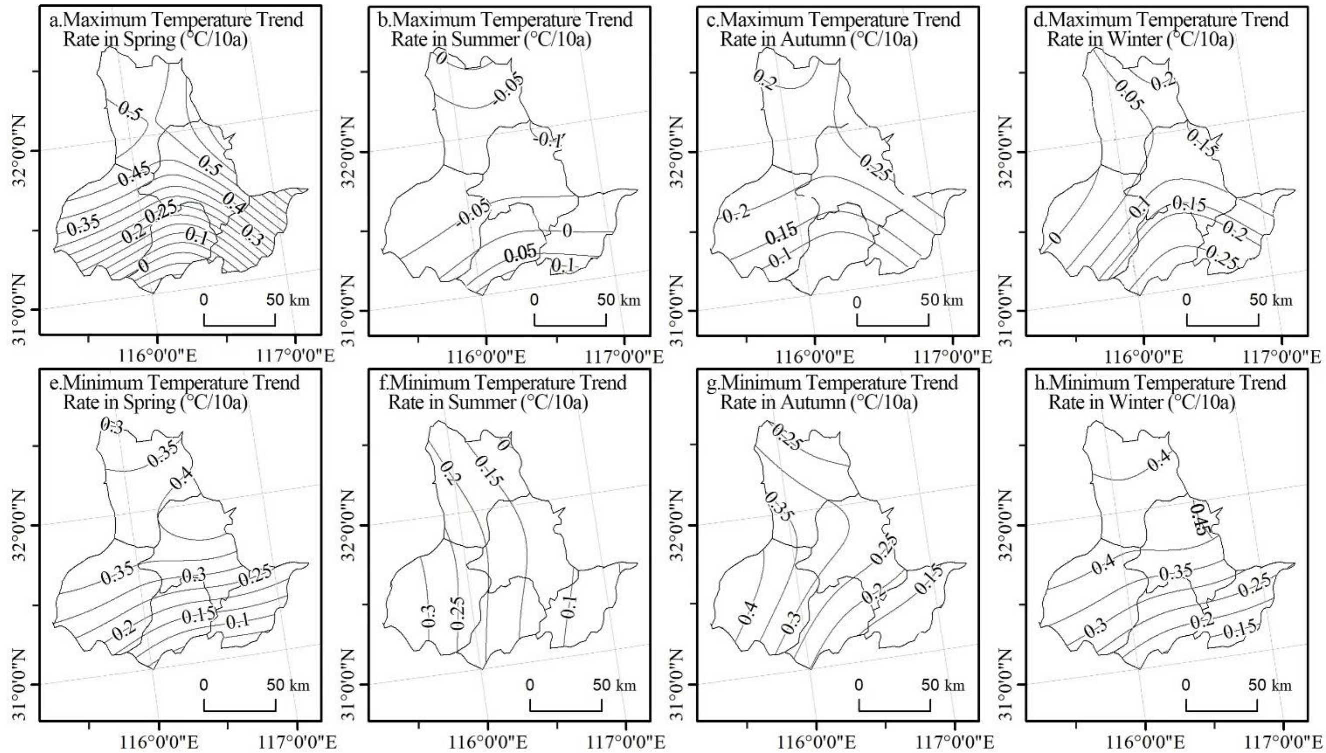

Figure 3: Distribution of seasonal trends of (a)–(d) maximum and (e)–(h) minimum temperatures in the city of Lu'an from 1960–2019. The isolines indicate the climatic trend rates.

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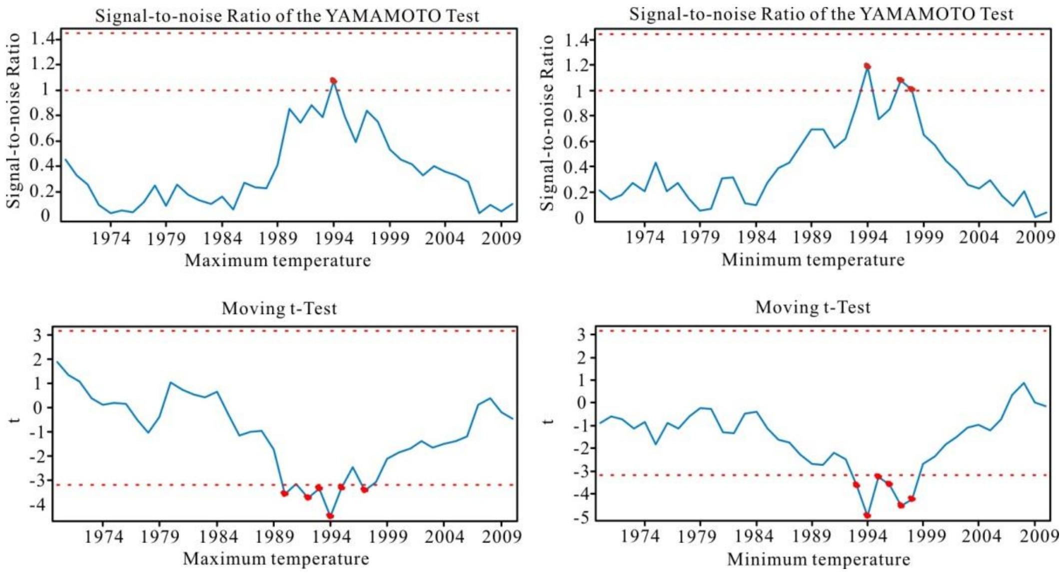

Figure 4: Abrupt change test for the maximum and minimum temperature series for the city of Lu'an from 1960–2019 (which passed the 0.01 confidence test). Red dotted lines indicate critical points for the examinations of abrupt change, red points are the possible abrupt change points, blue lines are the maximum or minimum temperature curves.

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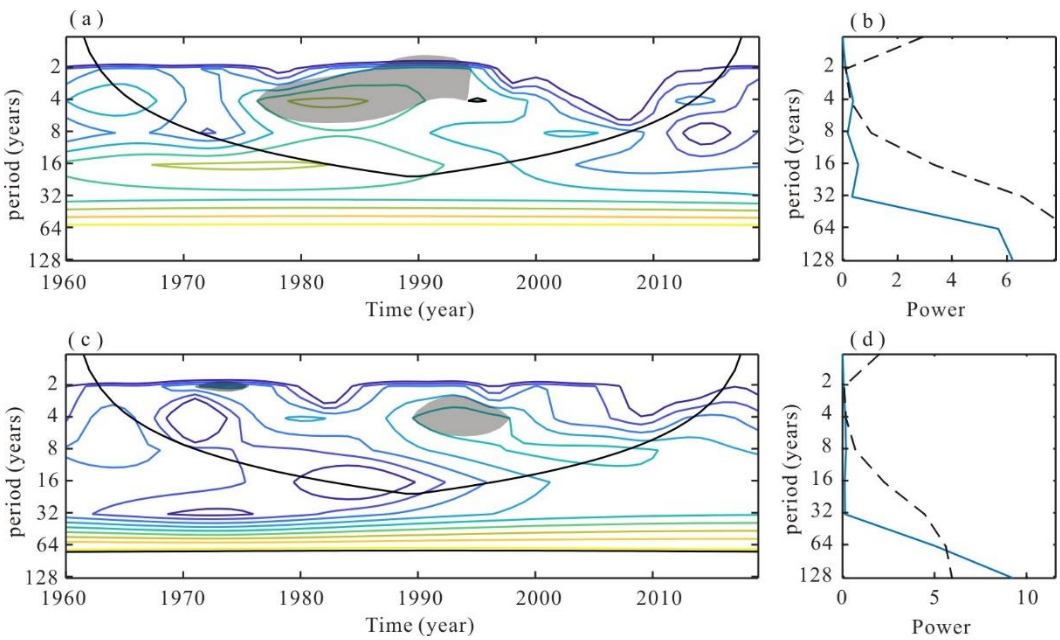

Figure 5: Period spectrum analysis of maximum and minimum temperatures in Lu'an City from 1960–2019: (a) Morlet wavelet spectral analysis of maximum temperature（the shaded areas are significant regions at the 95% confidence level）, (b) significant periods of maximum temperature (dashed line shows the 95% confidence level), (c) Morlet wavelet spectral analysis of minimum temperature（the shaded areas are significant regions at the 95% confidence level）, and (d) significant periods of minimum temperature (dashed line shows the 95% confidence level).

Table

Table 1: Annual and seasonal trends of change of maximum and minimum temperatures in the city of Lu'an.

	Maximum Temperature	Minimum Temperature	al difference (T_{max}-T_{min})
Annual	T_{max}=0.0198t +20.075	T_{min}=0.0262t+11.101	0.01
Spring	T_{max} =0.0456t+19.479	T_{min}=0.0305t+10.411	-0.02
Summer	T_{max} =-0.0014t+31.314	T_{min}=0.0153t+22.597	0.02
Autumn	T_{max} =0.0193t+21.131	T_{min}=0.0256t+11.982	0.01
Winter	T_{max} =0.0164t+8.3016	T_{min}=0.0342t-0.6129	0.02

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Table 2: Climatic trend rates of maximum and minimum temperature and diurnal range (°C/10 years).

Station	Maximum Temperature					Minimum Temperature					Diurnal range				
	Spr	Sum	Aut	Win	Yr	Spr	Sum	Aut	Win	Yr	Spr	Sum	Aut	Win	Yr
Huoqiu	0.48**	-0.02	0.21**	0.2	0.21	0.3**	0.1**	0.3**	0.4**	0.3**	0.1	-0.1**	-0.1	-0.2**	-0.1*
Lu'an	0.47**	-0.05	0.21**	0.2**	0.2**	0.4**	0.2**	0.3**	0.4**	0.3**	0.1	-0.2**	-0.1	-0.2**	-0.1**
Jinzhai	0.43**	-0.05	0.17**	0.05	0.2**	0.4**	0.3**	0.4**	0.4**	0.4**	0.1	-0.3**	-0.2**	-0.3**	-0.2**
Huoshan	0.45**	-0.1	-0.2**	0.15	0.2**	0.2**	0.2**	0.2**	0.3**	0.2**	0.2**	-0.2**	-0.05**	-0.1	-0.04
ShuCheng	0.52**	0.1	0.2**	0.25*	0.3**	0.2**	0.1	0.2*	0.3**	0.02*	0.3	0	0.1	-0.02	0.1**

** passed the 0.01 significance test, * passed the 0.05 significance test

Table 3: Comparison of temperature indexes before and after abrupt change (°C).

	Spr		Sum		Aut		Win		Yr	
	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
1960-1994	20.13	10.88	31.17	22.81	21.39	12.36	8.53	0.02	20.31	11.52
1994-2019	21.89	11.99	31.44	23.43	22.19	13.32	9.20	1.03	21.20	12.45
d	1.75	1.11	0.27	0.63	0.79	0.96	0.68	1.01	0.89	0.93

d is the average from 1994 to 2019 minus the average from 1960 to 1994

Table 4: Comparison of climatic trend rates before and after abrupt change (°C/10a).

	Spr		Sum		Aut		Win		Yr	
	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
1960-1994	-0.1	0.07	-0.46**	-0.03	0.03	0.03	0.07	0.49**	-0.15	0.12**
1994-2019	0.6**	0.26**	0.16	0.09	-0.07	0.21*	-0.16	0.02	0.14*	0.15*

** passed the 0.01 significance test, * passed the 0.05 significance test

Table 5: Climatic tendency rate of monthly maximum and minimum temperature in Lu'an City during 1960–2019

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max}	0.06	0.182	0.342*	0.236	-0.087	-0.492**	-0.558**	-0.692**	-0.298**	-0.015	-0.002	0.127
T_{min}	0.284**	0.439**	0.343**	0.322**	0.295**	0.215**	0.179**	0.118	0.218**	0.28**	0.165	0.248**