

An analysis on the effects of urbanization on the local climate of three inland developing cities in East China

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सार – चीन में शहरीकरण से स्थानीय जलवायु पर पड़ने वाले प्रभाव पर अधिकांश शोध विकसित तटीय शहरों के लिए किए गए हैं; आंतरिक विकासशील शहरों पर बहुत कम ध्यान दिया गया है। इस शोध पत्र में हमने पूर्वी चीन के तीन प्रमुख और उसके आस-पास के विकासशील शहरों (नानचांग, जिउजियांग और डीयान) का चयन किया है जिससे कि विगत 45 वर्षों के दौरान भिन्न-भिन्न आकृति (साइज) के आंतरिक विकासशील शहरों की स्थानीय जलवायु के ऊपर पड़ने वाले प्रभाव का तुलनात्मक अध्ययन किया जा सके। यह शोध राष्ट्रीय धरातलीय मौसम विज्ञान स्टेशन द्वारा प्रकाशित (1967-2012) मानवीय डेटा सेट्स पर आधारित है, इसमें स्थानीय आर्थिक, जनसांख्यिकी इत्यादि बातों पर ध्यान दिया गया है। हमारे द्वारा प्राप्त किए गए निष्कर्ष निम्नलिखित हैं : इन तीनों आंतरिक विकासशील शहरों के शहरीकरण की गति उनकी स्थिति एवं आकृतियों के अनुसार हैं। जिस शहर का आकार बड़ा है उसका शहरीकरण तेजी से हुआ है। तेजी से शहरीकरण का स्थानीय तापमान भिन्नता पर स्पष्ट प्रभाव पड़ा है। पिछले 45 वर्षों में नानचांग (बड़ा शहर) की उष्णता दर में वृद्धि की दर लगभग 0.27° सेल्सियस/ दशक जबकि जिउजियांग (मध्यम आकृति का शहर) में लगभग 0.23° सेल्सियस/ दशक रहा है। प्रेक्षित की गई उष्णता दर में शहर की आकृति के अनुसार वृद्धि पाई गई है। पिछले 45 वर्षों की अवधि में इन तीनों शहरों में उच्च तापमानों वाले दिनों (HTDS) की संख्या में महत्वपूर्ण वृद्धि हुई है। वर्ष 2003 से 2012 की अवधि के दौरान नानचांग, जिउजियांग और डीयान में उच्च तापमान वाले दिनों (HTDS) की संख्या में क्रमशः 9.8, 5.1 और 1.3 दिनों की वृद्धि हुई है, यह तुलना 1967-1976 की अवधि से की गई है। इस प्रकार देखा गया है कि जितना बड़ा शहर उसके उच्च तापमान वाले दिनों की संख्या में महत्वपूर्ण रूप से उतनी अधिक वृद्धि हुई है।

ABSTRACT. Most studies on the impact of China's urbanization on local climate focus on developed coastal cities, with little attention paid to inland developing cities. In the present study, we selected three representative and neighboring developing cities (Nanchang, Jiujiang and De'an) in East China to examine, through comparative analyses, local climate changes in inland developing cities with varying sizes during the past 45 years, based on homogenized datasets (1967-2012) released by the National Ground Meteorological Station, taking local economic, demographic, etc. factors into account. Our findings are as follows: The speed of urbanization in these three inland developing cities is correlated to their respective status and sizes - the bigger the city, the faster the urbanization occurring in said city. The pace of the urbanization has a clear impact on the local temperature variability. For the past 45 years, the warming rate in Nanchang (large city) was approximately 0.27 °C/decade while that in Jiujiang (middle-size city) was approximately 0.23 °C/decade and that in De'an (small town) was approximately 0.20 °C/decade. The warming rate was observed to rise in line with city size. The number of high temperature days (HTDs) increased significantly in all three cities over the course of the past 45 years. During the period of 2003 to 2012, HTDs in Nanchang, Jiujiang and De'an increased by 9.8, 5.1 and 1.3 days, respectively, compared with the period of 1967-1976. The larger the city, the more significant the increase in HTDs was observed.

Key words – Urbanization, East China, Inland developing cities, Local climate.

1. Introduction

Since the Industrial Revolution, Global Warming has received widespread attention across the world. A report released by the Intergovernmental Panel on Climate

Change (IPCC) in 2013 state that it is extremely likely that global warming observed since the Mid 1900s has been caused by human activities, with a likelihood estimated to be over 95 per cent. Global temperature has risen 0.85 °C over the past 130 years.

An increase in greenhouse gases, coupled with urbanization, makes climate warming more noticeable in urban areas. Many studies have been conducted by Chinese and foreign researchers regarding the impact of urbanization on regional changes in climate. After analyzing data published on 1,219 historical climate websites in the U.S., Karl and Diaz (1988) concluded that the influence of urbanization was ~ 0.06 °C/10a (1901-1984), but findings from a study by Kukla and Gavin (1986) suggest that the impact in North America tended toward 0.12 °C/10a. China has been one of the fastest-urbanizing countries in the world in the last 50 years, and the impact of urbanization on climate change has always remained to be a popular topic of scientific research in China. Zhao (1991) analyzed climate change between 1951 and 1989 based on data collected by 160 meteorological stations nationwide. He found that the temperature in China rose ~ 0.23 °C during the surveyed period of 39 years; the average rise in temperature was more significant in large cities (0.27 - 0.45 °C); by contrast, in small cities temperature only increased 0.04 - 0.12 °C during the same period. This was likely the first academic study in China that revealed a correlation between city size and the extent of climate warming. Ren *et al.* (2005) performed a systematic analysis on the temporal and spatial characteristics of the evolution of key near-surface climate elements in Mainland China beginning in 1951, drawing on surface climate data collected by national reference climatological stations and basic meteorological stations. Their findings indicate that the average surface temperature in China increased ~ 1.1 °C during the past 50 years, corresponding to a warming rate of close to 0.22 °C/10a, substantially higher than the global and hemispherical average during the same period. Zhao *et al.* (2011) analyzed the general trends and characteristics of yearly and seasonal changes in temperature, precipitation, relative humidity and wind speed in downtown and suburban Beijing, based on climate observations recorded by 12 stations in Beijing from 1961 to 2008. They concluded that average temperature rose sharply during the past 50 years, and the most significant increase occurred during winters, while climate warming has been least noticeable in the summer months. Both maximum and minimum air temperature kept rising during the last 48 years, with the impact of urbanization most visible in terms of minimum temperature. Nie (2011) introduced a new urbanization index using daily climate data collected by basic and reference national climatological stations from 1951 to 2009 and urban population data from 1986 to 2008. After analyzing overall urbanization features in representative cities and regions within the Beijing-Tianjin-Hebei city belt and city belts in the Yangtze River Delta and Pearl River Delta, and comparing urban climates and climatic effects in the three city belts, Nie concluded that urbanization led to significant increases in

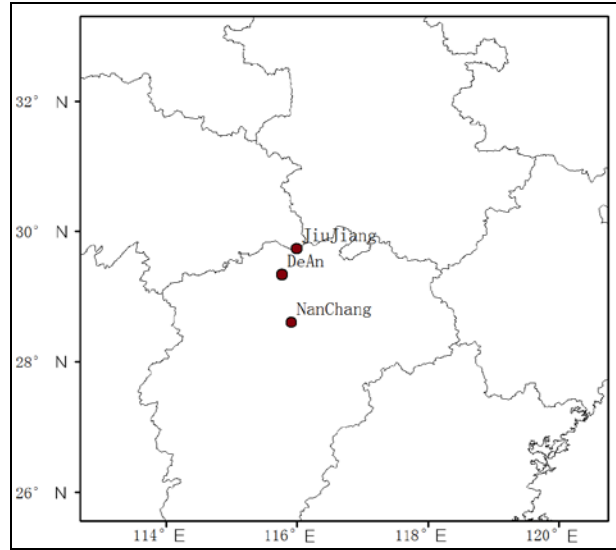


Fig. 1. The locations of the three cities examined

average temperatures and minimum temperatures in representative cities, and the strongest climatic effects were observed in the Yangtze River Delta, followed by the Beijing-Tianjin-Hebei city belt and finally the Pearl River Delta. By conducting comparative analysis on the population, GDP, urban areas and climatic factors pertaining to Shenzhen and Hong Kong, Li *et al.* (2015) found that rapid urbanization had a noticeable impact on the climate in Shenzhen. According to Li's analysis, The average temperature in Shenzhen had increased ~ 1.63 °C since 1968, and more than 80 per cent of the temperature increase was attributable to urbanization. Li *et al.* (2008) concluded that dramatic changes in the underlying surface properties of cities and human activities, *e.g.*, anthropogenic heat emissions caused by excessive population density, are the cause of climate changes occurring in urban areas, noting a linear correlation between the logarithm of population density and temperature as well as a linear correlation between urbanized area and temperature. Tang (2010) discovered a clear negative correlation between average annual relative humidity in Haikou and the degree of urbanization and hardened area in cities; and a relatively strong positive correlation between yearly temperature and degree of urbanization and hardened area in cities. Liu (2010) found that ground temperature in downtown Tianjin was significantly higher than that observed in suburban areas due to the Urban Heat Island Effect resulting from the urbanization process. The warming rate in downtown Tianjin was 0.42 °C/10a, and the local temperature increased 2.5 °C over 50 years.

However, there is still room for improvement in as far as warming rate-related research in China is concerned

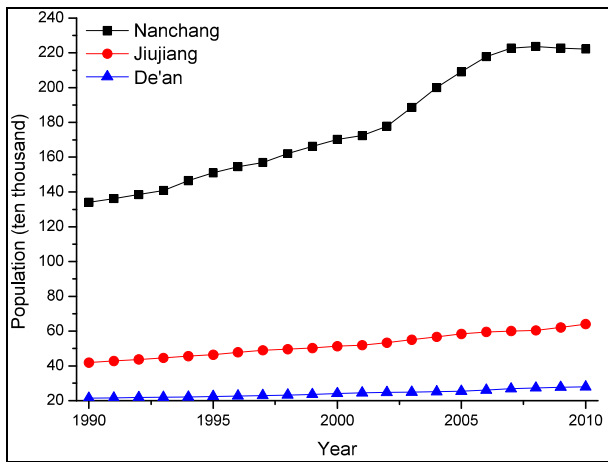


Fig. 2. The Population variations in Nanchang, Jiujiang and De'an by year (1990-2010)

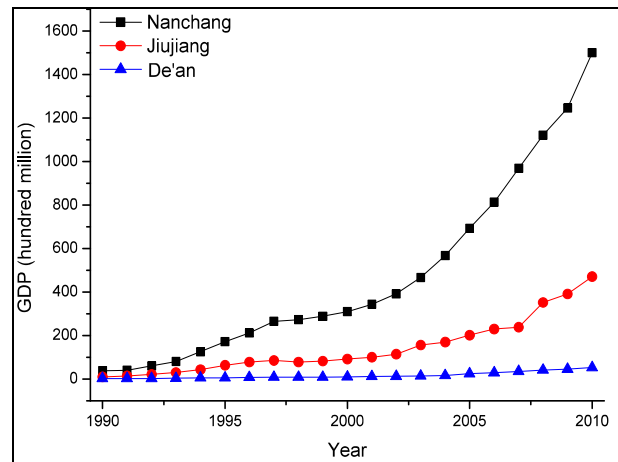


Fig. 3. GDP growth in Nanchang, Jiujiang and De'an (1990-2010)

though there had been so many relevant studies in this field. All the previous studies focused either on average changes in China as a whole or on developed coastal regions, with little attention paid to inland developing cities, despite the fact that these cities are the fastest growing and most dynamic regions in China today and are of essential significance for studies on general climate change at a national level. In an effort to partially remedy the situation, the present study chooses Nanchang as a representative of large-sized inland developing cities in East China, and Jiujiang and De'an as representatives of medium/small-sized developing cities in the region. By comparing urban development and typical changes in climatic factors in these three cities, we endeavor to further improve our understanding as to the impact of urbanization on local climate. As shown in Fig. 1, the three cities are located close to each other within the same background climate zone.

2. Materials and method

2.1. Meteorological data

Meteorological data used in this study were provided by the Jiangxi Provincial Meteorological Information Center (JPMIC). Meteorological data pertaining to Nanchang, Jiujiang and De'an were collected between 1967 and 2012, with relevant criteria including daily temperature and relative humidity and rainfall. Data were collected by weather stations in strict compliance with ground observation standards formulated by the China Meteorological Administration, and all data collected have been processed by the JPMIC for quality control and homogenization. Average annual data are derived from the observed data via calculation, including: annual average temperature, annual average maximum

temperature, annual average minimum temperature, daily temperature range (temperature at 2:00 pm minus temperature at 2:00 am) by year, annual average relative humidity and yearly rainfall.

2.2. Urbanization data

The data employed to assess the degree of urbanization mainly included urban population and GDP data during the period 1990 to 2010. Relevant data were provided by the Jiangxi Provincial Bureau of Statistics (1967-2012). The period of 1990-2010 was chosen as the temporal data range because digital statistics became available only after 1990. In addition to population and GDP statistics, data about built-up areas in Nanchang and Jiujiang were also collected. Unfortunately, De'an is a too small county and the local statistics bureau did not have any data available regarding built-up areas in De'an.

3. Urbanization in the three representative cities

Statistics data in 1990 show that the built-up area in Nanchang was 65km² in area and that of Jiujiang was 31 km² in area; according to the data as of the end of 2010, the built-up area in Nanchang was 208 km² in area and that of Jiujiang was 89 km² in area. In this section, the development of the three cities is compared and analyzed in terms of population, GDP and built-up area.

3.1. Population

Population changes in Nanchang, Jiujiang and De'an between 1990 and 2010 are shown in Fig. 2. Local population grew rapidly in all three cities. In 1990, the populations in Nanchang, Jiujiang and De'an were 1,340,200, 419,100 and 171,800 respectively; the

TABLE 1

The variation of the built-up areas in Nanchang and Jiujiang (km²)

Year	Nanchang	Jiujiang
2010	208	89
2005	109	48
2000	85	48
1997	85	48

populations of the same three cities later grew to 2,221,900, 640,200 and 231,000 in 2010, with growth rates of 2.56%, 2.14% and 1.33%, respectively. The population growth rates declined as the city size decreased, indicating a general inflow of population toward cities, especially large cities.

3.2. Economic growth

GDP growth represents another indicator of a city's development. The GDP changes in the three representative cities between 1990 and 2010 are shown in Fig. 3. The data show that all three cities underwent relatively fast development over the last 20 years. The GDP in Nanchang grew from CNY3.797 billion in 1990 to CNY150.098 billion in 2010, for a compound annual growth rate (CAGR) of ~20.18%; GDP in Jiujiang grew from CNY1.03 billion in 1990 to CNY47.084 billion in 2010, for a CAGR of ~21.06%; and GDP in De'an grew from CNY282 million in 1990 to CNY3.73 billion in 2010, for a CAGR of 13.78%. Therefore, all the three representative cities experienced rapid development throughout the past two decades. The medium and the large sized cities achieved similar growth rates which were substantially higher than those of the small county.

3.3. Built-up areas

Compared with the population and GDP statistics, the data pertaining to the built-up areas in the cities were more consistent but more difficult to collect. Furthermore, De'an is too small in size, and the data about the built-up area in the city are not available at the Jiangxi Provincial Bureau of Statistics. The built-up area data in Nanchang and Jiujiang in 1997, 2000, 2005 and 2010 are shown in Table 1 below. The yearly increase rates in the built-up areas of the two cities were 5.99% and 5.41%, respectively. As the data suggest, the built-up areas of Nanchang (a large-sized city) and Jiujiang (a medium-sized city) grew significantly during the 13 years examined, with that of Nanchang increasing 144 per cent and Jiujiang increasing 85 per cent.

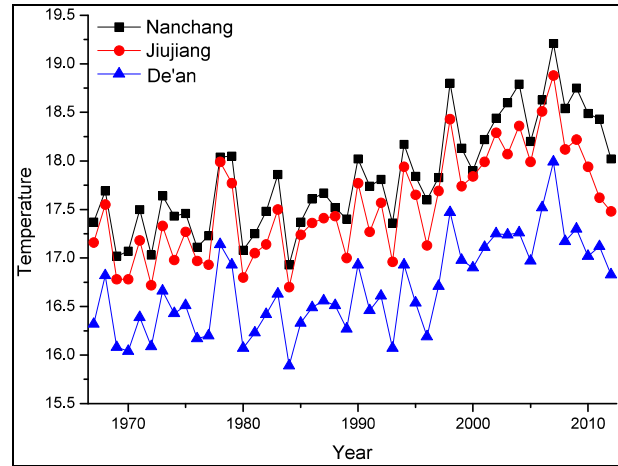


Fig. 4. The average temperature variations in Nanchang, Jiujiang and De'an by year (1967-2012)

The data show that all inland developing cities grew rapidly during the last two decades and there was a certain correlation between city size and the development speed. As the "large city" representative in this study, the capital of Jiangxi Province, and a regional economic and cultural center, Nanchang registered the fastest growth. Urbanization in Jiujiang, the representative of the medium-sized cities, developed slower than Nanchang but faster than De'an County, the latter representing small undeveloped counties. It should be pointed out that, though the total population and the GDP in De'an had also slowly increased over the last decades, the built-up area in this county is very small and the surrounding of the meteorological station of De'an has kept as a rural one over the period. Thus, it's reasonable to believe that the climate variation in De'an over the last decades is majorly determined by the regional background climate change.

4. Local climate change in the three cities

4.1. Average air temperature (T_a)

The average temperature changes for the three representative cities are shown in Fig. 4. From 1967 to 2012, Nanchang showed the highest average temperature at 17.76 °C; the average temperature in Jiujiang was 17.53 °C and De'an showed the lowest average temperature at 16.69 °C.

The temperature increases occurring in the three cities were calculated by using the method adopted by Li *et al.* (2015). Average temperatures in Nanchang, Jiujiang and De'an during the period of 1967 to 1976 and the period of 2003 to 2012, denoted as $T_{1967-1976}$ and $T_{2003-2012}$, respectively, were calculated first, after which the temperature increase over the last 45 years was calculated

TABLE 2
The comparison of warming rates of some cities in China

City	Warming rate	Period of data	Original reference
Beijing	0.45 °C/10a	1961-2008	Zhao <i>et al.</i> , 2011
Hong Kong	0.10 °C/10a	1968-2013	Li <i>et al.</i> (2015)
Shenzhen	0.35 °C/10a	1968-2013	Li <i>et al.</i> (2015)
Shanghai	0.397 °C/10a	1951-2006	Cao <i>et al.</i> (2008)
Average value of Mainland of China	0.25 °C/10a	1951-2005	Ren <i>et al.</i> (2005)
Nanchang	0.27 °C/10a	1967-2012	Current study
Jiujiang	0.23 °C/10a	1967-2012	Current study
De'an	0.19 °C/10a	1967-2012	Current study

by deducting $T_{1967-1976}$ from $T_{2003-2012}$. The temperature increase in Nanchang occurring over the past 45 years is 1.23 °C, implying a warming rate of 0.27 °C/decade; the temperature increase in Jiujiang during the same period is 1.05 °C, implying a warming rate of 0.23 °C/decade; while that of De'an is 0.89 °C, corresponding to a warming rate of 0.20 °C/decade. The temperature increases and the warming rates observed in the three cities were found to be positively correlated to their respective sizes and urbanization speeds. Furthermore, linear increases in average temperatures measured for the three cities were evaluated as statistically significant, at a confidence level of 0.01.

An analysis on the regional warming rate was also performed by using National Centers for Environment Prediction - National Center for Atmospheric Research (NCEP- NCAR) reanalysis data with a resolution of 2.5°, which showed that the warming rate in the grid comprising the three cities is 0.22 °C/decade in the period of 1967-2012. It is quite interesting that the regional warming rate is lower than that of Nanchang but higher than that of De'an, which shows the urbanization in this area have already had quite significant impact on regional scale climate.

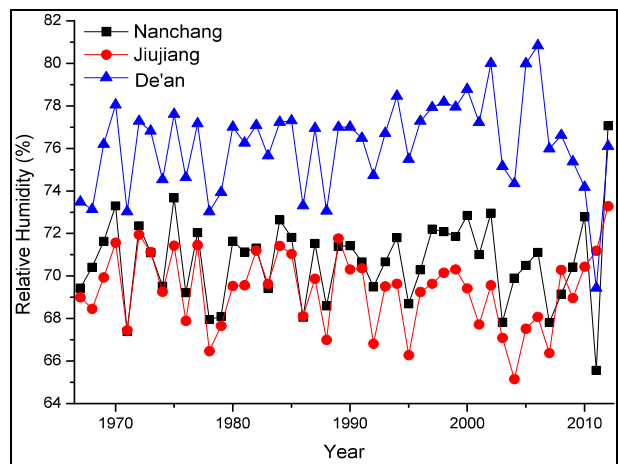
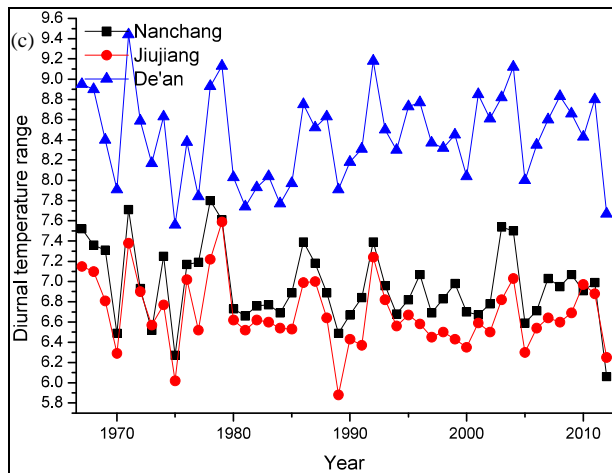
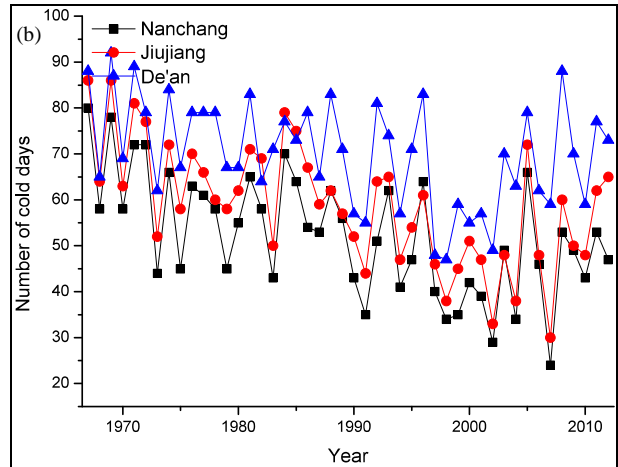
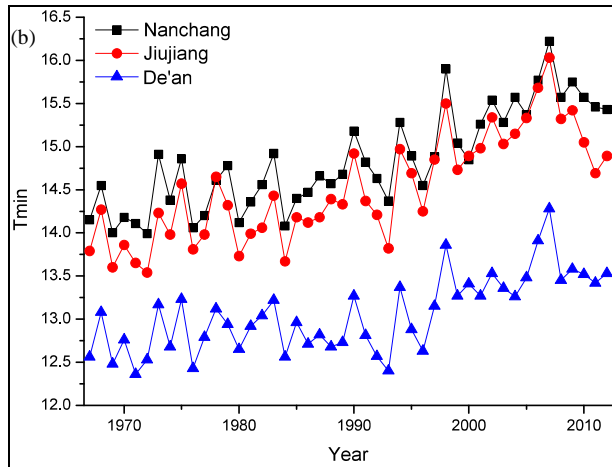
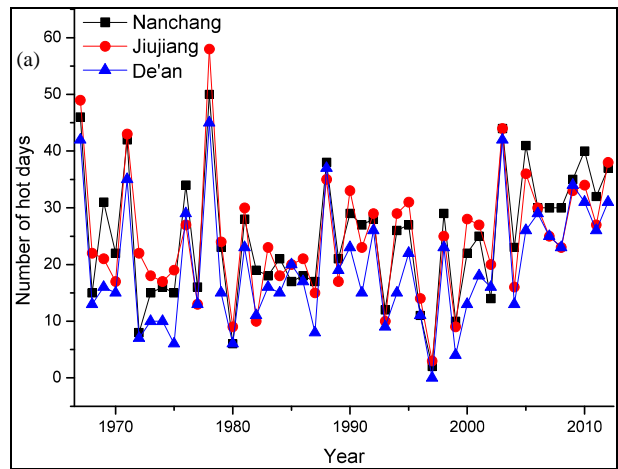
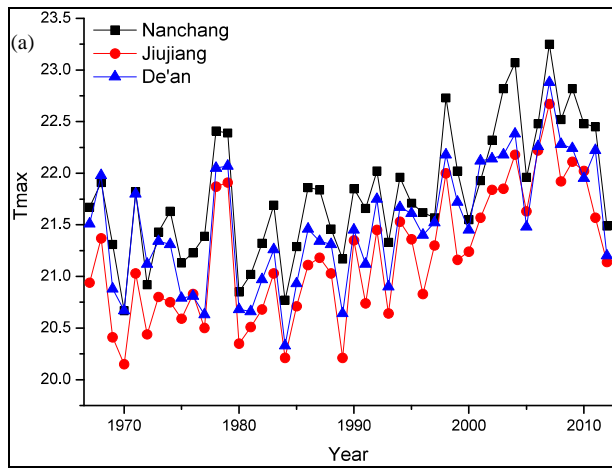
As introduced in section 3.3, the warming trend of De'an can be taken as the background warming rate caused by regional warming. Thus the contribution of the urbanization on the warming rate in Nanchang can be estimated as $(0.27-0.20)/0.27$, namely, 25.9%. The urbanization contribution in Jiujiang is only 13.0%, which is lower than that in Nanchang.

In order to compare the warming rates of the 3 inland cities with those of other major cities in China, Table 2 illustrates some data collected from Chinese literatures.

From Table 2 it can be found that the warming rates of different cities are closely related to the urbanization and development levels of the cities, though the periods of study and the methods used for different cities may be different. The warming rate in Nanchang is lower than that in Beijing, Shanghai and Shenzhen (these three cities are called as the first-class cities in economy and population), and the development and urbanization level of Nanchang is also lower than those in the three first-class cities. Hong Kong is an exception for its warming rate in the last 45 years is lower than that of Nanchang. As explained by Li *et al.* (2015), in 1960s, Hong Kong had almost finished its urbanization process and had already been a developed city since then. Thus, the warming rate of Hong Kong is quite low since 1960s. Table 2 also shows that the warming rates of Jiujiang and De'an are lower than the average rate of mainland of China, which may suggest that the development of the inland medium and small cities in China may be slower than the average level of the whole China.

4.2 *Maximum air temperature (T_M), minimum air temperature (T_m) and daily temperature range (DTR)*

Figs. 5(a-c) shows the variations in annual average T_M , T_m and DTR. During the 45-year period examined, the average annual maximum air temperature in Nanchang increased sharply, with $T_{M2003-2012}$ 1.16 °C higher than $T_{M1967-1976}$. The linear increase trend in average temperature observed in Nanchang was deemed statistically significant at a confidence level of 0.01. The average annual maximum air temperature in Jiujiang also rose sharply, with $T_{M2003-2012}$ calculated to be 1.20 °C higher than $T_{M1967-1976}$. The linear increase trend in average temperature observed in Jiujiang was also deemed statistically significant at a confidence level of 0.01.



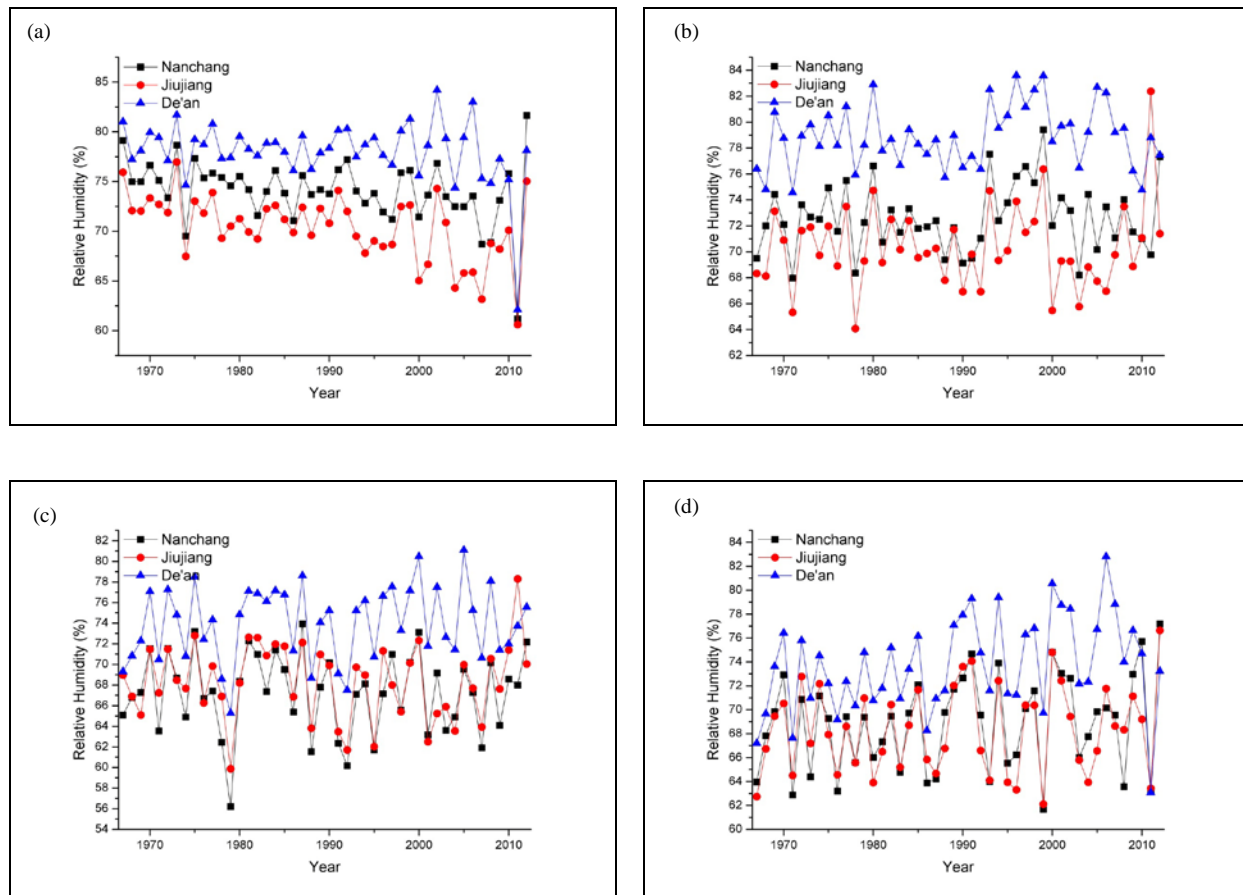
Figs. 6(a&b). Changes in the number of hot days (a) and cold days (b) in Nanchang, Jiujiang and De'an (1967-2012)

Figs. 5(a-c). Temperature changes in Nanchang, Jiujiang and De'an by Year (1967-2012): (a) Average maximum air temperature; (b) Average minimum air temperature; (c) Daily temperature range

Fig. 7. Changes in Relative Humidity in Nanchang, Jiujiang and De'an by Year (1967-2012)

De'an also saw an increase in average annual maximum air temperature, with $T_{M2003-2012}$ calculated to be $0.89\text{ }^{\circ}\text{C}$

higher than $T_{M1967-1976}$. The linear increase trend in average temperature observed in De'an was deemed



Figs. 8(a-d). The changes in relative humidity in Nanchang, Jiujiang and De'an in different seasons by year (1967-2012) (a) Spring, (b) Summer, (c) Autumn and (d) Winter

statistically significant at a confidence interval of 0.05, but failed a significance test at a confidence level of 0.01. These results suggest that there has been a greater T_M increase in the medium and large sized cities versus the small county.

The changes in average minimum air temperature by year are shown in Fig. 5(b). During the 45 years, the increase in Nanchang's minimum temperature was greater than that observed in its maximum temperature, with $T_{m2003-2012}$ calculated to be 1.27°C higher than $T_{m1967-1976}$. During the same period, the minimum air temperature in Jiujiang increased 1.33°C and that in De'an increased 0.85°C. The linear increase trends in average minimum air temperature for the three cities were established at a significance level of 0.01. During the 45-year period spanning 1967 to 2012, the average values of the minimum air temperature in Nanchang, Jiujiang and De'an were 14.74°C, 14.51°C and 13.06°C, respectively. The average minimum temperatures in Nanchang (a large city) and Jiujiang (a medium-sized city) were

similar to each other, with both ~1.5°C higher than that the average minimum temperature recorded for De'an (b) small county), indicating that city size also has a significant impact on the local minimum temperature.

The changes in the yearly average DTRs in Nanchang, Jiujiang and De'an are shown in Fig. 6(c). During the 46-year period examined, the average DTRs measured for Nanchang and Jiujiang were 7.0°C and 6.7°C, respectively. The DTR in De'an (8.4°C) was significantly higher than large and medium sized cities. By comparing changes in $DTR_{2003-2012}$ and $DTR_{1967-1976}$ in these three cities, we found that the DTRs in Nanchang and Jiujiang fell 0.12°C and 0.13°C, respectively. By contrast, the DTR in De'an rose 0.09°C during the same period. These results suggest that the change in DTR in a given city is correlated to the size of the city: faster urbanization in large and medium cities resulted in a gradual decrease in DTR, whereas small cities saw a slight increase in DTR due to the relatively slow pace of

the urbanization process. However, changes in DTR observed in the three cities were not evaluated as significant at a significance level of 0.01. Therefore, it can be concluded that the DTRs measured in the three cities were not been significantly affected by urbanization, contrary to findings derived from studies on developed coastal cities.

4.3. Hot days and cold days

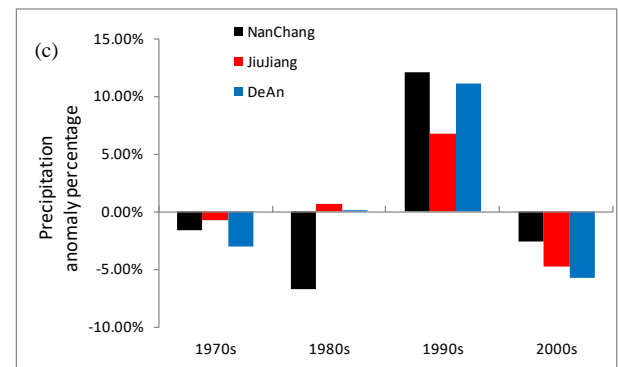
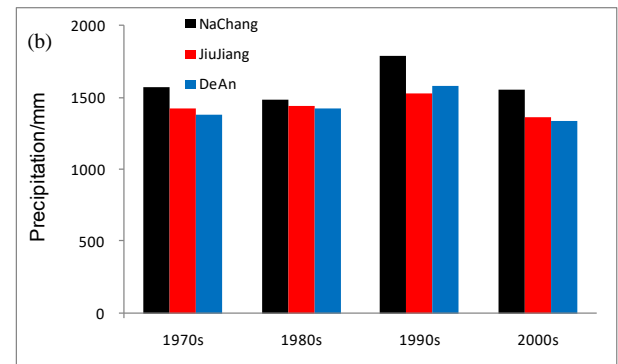
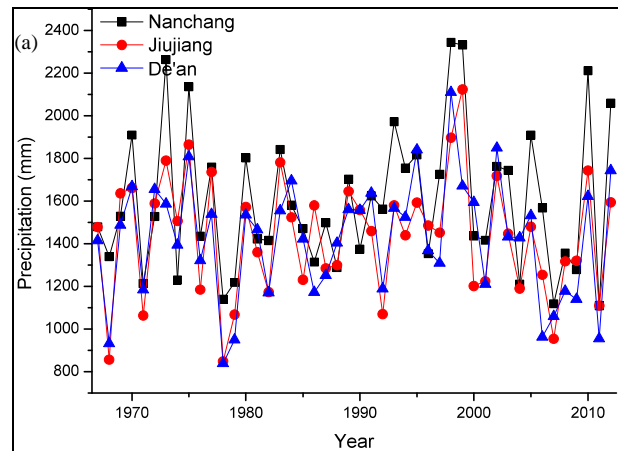
Fig. 6(a) shows the number of days when the temperature exceeded 35 °C (the heat alert threshold) in the three representative cities. As shown in the figures, the number of the hot days increased significantly in Nanchang and Jiujiang during the past 45 years, with increases of 9.8 days and 5.1 days recorded for the two cities respectively in the period of 2003-2012 compared with the period of 1967-1976. In the case of De'an, the number of hot days only increased by 1.3 days. However, the changes in the number of hot days in the three cities were not deemed statistically significant at a significance level of 0.01.

If the temperature drops to or below 4 °C, the Jiangxi Meteorological Bureau will issue a cold wave warning to alert the public to the upcoming cold weather. The changes in the number of cold days in the three representative cities are shown in Fig. 6(b). In Jiangxi Province, the number of cold days in Nanchang, Jiujiang and De'an decreased significantly during the 45-year period examined. The number of cold days noted for Nanchang, Jiujiang and De'an decreased by 17.2, 18.8 and 9.5 days respectively in the period of 2003-2012 compared with the period of 1967-1976. Decreases in the first two cities were deemed significant at a confidence level of 0.01, indicating that the number of cold days fell sharply along an obvious downward trajectory in inland cities in East China as a result of the urbanization process.

4.4. Relative humidity

The changes in the relative humidities in the three representative cities observed since 1967 are shown in Fig. 7. The relative humidity changes observed in all three cities were not dramatic, and were not deemed statistically significant at a confidence level of 0.01.

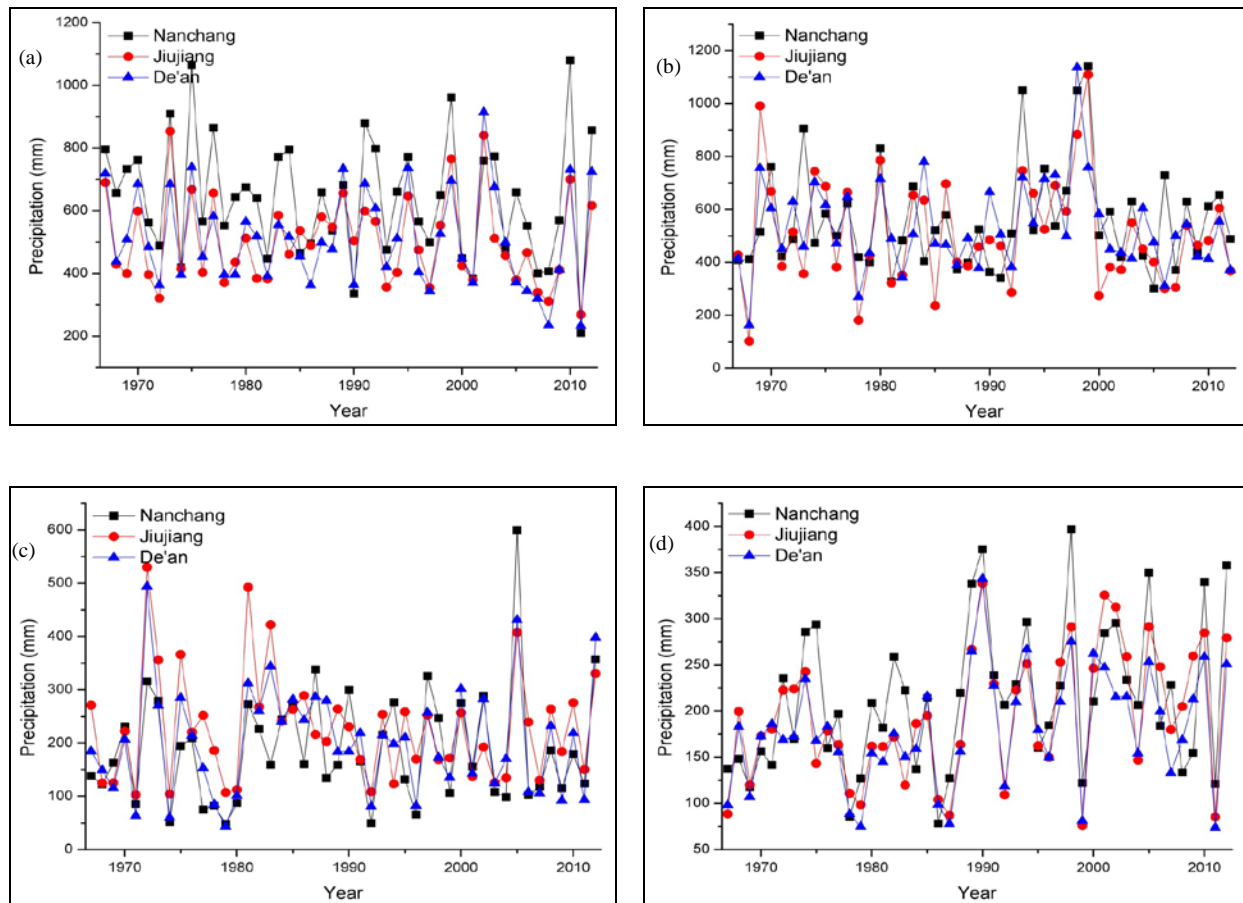
In De'an, the relative humidity rose 2.10%, corresponding to an increase trend of $\sim 0.46\%$ /10a. According to Zheng and Liu (2008), the relative humidity in downtown Beijing fell as urbanization progressed, in contrast to the slight rise in the relative humidity observed in suburban areas. As introduced in the previous sections, De'an is located between Nanchang and Jiujiang and the



Figs. 9(a-c). Precipitation in Nanchang, Jiujiang and De'an (1967-2012) (a) by year; (b) by decade; (c) anomaly percentage by decade

urbanization in De'an remained slow. In this respect, De'an can be regarded as the suburbs of Nanchang (a large city) and Jiujiang (a medium city) and therefore shares similar changes in the relative humidity with Beijing's suburban areas.

The decreases in the relative humidity in Nanchang (a large city) and Jiujiang (a medium city) can be seen in



Figs. 10(a-d). The variations of precipitation in Nanchang, Jiujiang and De'an in different seasons by Year (1967-2012) (a) Spring, (b) Summer, (c) Autumn and (d) Winter

Fig. 7. Comparing the period of 2003-2012 with the period of 1967-1976, the relative humidities in the two cities fell 0.85 per cent and 1.4 per cent respectively, corresponding to decline trends of 0.18%/ 10a and 0.30%/ 10a, respectively. The reason why the humidities in Nanchang and Jiujiang declined can be attributed to the change of the underlying surface during the urbanization processes of the two cities. Accompanied with the expansion of the urban area, more impervious surfaces appeared in the cities, which reduced water content and thereby causing changes in relative humidity [Chandler (1967), Lee (1991)].

Figs. 8(a-d) illustrates the variation of the relative humidities of the three cities in different seasons, from which it can be found that most obvious differences between De'an and the other two cities can be observed in summer, for summer is the rainy season in the three cities and the impact of the impervious surface on the water content and relative humidities are most obvious in this season.

4.5. Precipitation

As far as the impact of urbanization on the precipitation, relevant research findings vary from region to region. Figs. 9(a-c) shows the annual precipitation in the three cities examined. As shown, the annual precipitations in Nanchang, Jiujiang and De'an fluctuated widely during the past 45 years. Comparing the period of 2003-2012 with the period of 1967-1976, the average annual precipitation decreased in Nanchang, Jiujiang and De'an by 3.1%, 8.5% and 9.8%, respectively. However, the decrease in the precipitation during the first ten years of the 21st century may be attributable to interdecadal changes in background climate in the region, and is not necessarily correlated to urbanization, given that all three cities showed greater precipitation in the 1990s (a period characterized by rapid urbanization) than in the 1970s and 1980s [Figs. 8(b&c)].

When checking the situations in different seasons (Figs. 10(a-d)), it is interesting to find that though the

trends in spring, summer and autumn are not significantly obvious, an increasing trend can be detected in winter. This is possibly related to the seasonal variation of the urban heat island in Nanchang. In some previous studies, more obvious urban heat island cases are observed in winter than in the other 3 seasons [Wanyou and Xiaoming (1998)] and many previous studies showed that the urban heat island will induce convection and consequently will bring more precipitation [Dixon and Mote (2003)].

4.6. Analysis and discussion

The populations, the GDPs and the built-up areas of the Nanchang and Jiujiang continued to grow as urbanization proceeded in the last decades, whilst the development of De'an is not fast and keeps as an undeveloped small county. The speed of the urbanization was correlated to city size: Nanchang, as a large city, witnessed the largest increase in the population, the GDP and the built-up area, followed by Jiujiang and De'an, in that order. In particular, due to its small size, the underlying surface of De'an, dominated by forests, farmlands and water bodies has remained largely unchanged, despite the economic growth and the urban expansion of the city.

The paces of urbanization varied between the three cities, resulting in different effects on local climates. The three cities show a similar a pattern of changes: the increases in T_a , T_m , T_M and the number of hot days, and the decreases in the number of cold days. However, the extent of the changes observed varied among different cities. The DTR dropped slightly in Nanchang and Jiujiang, but increased moderately in De'an. Similarly, the relative humidity fell in Nanchang (a large city) and Jiujiang (a medium city), but increased slightly by 2.1 per cent in De'an (an undeveloped small county).

The correlation coefficients for population and the annual average of the five climatic factors measured in the three representative cities between 1990 and 2010 are shown in Table 3. As can be seen, the correlation coefficients for the three climatic factors, *i.e.*, T_a , T_M and T_m , and the local population were also correlated to city size, with the highest coefficients assigned to Nanchang, followed by Jiujiang and then De'an. The correlation coefficients for population and the aforementioned three climatic factors in all three cities passed a statistical significance test at a confidence level of 0.01 and a positive correlation was established between the climatic factors and the population. The absolute values of the correlation coefficients between DTR/RH and the population were found to be relatively small in all three cities, indicating that DTR and RH are not closely

TABLE 3

Correlation coefficients between population and the different climate criteria

City	T_a	T_M	T_m	DTR	RH
Nanchang	0.77	0.72	0.75	0.13	-0.20
Jiujiang	0.63	0.70	0.69	0.04	-0.09
De'an	0.55	0.63	0.57	0.13	0.05

correlated to the population growth. Therefore, the urbanization's impact on the local climate in the cities was deemed to be primarily reflected in the first three climatic factors, namely, T_a , T_M and T_m .

It is worth pointing out that the changes in the climate were found to be least significant in De'an, the smallest city of the three representative cities selected. This may have certain implications for the development of Chinese inland cities in the future. De'an showed the slowest urbanization speed and the smallest built-up area, and is located between a large city and a medium-sized city. It serves as an "ecological isolation corridor" (where the climate tends to be relatively stable) between the two cities, preventing excessive changes to the climate of the region. This is possibly one of the reasons why medium-to large-sized cities such as Nanchang and Jiujiang have lower temperature variability than some cities in coastal areas.

Located within an urban cluster, Shenzhen recorded a temperature rise of 1.63 °C during the same period, far higher than the increase of 1.23 °C measured in Nanchang. Therefore, the disordered sprawling of the built-up areas in Chinese cities should be avoided as the development proceeds in the future, and some ecological corridors with reasonable sizes should be designed to ensure effective protection of the natural underlying surface.

5. Conclusions

This study compared and examined the urbanization processes and the local climate changes in three inland developing cities in East China over the past 45 years (*i.e.*, 1967-2012). The conclusions are as follows:

(i) The speed of the urbanization in eastern inland cities was correlated to their regional status and original size: the bigger the city, the faster the urbanization process. The provincial capital and the regional center developed significantly faster than small county. The economic size, the population and the built-up area in the medium/large-

sized cities grew much faster than in the small county. From 1990 to 2010, the population growth rates in Nanchang (a large city), Jiujiang (a medium-sized city) and De'an (a small county) were 2.56%, 2.14% and 1.44%, respectively, indicating that the medium/large-sized cities far outstrip the small county in terms of the population growth. The annual GDP growth rates observed for Nanchang, Jiujiang and De'an were 20.18%, 21.22% and 13.72%, respectively. The urbanization proceeded faster in the medium/large-sized cities when compared with the small county. The built-up areas in Nanchang (a large city) and Jiujiang (a medium-sized city) grew 5.99% and 5.41%, respectively. The surrounding of the meteorological station of De'an has generally kept as a rural one over the period.

(ii) From 1967 to 2012, the warming rate measured for Nanchang was 0.27 °C/decade. The warming rate measured for Jiujiang was 0.23 °C/decade, and that measured for De'an was 0.20 °C/decade. The warming rate rose in line with the increase of the city size. In a comparison of 1967-1976 and 2003-2012 data, the average maximum air temperatures in Nanchang, Jiujiang and De'an increased 0.25 °C/decade, 0.26 °C/decade and 0.20 °C/decade, respectively; and the average minimum air temperatures in Nanchang, Jiujiang and De'an increased 1.27 °C/decade, 1.33 °C/decade and 0.85 °C/decade. Assuming the warming of De'an was caused by global warming, the contributions of the urbanization to the warming rate in Nanchang and Jiujiang are 25.9% and 13.0%, respectively.

(iii) The number of hot days increased significantly in Nanchang, Jiujiang and De'an during the 46-year period examined, with increases of 9.8 days, 5.1 days and 1.3 days recorded for the three cities respectively in the period of 2003-2012 compared with the period of 1967-1976. The larger the city, the greater the increase can be observed. By contrast, the number of cold days in Nanchang, Jiujiang and De'an decreased significantly by 17.2, 18.8 and 9.5 days respectively in the period of 2003-2012 compared with the period of 1967-1976.

(iv) A comparison of 2003-2012 and 1967-1976 data showed that relative humidities in Nanchang (a large city) and Jiujiang (a medium-sized city) fell 0.84% and 1.4% respectively, corresponding to decreases of 0.18%/10a and 0.30%/10a, respectively. In the case of De'an (which can be regarded as the outer suburbs of Nanchang and Jiujiang), the relative humidity rose 2.10% during the same period, corresponding to a growth rate of 0.46%/10a. From the perspective of seasonal humidities, most obvious differences between De'an and the other two cities can be observed in summer.

(v) A comparison of 2003-2012 and 1967-1976 data showed that the total precipitation declined in all three cities. However, due to the limited scope of data and analysis used in this study, we are unable to establish any correlation between the decline in rainfall and urbanization. However, an increasing trend can be detected in winter, which is possibly related to stronger urban heat island in winter.

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