URBAN SPRAWL AND WARMING - RESEARCH ON THE EVOLUTION OF THE URBAN SPRAWL OF CHINESE MUNICIPALITIES AND ITS RELATIONSHIP WITH CLIMATE WARMING IN THE PAST THREE DECADES

Xu Zhang [1], Blanca Arellano Ramos [2] *

[1] CPSV, Technical University of Catalonia, 08028 Barcelona, Spain - zxhlang960@gmail.com
[2] CPSV, Technical University of Catalonia, 08028 Barcelona, Spain - blanca.arellano@upc.edu

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ABSTRACT:

China is experiencing the largest and fastest urbanization process in the world (Kneebone E., 2013). At the same time, its current rapid urbanization process is almost simultaneously accompanied by urban sprawl. Since the 1990s, the sprawl process of Chinese cities has begun to reach a climax (Shan Baoguo, 2018). As the largest developing country in the world, China is also one of the countries most vulnerable to the coercion of climate change. This research takes the four municipalities that are China's urban development orientation as typical representatives, and uses multiple indicators to measure urban sprawl and climate change in them. Finally, models are established to explore the impact of urban sprawl on climate warming. The results showed that all four cities experienced sprawl, but to varying degrees. Shanghai is very compact. Also, the climate warming is definitely, yet urban sprawl doesn't always contribute to its deterioration. The proportion of arable land had the least impact on global warming, but it was the only factor that could improve temperatures, albeit conditionally. Fragmented built-up land heating the climate is most critical.

1. INTRODUCTION

Since the founding of New China, the level of urbanization in China has increased by about 50%. By the end of 2020, the urban permanent population accounts for about 60.6% of the total population, and a very large urban system has now been formed. However, unlike the typical urbanization process in the West, China's current rapid urbanization process is almost simultaneously accompanied by urban spraw (Hong Shijian *et al*, 2013). According to the prediction of the National Bureau of Statistics, 867,000 km^2 of cultivated land will be occupied by 2025. Many problems caused by urban sprawl have become one of the major practical problems that hinder the sustainable development of Chinese cities (Newman P. *et al*, 2011; Deng X .*et al*, 2015; Wang Jiating *et al*, 2016).

Global climate change characterized by climate warming has brought severe challenges to the sustainable development of global society, economy and environment (Uejio C K., 2011; Guo Yeyu, 2020). Due to dense population and urban heat island effect, urban areas are more vulnerable to the negative effects of climate warming (Ao Xiangyu *et al*, 2019). As the largest developing country in the world, China is also one of the countries most vulnerable to the coercion of climate change (Wang Xinyu, 2016). As the development orientation of Chinese cities, China's four major municipalities are the cities with the fastest urban development and sprawl. Through the measurement of the sprawl history of the four cities and the study of the relationship between the sprawl indicators and climate warming, we can find the law and characteristics of the sprawl of China's megacities, and better understand the relationship between urban expansion and modern climate warming. Therefore, it is more scientific and easy to find reasonable countermeasures to control the uncontrolled spread of cities and improve climate warming, and it is of reference significance to promote the sustainable development of cities and human beings.

2. METHODOLOGY

The target cities we chose are four municipalities directly under the Central Government in China. As the development orientation of Chinese cities, they are representative cities to study the sprawl and climate warming of China's megacities.

This research can be divided into two stages to develop.

The first is the theoretical research stage. Not only in China, but internationally, it has been widely recognized that China is the fastest-growing country with very high population density in urbanization (Blanca Arellano *et al*, 2016). The contradiction between the limited urban land resources and the ever-increasing population will inevitably trigger the outward expansion of cities. Compared with the advanced urban management concepts in developed countries, the theoretical and disciplinary research of urban planning in China in recent years is in its infancy, and the result is the disorderly sprawl of megacities. To this day, scholars in the world still have not made an exact and unified definition and measurement method for urban sprawl, even though the United States has taken the lead in researching urban sprawl phenomena since the middle of the last century. Because of that, we need to research and organize various indicators and measurement methods.

On the surface, climate change is negatively affected by urban development (Blanca A. *et al*, 2015). However, scholars in different fields have different opinions on this issue. High-density population and buildings are indeed the main culprits of climate deterioration. The increase in commuting distance leads to massive fuel consumption and more greenhouse gas

* Corresponding author

emissions. But fragmented construction land has brought hope to climate restoration. Based on this, I need to consider the relationship between different sprawling indicators and climate change in the next empirical study.

The second stage is to analyze the four municipalities directly under the Central Government in China. Different countries and regions have different development characteristics, and their urban sprawl characteristics are also different (Roca J. *et al*, 2011). So we want to study and sort out the different measurement methods between international and Chinese scholars, and summarize and analyze the different classification indicators applicable to China's urban development. Among them, the most important thing is to take population as the key research object, and it also contains the most indicators. Different scholars have also put forward different analysis standards regarding temperature rise. We will use the heat index calculation formula and grading standard published by the National Meteorological Administration of the United States, as well as the frequency of high temperature weather, the maximum duration and other indexes for quantitative analysis based on the classification standards of the Chinese Meteorological Administration for the temperature of Chinese cities. Finally, an analysis model is established to find the correlation between the different indexes between the two and compare them, analyze the correlation degree of the different indexes, and also summarize the evolution law of urban sprawl and climate change.

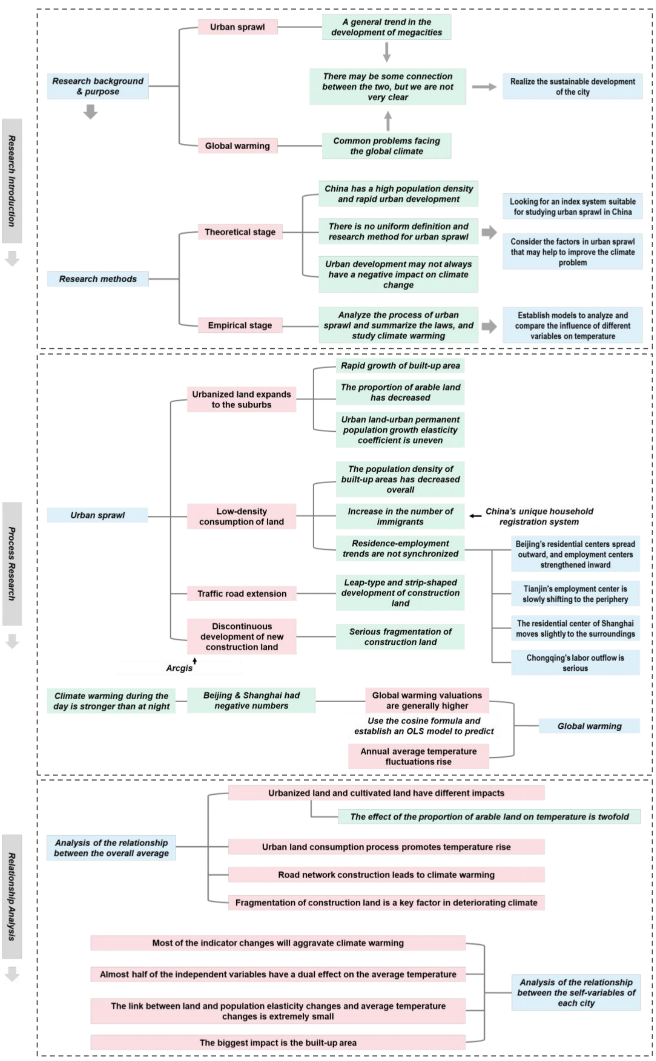

Figure 1. Research method flow chart.

3. URBAN SPRAWL PROCESS

This part will measure the sprawl process of China's four major municipalities from 1990 to 2019 from indicators such as different types of land use increments, population density and urban land spatial morphology and analyse the characteristics of the development of urban sprawl phenomenon.

3.1 Urbanized land expands to the suburbs

Built-up areas refer to urbanized areas in cities in China. China's statistics department uses built-up areas to reflect the size of a city's urbanization area. Since the establishment of the four major municipalities in China, the rate of urbanization has accelerated rapidly, and the built-up areas have continued to expand and expand to the surrounding areas. From 1990 to 2019, they generally increased by about 3-4 times of their own. One of the most noteworthy is Chongqing's urbanized land, which has been growing rapidly for 30 years. From 87km^2 in 1990, it was the smallest of the four cities at this time, an increase of more than 34 times, becoming the city with the most urbanized land area.

While the area of urban land has spread outward, agricultural land will inevitably decrease. Beijing is the city with the most expansion of non-agricultural land, and the proportion of arable land has been declining. It dropped to about 13% in 2019, and it did not exceed 25% at the highest point. Next is Shanghai, which dropped from 50.97% to the final 30.52%, but its situation has improved after 2013, and the trend has changed to a slow rise. The proportion in Tianjin is the most stable among the four cities. It has experienced a process of slow decline and recovery, although in the end it was only reduced by about 3% from the beginning. What is different is that the proportion in Chongqing is on an overall upward trend. It has experienced a substantial increase almost every five years.

The growth rate of urbanized land area is greater than the growth rate of non-agricultural permanent population is the most significant feature of urban sprawl. During the 30 years of the study period, the growth rate of urban area land in China's four major municipalities far exceeded that of urban residents (Table 1). The growth rate of Tianjin, where the difference between the two is the smallest, is that the expansion rate of built-up areas in Tianjin is also twice the rate of urban population growth. Chongqing has a vast area and more land can be developed and used as urban land and the growth rate of land is about twice the population.

Item	Beijing	Tianjin	Shanghai	Chongqing
Growth rate of built-up area (%)	270.1%	243.6%	395.2%	1831.6%
Growth rate of urban permanent population (%)	133.7%	167.5%	148.0%	466.2%

Table 1. Comparison of the growth of built-up area and the growth of urban permanent population from 1990 to 2019.

The United States and other Western developed countries usually compare the growth rate of urbanized land with the growth rate of population as an important indicator of urban sprawl. That is, the sprawling city usually has a significant increase in the area of urbanized land and is faster than the population growth rate in the duration. This indicator is often used as one of the indicators for judging the degree of sprawl of

Chinese cities because of its quantifiable nature. The calculation formula of land-population elasticity coefficient is as follows:

$$D = \frac{\Delta T}{\Delta R} * \frac{R}{T} = \frac{\Delta T / T}{\Delta R / R} \quad , \tag{2}$$

Where D = the elasticity coefficient of land population
ΔT = the change value of land area over a period of time
ΔR = the value of population change over a period of time
R and T = represent the initial land area of this type and the number of permanent residents

Through the analysis of the growth elasticity coefficient of the urbanized land area and the urban permanent population in the four municipalities directly under the Central Government (Figure 2), we can directly know that most of the four cities have been in the sprawl stage during the past 30 years. Only in a few years, the increase in urban land area of some cities is smaller than the increase in urban population, which belongs to concentrated development or compact development. Especially in recent years, that is, after 2015, the urban land and population elasticity coefficients have shown large-scale negative values.

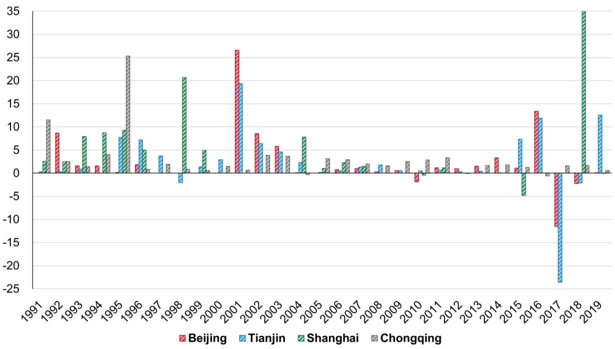

Figure 2. Land area of built-up area-urban non-agricultural permanent population growth elasticity coefficient.

3.2 Low-density consumption of land

In 1990, Chongqing and Shanghai were the two cities with the highest density of residents among the four major municipalities in China, with 42,368.97 people/km^2 and 34,578.4km^2, respectively. However, the non-agricultural population density of Chongqing declined the fastest, with Beijing and Tianjin in 2019. The data is similar, about 12,400 people/km^2. Shanghai can be regarded as an intensive urban development in terms of land utilization per unit of population.

The larger the foreign population, the inevitably leading to the spread of urban land. Except for Chongqing, the proportion of foreign population in other cities increased first and then stabilized or declined slightly. The population inflow rate was relatively fast in 2006-2014, and reached its peak in 2014. On the contrary, Chongqing's attractiveness to the population is very small, and the number of registered population is smaller than the permanent population, which shows that there is a serious population exodus.

In addition, there has also been a phenomenon of dislocation of residence and employment (Figure 3): the residential centers in Beijing and Shanghai have moved out, and the employment centers have been strengthened inward; the Tianjin employment centers have moved to inner city; Chongqing has a serious labour loss.

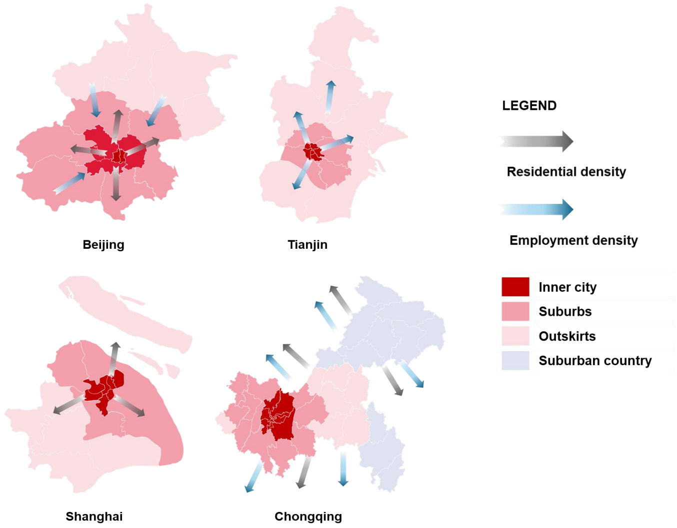

Figure 3. Residential employment centre moving.

3.3 Traffic road extension

Another important manifestation of urban sprawl is that as the area of urban land becomes larger and larger, the places of residence and employment of residents are misaligned, urban commuting roads also need to be continuously lengthened, and the road network is becoming more and more dense. We found that in the past 30 years, the mileage of traffic roads has generally increased by more than 3-4 times, especially in Chongqing, where the road length at the end of 2019 was 10 times the original.
At the same time, the density of the highway network has also experienced substantial growth. However, Tianjin's overall growth has been slightly slower, and even the density of the road network has decreased in recent years, making it the smallest of all cities, about 1.276km/km^2.

3.4 Discontinuous new construction land

We drew a map of the changes in the distribution of construction land in major years for the four municipalities (Figure 4), also marked the railways and major highways (national highways) in 2020. It is obvious that the construction land of each city has evolved from being compactly concentrated in the central urban area in 1990 to a fragmented layout that is almost all over the city. Jumping and striping have become the main features of new construction land.

In order to digitize the degree of fragmentation of the newly added construction land, so that further research can be carried out more smoothly, we first reduced the resolution of the grid map of construction land in 2000, 2010 and 2020 to 1000 meters, and then analyzed all the data from 1990 to 2020. The raster maps of the main years are transformed into vectors, and finally the distribution map spots of construction land are obtained. Finally, the statistics of the number of map spots for construction each year show the degree of fragmentation of construction land, and it is found that the growth patterns of the four cities are very the same on the whole. The number of fragments is increasing rapidly, and the degree of fragmentation is getting worse.

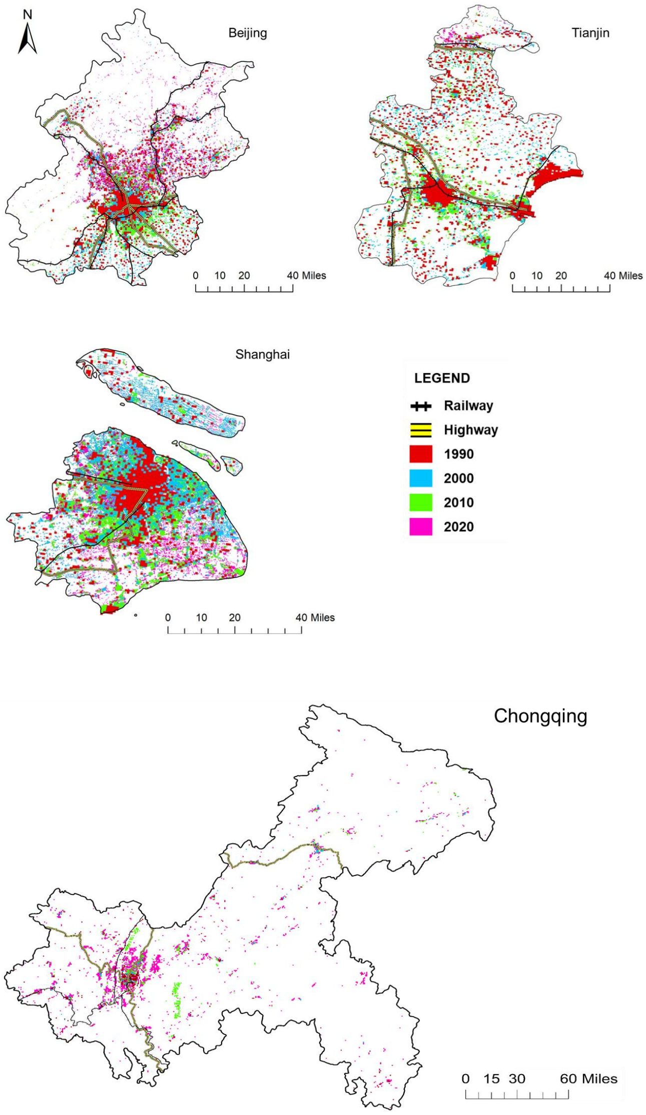

Figure 4. New construction land changes in major years.

4. CLIMATE WARMING ANALYSIS

China is one of the sensitive areas of climate change. The problem of climate warming and the threats it poses to people's living and working, industrial manufacturing, and agricultural production are particularly serious. China has a vast territory with a latitude span of approximately 49°, complex topography and landforms, and diverse climate types. The four municipalities are distributed in different latitudes, inland and coastal areas in China, and their temperature warming is also different. This part will measure the average temperature of each city and their rate of increase, as well as the 30-year global warming predicted by the OLS model.

4.1 Global warming valuations are generally higher

In order to analyze global warming, the study obtained the monthly average temperature of the four municipalities directly under the Central Government from the China City Statistical Yearbook, which is currently the smallest event unit of Chinese city meteorological data that can be obtained. Use monthly temperature to find the month with the highest temperature, which is jointly represented here as July. Then use the cosine formula (2) to calculate the month*.

$$month^{*} = cos\frac{2\pi(m - m_{max})}{12} \quad , \tag{2}$$

Where Month* = the cosine month code
m = the month code, from 1 to 12
m_{max} = the month with the highest temperature (℃)

Then only the year, month*, average temperature, maximum temperature and minimum temperature are used to construct the OLS regression model. Finally, multiply the regression coefficient of the year by 30 to get the global warming prediction index for that temperature (Figure 5).

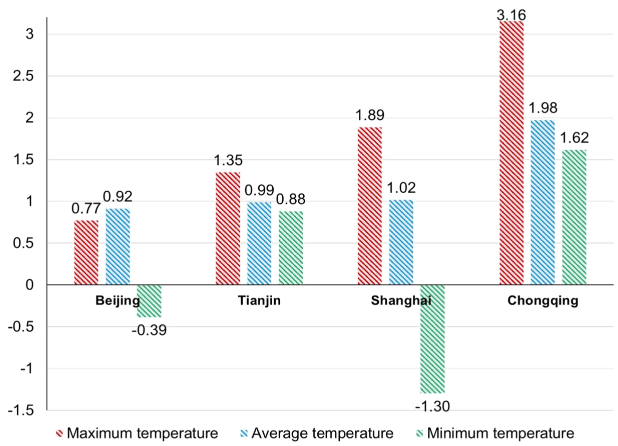

Figure 5. Global warming valuation.

Obviously, from 1990 to 2019, Chongqing was the city with the highest global warming index among the four municipalities directly under the Central Government. The most prominent was the highest temperature, which was as high as 3.16s°C. The average temperature and the smallest temperature were 1.98°C and 1.62°C, respectively. This is followed by Shanghai, whose maximum temperature is predicted to warm by 1.89°C. The average temperature of the other three cities is predicted to be around 1°C.

Beijing has the smallest global warming, with a maximum temperature of 0.77°C, which is less than the average temperature. The maximum temperature in Tianjin is 1.35°C, and the minimum temperature and the average temperature are similar to about 0.88°C.

However, there is a different situation. The minimum temperature of Beijing and Shanghai have a negative estimate of global warming. In particular, Shanghai has become colder by 1.3°C in 30 years. If the maximum temperature is regarded as the temperature during the day and the minimum temperature is regarded as the temperature value measured at night, it can be explained that the intensity of global warming experienced by each city during the day is more intense than at night, and the night temperature in Beijing and Shanghai is improving. Global warming has been improved during this period.

4.2 Annual average temperature fluctuations rise

Overall, the general trend of the annual average temperature of each city in 30 years has been rising, but fluctuating greatly (Figure 6).

The temperature changes in Beijing and Tianjin are almost synchronized, but Tianjin has better temperature control capabilities than Beijing. The temperature in the two cities has risen from 13°C in 1990 to about 14°C in 2019. The temperature in Tianjin is about 0.5°C cooler than Beijing as a whole, but it is 0.4°C hotter than Beijing in the last few years.

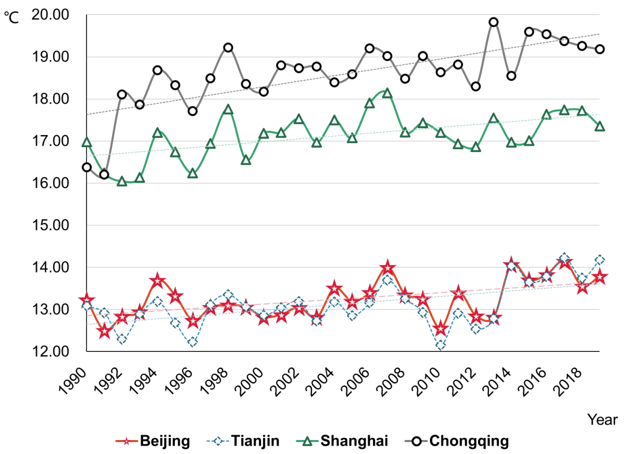

Figure 6. Average temperature change from 1990 to 2019.

Chongqing has the highest temperature and the fastest rising speed, which changed from 16.38°C at the beginning to 19.18°C at the end. However, its warming situation has improved after 2015, and the temperature has continued to drop for 5 years.

The average temperature of Shanghai is 1°C-2°C lower than that of Chongqing, and its trend line has the smallest slope, which means that the rate of climate warming is the slowest.

However, it was warmer than Chongqing in 1990, about 16.98°C. In the following 30 years, it has risen by less than 1°C. Its temperature reached its peak in 2017, about 18.15°C.

5. RELATIONSHIP RESEARCH

Urban sprawl is the most prominent manifestation of urbanization, and climate change is one of the most obvious problems brought about by the process of urbanization. Therefore, we have reason to propose a conjecture that there are some or more internal connections between urban sprawl and climate warming and worthy of being studied. Therefore, this chapter will focus on the research and analysis of the relationship between the two.

Based on the various indicators of urban sprawl we analyzed above, we can take the different performance aspects of urban sprawl as independent variables, and the average temperature as the dependent variable, and analyze the impact of different indicators on climate change through regression models. We can classify which indicators support climate deterioration and which ones are conducive to climate recovery.

5.1 The relationship between the overall averages

In order to explore the rough relationship between each indicator and temperature changes and find an overall representative law, we took an average value for each research indicator of the four municipalities, and analyzed the common relationship between urban sprawl and climate warming in the four municipalities. In the next part, we will analyze more characteristic influence relationships for each city.

5.1.1 Urbanized land and cultivated land have different impacts: By studying the relationship between the average temperature change and the various indicators analyzed in the research section of urbanized land area, we can believe that the expansion of urbanized land will exacerbate global warming, but the role of arable land content is not single.

First, with the expansion of the built-up area of urban land, the average temperature gradually rises. At the same time, it can also show that as the built-up area expands, the rate of temperature rise is slower and slower. When the area of the built-up area continues to increase, the rate of temperature rise will infinitely approach zero, even if it will still increase indefinitely in theory, but at that time it has reached a level of saturation, and the growth of urban land area has almost no effect on climate warming.

Secondly, what is interesting is that the proportion of cultivated land has a two-way effect on temperature. The relationship between them is a quadratic polynomial. Through calculation, we can find that the minimum value of this formula is about 23.44%, which results in a slope of 0. When the proportion of cultivated land is less than that, the temperature will slowly become colder as the proportion of cultivated land increases; when the proportion of cultivated land is greater than this number, the increase in the proportion of cultivated land will accelerate the deterioration of the climate.

Finally, the area of built-up areas and the elasticity of population growth will also make climate warming worse, and their relationship can also be expressed by a quadratic polynomial. When the coefficient of elasticity exceeds 84.33, the temperature will not increase but will be improved, but this also means that the growth rate of the built-up area is more than 80 times that of the population, which is almost impossible to achieve.

5.1.2 Urban land consumption process promotes temperature rise: We can clearly find such a trend. As the population density in built-up areas increases, the average temperature decreases significantly. Combined with the results of the previous analysis, the overall urban population density of the four cities has shown a decreasing trend, which shows that the temperature is increasing with the low-density consumption of urban land.

Another indicator is the degree of residence-employment misalignment in the central area. In order to more easily analyze its relationship with climate warming, we use the calculation result of formula (3) to reflect the degree of misalignment.

$$D = \left| \frac{\rho E}{\rho R} - 1 \right| \quad , \tag{3}$$

Where D = the degree of dislocation between population residence and employment in the central city

ρE = the employment density of the central city

ρR = the housing density

The result obtained by calculation is that the figure of the degree of dislocation in the city center has been reduced. The relationship between them is more in line with the power function equation. The greater the value degree of dislocation between the residence and employment of the permanent residents in the urban center area, the cooler the temperature will be, and its slope will gradually become smaller, which means that the rate of cooling will become slower and slower.

5.1.3 Road network construction leads to climate warming: Another contributing factor to climate warming is the intensive construction of road networks. Studies have found that there is a positive correlation between road network density and average temperature, and this promotion relationship is weakened as the road network becomes denser. It means that the rate of temperature rise will become slower and slower.

5.1.4 Fragmentation of construction land is a key factor in deteriorating climate: Since the latest data we can get over the years is for 2020, but there is no data for 2019, we need to model the temperature data and calculate the average temperature for 2019 in order to compare the relationship.

Through the comparison of seven data, we can see that the average temperature is proportional to the number of debris in the construction land. R^2 is very high, reaching 0.783, and the correlation between them is the closest. Through the analysis of the relationship, it can be known that with the accuracy of 1km, the average temperature will increase by 0.2°C for every 1,000 pieces of debris increase.

Moreover, from the above model, it can be seen that the slope of the curve of the relational expression is mostly less than 45°C. Even if there is, it is only when there is only one value. This shows that the average temperature and the urban sprawl analysis variables develop at different speeds, and the change speed of the spread indicators is faster than the temperature change.

5.2 Analysis of the relationship between the self-variables of each city

The above content analyzes the relationship between the average value of all the sprawl indicators and the average temperature in the 4 cities. Next, it is very necessary to explore and explain the relationship between the independent variables of each city and their average temperature in order to clarify their own development, features and differences compared to the overall change relationship.

Obviously, there is generally a strong positive relationship between the increase in the urbanization built-up area of each city and the increase in average temperature. Among them, the role of Shanghai and Chongqing is one-way, and the temperature rises slowly with the increase of built-up area, and the slope will gradually tend to zero. Theoretically, the impact of Tianjin's urbanized land area on temperature is two-way, with 500km^2 as the axis of symmetry. But in fact, the equation image we get almost only retains the right half, which is the part that promotes the temperature rise. Even if there are still some area values less than 500km^2, their slope is almost 0, and the effect on temperature can be ignored. While the Beijing model curve shows obvious bidirectionality. When the area is less than 850km^2, the expansion of urban land will cool the temperature, and if it exceeds this number, it will heat the temperature. However, the data shows that in 30 years, more than 850km^2 will be the majority, and the built-up area will become larger and larger in the future. Contrary to the previous group of cities, when the built-up area of Beijing and Tianjin is heating up, the temperature increases faster and faster, but the opposite is true when cooling down.

The relationship between the climate of Beijing and Tianjin and the proportion of cultivated land is not obvious, but there are two modes of change in Shanghai and Chongqing. First, when the agricultural land in Shanghai accounts for more than 35% of the total area, the average temperature rises at a slower rate as the proportion of cultivated land decreases. When the proportion of arable land continues to decrease, the temperature will decrease and the speed will increase. Different from other cities, according to the previous analysis, the overall trend of the proportion of cultivated land in Chongqing is gradually increasing, but the average temperature will not improve, instead it will increase, and its speed will slow down.

Similarly, Shanghai and Chongqing show a stronger relationship between population density and temperature in built-up areas than the other two cities. As the population density decreases, the average temperature also rises. Although it is more appropriate to use a quadratic polynomial in Chongqing's relational expression, it only retains the image on one side. The Shanghai model formula is linear, and the slope will not change but less than 45°. The rate of temperature increase in Chongqing is gradually decreasing.

When analyzing the relationship between major road networks and temperature changes, Chongqing's relationship model fits better. The denser the road network, the higher the average temperature, but the speed will continue to decrease.

Chongqing has the highest correlation between the increase in the number of construction land fragments and the increase in temperature, with an R^2 of 0.71. The temperature rises steadily with the increase in the number of fragments. In this analysis, the slope of the curve is very small, gradually tending to zero. The second is Shanghai, where there is a linear relationship between the number of construction land fragments and the temperature. The temperature rises by approximately 0.3°C for every 1,000 additional construction map spots. Its slope is still less than 45°.

6. FINAL CONCLUSION

Generally, the four cities have experienced different degrees of sprawl in 30 years, and this sprawl is accompanied by a higher population density. At the same time, the three cities except Chongqing attract a large number of migrants. We can roughly divide their development process into three stages:

1. The first is the slow development stage, that is, before 1996-2000, all cities are in the initial stage of development, and at that time the economy and productivity have just recovered. Although the city has been developed to a certain extent, the degree of development is far from enough. The population is greatly affected by the household registration system, and urban sprawl is proceeding smoothly.

2. The second stage is a period of rapid development. Due to various population and land development policies, and greatly improved living standards, the original urban standards can no longer meet the needs of the society. A large amount of rural land has been developed into built-up areas, and most cities have entered a stage of rapid spread.

3. Finally, after 2012 or so, due to the limited urban space and the government's control by relevant measures, people realized the problems and certain negative effects brought about by excessive urban sprawl. The speed of urban sprawl has slowed down, and some of these indicators have even reversed. However, indicators such as the fragmentation of construction land and the area of built-up areas continue to increase or even become more rapid.

Beijing is a typical representative of urban sprawl. The various indicators measured are in line with the characteristics of urban sprawl, and most of the indicators have developed rapidly. On the contrary, some indicators in Shanghai are characterized by compact development, especially the distribution of construction land, which is evenly spread across the entire range. The population density is also the highest. Chongqing developed slowly in the early days. After it was established as a municipality directly under the Central Government in 1997, urban sprawl began to progress rapidly, but the proportion of cultivated land showed a significant increase, and a large amount of labor was lost. The development process of Tianjin is the most stable, and the characteristics of the multi-center model of construction land clusters are obvious.

The relationship model established by using the overall average value can more clearly see how the different performance characteristics of urban sprawl affect the increase in average stability:

1. Fragmentation of construction land is the main factor that has the greatest impact on climate warming, and it is directly proportional to the rise in temperature.

2. The second is the degree of housing-employment misalignment in the central area. The built-up area and urban population density will worsen the climate warming problem.

3. Although the population elasticity coefficient of the built-up area does not have a particularly significant development law, its growth will also cause the temperature to become hotter.

4. In addition, the least influential is the proportion of arable land, but it is the only factor that can improve climate warming. At the same time, it also verifies the hypothesis that not all spreading features will accelerate the temperature increase, though such improvement is conditional. Before reaching a certain value, the decrease in the proportion of arable land will cool the temperature. Once this number is exceeded, the effect will be the opposite.

5. The rate of change of all independent variables and the average temperature is not the same, they develop at an allometric rate, and the rate of change of most independent variables exceeds the rate of temperature.

If we analyze the sprawl indexes and average temperature of each city, we can find that it is difficult for them to have a high degree of correlation with temperature changes on the same independent variable, which shows that their respective influence methods and main factors are different. The most relevant is the area of built-up areas. On the contrary, the elasticity of land population has almost nothing to do with climate change. But roughly speaking, their spreading indicators are all aggravating climate deterioration, and models with factors that improve the climate function all have a negative influence at the same time.

Therefore, we can consider that urban sprawl can improve climate warming to a certain extent, but its more main function is to make the temperature hotter.

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