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Quantitative Assessment of Climate Carrying Capacity for Cities: A Case Study of Shanghai City

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Abstract: The concept of climate carrying capacity has been proposed recently for climate risk management. Based on identification of the concept of climate carrying capacity and analysis of the relationship among its influencing factors, this study established a comprehensive assessment indicator system of climate carrying capacity from aspects of the climate situation, the level of climate usage, and the development potential of cities. Taking Shanghai City as a case study, we developed a quantitative assessment model of climate carrying capacity. The climate carrying capacity and its influencing factors were analyzed and discussed in relation to the period 2004–2013. The results were as follows. (1) Current climate natural capacity indicator showed that the climatic situation of Shanghai City was inferior to its base climatic value and it had been in a state of fluctuation. (2) The climate stress and urban coordinated development capacity indicators increased steadily, but the growth rate of the urban coordinated development indicator was less than the growth rate of urban climate stress. (3) The climate carrying capacity was far lower than the benchmark value and it had been in a state of fluctuation mainly due to the effect of current climate situation. (4) According to a principal component analysis, seven factors of urban population density, per capita GDP, energy consumption per unit GDP, total industrial output value, investment in environment protection, spending on science and technology, and green area per capita were main influential factor of climate carrying capacity. It was proved that the proposed system for assessment of climate carrying capacity of a city was feasible. It can be used to describe the spatiotemporal changes of cities, and identify problems of regional climate carrying capacity associated with their development and function. This assessment system can provide a reference for the construction of an early warning system of climate carrying capacity for cities.

Key words: climate carrying capacity; quantitative assessment; climate of cities; Shanghai City

1 Introduction

Climate is one of the most important factors in relation to the survival of the human species and all other living things (Huang and Xu 1996). According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the health of the human population is sensitive to shifts in weather patterns and other aspects of climate change (Field *et al.* 2014). These effects occur directly via change in both temperature and precipitation and in relation

to the occurrence of heat waves, floods, and droughts. In addition, health could be damaged because of ecological disruption attributable to climate change or to the consequent social response. As the most populous and fastest-developing country in the world, China is faced with serious challenges related to climate change.

From the perspective of the survival and development of human society, cities, as the major carriers that fully reflect the interaction between humans and the natural environment, are susceptible to risks related to climate change. Climate

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risk includes an increase in the frequency of extreme rainfall events, an increase in the occurrence of heat waves, and an expansion of urban areas at risk of flooding, as well as an increase in climate vulnerability due to underlying surface changes of cities (Liu and Qin 2013). Faced with increasingly serious climate-related problems, the implementation of sustainable development adaptations is the inevitable consequence for continued socioeconomic development. Cities, especially megacities, represent the forefront of a country's socioeconomic development and they are at the heart of response to climate change. Therefore, cities should adopt sustainable socioeconomic development planning appropriate to the scale of the climate carrying capacity.

Similar to many estuary cities, Shanghai City has a fragile ecological environment that is sensitive to climate change (Wang *et al.* 2015). Its rapid economic development and urbanization process has caused considerable change to its underlying surface properties, and anthropogenic heat emission problems make Shanghai City highly susceptible to the effects of extreme climate events triggered by climate change. It is particularly important to assess quantitatively the ability of the climate conditions to support socioeconomic activities and to maintain ecosystem health. The climate carrying capacity could be the best indicator with which to represent this type of carrying capacity (Zhang *et al.* 2015). Climate carrying capacity research is at an early stage and there is currently no consensus regarding the concept or its connotations and assessment methods. This study proposed a new method with which to evaluate quantitatively the climate carrying capacity of Shanghai City. A quantitative assessment method of climate carrying capacity can provide a decision basis for the sustainable development of a city, and enrich assessment theory and methodology related to urban climate carrying capacity.

2 Concept of climate carrying capacity

Carrying capacity is a concept related to ecology that originated in ancient Greece (Long and Jiang 2004). Subsequently, its research area has been extended from ecology to urban areas. In the early 1980s, the United Nations Educational Scientific and Cultural Organization (1985) proposed the concept of "resource carrying capacity." This referred to how a country or a region with a certain resource status, which satisfied a standard of living in keeping with its social and cultural norms, used its local energy, natural resources and intellectual, technical, and other capabilities to support the population of that country or region over a predictable period (Lv *et al.* 2008). Since then, the concept of sustainable development has gradually been introduced to the carrying capacity. In terms of generalization, carrying capacity is closely related to resource endowment, technologies, social choice, and human values (Pan *et al.* 2015). The essence of the carrying capacity lies in reciprocal relationship between the subject and the object; the subject plays the role

of bearing the object through exerting due functions (Kenneth *et al.* 1995).

Recent research on carrying capacity has mostly focused on ecological carrying capacity, water resources carrying capacity, land carrying capacity, population carrying capacity, and environmental carrying capacity. However, such research has often treated the climate condition as a stable background factor, failing to consider the effects of climate change or the interactions among anthropogenic activities, climate, and the environment. According to the scientific assessment reports on climate change, released by the IPCC (Field *et al.* 2014), there is no doubt that the global temperature is increasing and anthropogenic factors are most likely the principal causes of climate change (Shen and Wang 2013).

Recently, based on an analysis of the climate system, Yu *et al.* (2015) offered a clear definition of the climate carrying capacity. They claimed it was the carrying capacity of the climate system to sustain socioeconomic development. This reflected the ability of climate resources, e.g., light, temperature, water, and wind, to support any area of the social economy, such as agriculture, water resources, ecology, and population, up to regional-scale sustainable socioeconomic development within a certain time and space. The climate carrying capacity emphasizes the scale of socioeconomic activities that can be supported within the scope of the available climate resources. The essence of the climate carrying capacity is to define the influence of climate resources on human sustainable development, and to set a long-term but reasonable limit for the scale or intensity of socioeconomic development and resource exploitation. This paper considered that the climate carrying capacity reflected a mutual feedback relationship between the socioeconomic and climate systems. Climate resources can support the socioeconomic system; however, urban development affects the climate environment, changing the degree of coordination between socioeconomic development and climate resource utilization. In this environment, climate elements can change rapidly and increase climatic uncertainty, making the human-ecosystem relationship more complex. Therefore, there is strong need for a scientifically based indicator with which to evaluate quantitatively the ability of climate conditions to support socioeconomic activities and the ecosystem.

3 Quantitative assessment of climate carrying capacity for cities

3.1 Construction of climate carrying capacity indicator system

Climate carrying capacity could be measured by the direction, intensity, and scale of anthropogenic activities because the climatic environment is a receptor of anthropogenic activities (mainly socioeconomic activities). For climate elements, the pressure from anthropogenic activities is mainly embodied in underlying surface changes due to urbanization

and in physical changes of atmospheric composition due to energy consumption associated with socioeconomic development. The urban socioeconomic system and the climate system constitute a loop linking energy consumption behavior with underlying surface changes, as shown in Fig. 1. Initially, fossil fuel energy is consumed in the process of socioeconomic development, which produces large amounts of carbon dioxide and other greenhouse gases that have led to climate warming. In metropolitan areas, the building environment has experienced large changes relative to other areas. This has concentrated the discharge of residual heat, which has made the climate warming trend of metropolitan areas more obvious, and increased the risk to metropolitan areas of major disasters associated with global warming. Additionally, climate has impacted socioeconomic development via energy consumption. It has caused a considerable increase in energy consumption used for temperature control in response to climate warming. This has aggravated energy shortages and increased economic losses, thereby affecting sustainable socioeconomic development.

To evaluate the regional climate carrying capacity accurately and objectively, we constructed a complete indicator system that had a fundamental condition and theoretical basis (Zeng *et al.* 1991). The regional climate carrying capacity indicator system was an integral system that comprised a series of indicators reflecting the carrying capacity of all aspects of regional climate and socioeconomic development. These indicators, which can be quantified, were independent but interconnected, with hierarchical and structural characteristics. The goal of the indicator system was to obtain an absolute or relative comprehensive parameter that reflected the carrying condition of the climate system. The indicator selection should follow scientific, comprehensive, sensitive, dynamic, rational, and practical principles. The indicators were selected through analysis of the connotation, characteristics, and influencing factors of the urban climate carrying capacity, in conjunction with the characteristics of the study area and expert opinion. A comprehensive indicator system was proposed in this research for the assessment of the climate carrying capacity from aspects of the climate situation, the level of climate usage, and the development potential of cities. It included three criteria layers: current climate natural capacity, urban climate stress, and ability for urban coordinated development

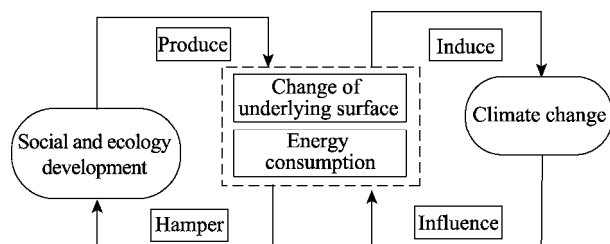


Fig.1 Closed loop between an urban socioeconomic system and the climate system

accordingly. Eventually, 24 indicators were selected to establish the climate carrying capacity assessment indicator system (Table 1).

3.1.1 Current climate natural capacity

With urbanization of almost 90% in 2013, the climate of Shanghai City is clearly subject to the stress. Socioeconomic development aggravates climatic problems such as the occurrence of heat waves and extreme precipitation events that can result in a deterioration of living conditions. Thus, the climate element condition forms the basic component in the assessment of climate carrying capacity. The concept of current climate natural capacity was used to evaluate the degree to which all climate elements deviate from the basic climatic value. If a particular climate element should deviate significantly from the basic value, then the climate carrying capacity for that year would inevitably be restricted by this particular climate factor, which would reduce the capacity of the climate to support socioeconomic development. The difference between the present situation of the climate development of a region and that of a target or ideal value was clarified through the analysis of the current climate natural capacity indicator. Therefore, this indicator could be used to evaluate the state of the climate conditions relative to the base year value. According to the level of importance of climate elements on human survival and socioeconomic development, five basic elements were chosen: mean annual precipitation, mean wind speed, extreme maximum temperature, average temperature, and extreme low temperature. These were compared with their respective 30-year (1961–1990) climate baseline values to analyze the changes of the regional climate.

3.1.2 Urban climate stress

Urban climate stress mainly refers to the pressure on the climate system caused by anthropogenic and socioeconomic production activities. These indicators can directly reflect the quality of the human living environment and the problems that might existed regarding socioeconomic development. City infrastructure construction is intended to benefit the population by improving living conditions. However, improper planning of city infrastructure construction can also result in many climatic problems. Waste gas emissions produced by industrial and transportation activities are another important source of climate stress. Thus, the urban climate stress indicator was defined in terms of urban construction and socioeconomic development. We mainly considered the impact on the microclimate caused by changes to the underlying surface because of urban construction and the warming effect due to greenhouse gas emissions in the socioeconomic development area. Urban construction was considered from the aspects of housing construction and traffic construction to analyze the influence of urbanization on the underlying surface. Socioeconomic development was mainly measured from the aspects of energy consumption, economic growth, population pressure, lifestyle, industrial and agricultural production, and environmental pollution.

Table 1 Assessment indicators and their weights in the climate carrying capacity of Shanghai City.

Target hierarchy	Rule hierarchy	Monomial indicator/Weight	Unit
Assessment indicator system of climate carrying capacity	Current climate natural capacity	A1. Mean annual precipitation/–	%
		A2. Average wind velocity/–	%
		A3. Extreme high temperature/–	%
		A4. Mean temperature/–	%
		A5. Extreme low temperature/–	%
	Urban climate stress	A6. Per capita housing area of completion/0.023	Square meters per person
		A7. Number of more than 8 layers of housing construction/0.282	–
		A8. Road length per capita/0.017	Meters per person
		A9. Urban population density/0.012	People per sq. km
		A10. Civilian vehicle ownership/0.027	Ten thousand cars
		A11. Per capita water consumption/0.007	Liter
		A12. Per Capita GDP/0.066	RMB
		A13. Energy consumption per unit GDP/0.04	Tons of standard coal per 10 000 RMB
		A14. Energy consumption elasticity coefficient/0.375	%
		A15. Total industrial output value/0.102	Hundred million RMB
		A16. Average yield per unit area/0.001	Tons per person
		A17. Urban residents family Engel's coefficient/0.001	
		A18. Per capita energy carbon emissions intensity/0.002	Tons per person
		A19. Industrial waste gas total emissions/0.045	Hundred million standard cubic meters
	Urban coordinated development ability	A20. Growth rate of GDP/0.169	%
		A21. Investment in environment protection/0.242	Hundred million RMB
		A22. Spending on science and technology/0.565	Hundred million RMB
		A23. Green area per capita/0.02	Mu/ten thousand
		A24. Proportion of tertiary industry/0.04	%

Note: indicators A6–A10 and A11–A19 reflect the urban climate stress caused by urban construction and socioeconomic development, respectively.

3.1.3 Ability of urban coordinated development

The ability of urban coordinated development means the positive contribution to the climate resulting from the development of the socioeconomic support system under the premise of the urban composite system maintaining sustainable development. The economic and social support system was analyzed mainly in terms of improving the carrying capacity of the climate and reducing climate stress caused by anthropogenic activities. The ability of urban coordinated development is influenced by the level and structure of socioeconomic development and scientific innovation and technology, which are closely related to the improvement of the human living environment. For example, the expansion of green areas not only contributes to improving the natural landscape and protecting biodiversity, but also lowers the surrounding ambient temperature. Growth of gross domestic product (GDP) means earning sufficient money to take action to improve climatic conditions. Increasing investment in environmental protection would strongly support the upgrading of traditional industry and accelerate the socioeconomic transformation. Increased spending on science and technology would also be useful in speeding up the pace of technological innovation and in

promoting breakthroughs in areas of core technology for addressing climate problems. An increase in the proportion of tertiary industry is indicative of the climate-friendly development of the economic structure. Development capacity assessment should consider the time factor, because the influences of the direction and intensity of economic and social change on climate pressure differ as a result of their different development levels during the same period (Wang *et al.* 2016).

3.2 Assessment methodology

In this study, the constructor was used to evaluate the regional climate carrying capacity. First, three indicators of the rule layer, i.e., current climate natural capacity (CNC), urban climate stress (UCS), and urban coordinated development ability (CDA), were used to calculate the climate carrying capacity of the target layer. The Nemerow Indicator method (Zhou *et al.* 2014) was used for calculating the CNC indicator. A comprehensive assessment method, based on entropy weight, was used for evaluating the UCS indicator and the CDA indicator. Finally, the climate carrying capacity of Shanghai City was calculated using the constructor.

3.2.1 Current climate natural capacity calculation based on the Nemerow Indicator method

The current climate natural capacity was determined according to the ratio of real values of all climate elements to the threshold values of regional climatic factors. The values of climate parameter thresholds were derived as the optimum theoretical values or the expected target (standard) values. Here, the climate capacity threshold was based on the regional 30-year (1961–1990) climate baseline values. Using the Nemerow Indicator method to calculate the current climate natural capacity indicator could highlight the influence and function on the climatic resource environment of the elements with the greatest loading rates in each single factor, and it could overcome the problem of various elements influencing each other when using the average method (Zhou *et al.* 2014).

The current climate natural capacity indicator calculation function is as follows:

$$CNC = \sqrt{\frac{(\bar{P})^2 + P_{\max}^2}{2}}, \quad (1)$$

where CNC is the current climate natural capacity indicator, P_{\max} is the maximum value of the single elements of climate capacity, and \bar{P} is the average value of the single elements of climate capacity.

3.2.2 Comprehensive assessment method based on entropy weight

The entropy weight method determines the factor weightings by evaluating the differences of the indicator values. This can avoid the problem of obtaining subjective weightings, which usually occurs when using the method of hierarchical analysis. According to the characteristics of entropy, the discrete degree of an indicator is determined by calculating its entropy value; the bigger the discrete degree, the more influence the indicator has on the comprehensive assessment, and the larger its weighting (Liu and Wang 2012, Zou *et al.* 2005).

First, we used the ratio method values to standardize the data, and then obtained normalized values for indicators. The target indicator method was used as a standardized method. The status of climate pressure (or the ability of development) could be evaluated conveniently by comparing the current status value with the indicator value for Shanghai City in the benchmark year (i.e., 2000). Suppose we have n evaluating objects and m evaluating indicators (here the evaluation period was from 2004 to 2013, $n = 10$; evaluating indicators referred to urban climate stress indicators, $m = 14$), then the information utility value of the indicator i can be expressed by:

$$d_i = 1 + c \sum_{j=1}^n p_{ij} \ln p_{ij}, \quad (2)$$

in which

$$P_{ij} = f_{ij} / \sum_{j=1}^n f_{ij}, \quad (3)$$

$$c = \frac{1}{\ln n}, \quad (4)$$

where d_i is the information utility value of indicator i , n is the total number of evaluating objects, c is a constant associated with n , P_{ij} is the proportion of the j th evaluating object's normalized value in the sum of all evaluating objects' normalized values for the i th indicator, and f_{ij} is the normalized value of the j th evaluating object on the i th indicator.

Finally, we determined the weightings of the evaluating indicators. The weight of indicator i can be expressed as (Liu and Wang 2012, Zou *et al.* 2005):

$$w_i = d_i / \sum_{i=1}^m d_i, \quad (5)$$

where w_i is the weight of indicator i , d_i is the information utility value of indicator i , and m is the total number of evaluating indicators.

The weight of each indicator was calculated using Eq. (5) and the results are shown in Table 1. A comprehensive assessment method was used to calculate the indicators of urban climate stress and of urban coordinated development. First, using the entropy weight method, we obtained the indicator weight of urban climate stress and then constructed a comprehensive assessment function. The calculation of the urban coordinated development ability indicator adopted the same method. The comprehensive assessment function can be expressed as:

$$E = \sum_{i=1}^m f_i W_i, \quad (6)$$

where E is the comprehensive evaluating indicator, f_i is the standardized value of indicator i , m is the total number of evaluating indicators, and W_i is the weight of indicator i .

3.2.3 Urban climate carrying capacity calculation

Based on the definition of climate carrying capacity, we used the current climate natural capacity, urban climate stress, and the ability of regional coordinated development to construct the function of urban climate carrying capacity. The formula is as follows:

$$CCI = \frac{CDA}{CNC \cdot UCS}. \quad (7)$$

where CCI is the indicator of urban climate carrying capacity, and CNC , UCS , and CDA are the current climate natural capacity indicator, the urban climate stress indicator, and the urban coordinated development ability indicator, respectively.

The current climate natural capacity indicator and the urban climate stress indicator were the contrary indicators, and the city coordinated development capability indicator was the positive indicator. Clearly, the urban climate carrying capacity indicator was a positive indicator, i.e., greater indicator values meant better urban climate carrying capaci-

ty. This meant that the smaller the value of the current climate natural capacity indicator, the closer the climate was to the baseline and thus, the larger the corresponding climate carrying capacity. Reference standards of climate stress and urban coordinated development ability were Shanghai City's indicator values in 2000. The smaller the value of climate stress, the better the ability regional development and thus, the larger the regional climate carrying capacity of the city. If the value of the regional climate carrying capacity was larger than 1, it meant that the current climate carrying capacity was superior to that of the target; otherwise, it meant the climate carrying capacity had not yet reached the target.

4 Comprehensive analyses of the climate carrying capacity of Shanghai City

The indicator data for Shanghai City during 2004–2013 were obtained from the *Shanghai City Statistical Yearbook*, *China Compendium of Statistics*, *China Energy Statistical Yearbook*, and *China Urban Construction Statistical Yearbook*. The calculation of emissions of carbon dioxide per capita in Shanghai City was based on three types of energy production: raw coal, crude oil, and natural gas. The consumption of these three types of energy accounted for more than 85% of the total energy consumption in Shanghai City during the studied years. The carbon emission coefficients of the different energy types were derived from related research (He 2015). The average agricultural output per unit area was defined as the ratio of agricultural production to the area of arable land available. Using Eq. (1) and the comprehensive assessment method based on entropy weight, we calculated Shanghai City's current climate natural capacity, urban climate stress, and urban coordinated development ability indicators. Shanghai City's climate carrying capacity and the measurement results for each rule layer during 2004–2013 are shown in Figs. 2 and 3.

4.1 Current climate natural capacity

Figure 2 shows that the current climate natural capacity indicators for Shanghai City increased slowly from 2004 to a peak in 2007, and then fell quickly, reached the lowest point in 2009, following which they increased slowly with greater volatility. Overall, the climatic condition of Shanghai City

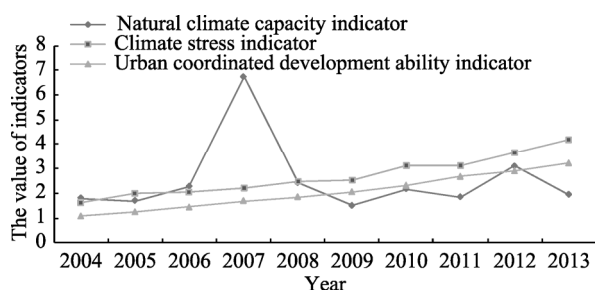


Fig.2 Variation tendency of climate natural capacity, urban climate stress, and urban coordinated development ability indicators for Shanghai City

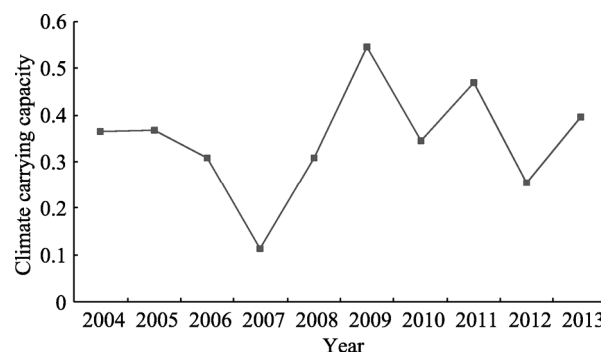


Fig.3 Variation tendency of climate carrying capacity indicators for Shanghai City

was inferior to its base climatic value and in recent years, it had been in a state of fluctuation. Based on the indicator level analysis, the reason for the large deviation in 2007 was mainly because the value of the extreme low temperature indicator in this year was 9.18 times that of the value of the reference benchmark, which caused the current climate natural capacity indicator to be extremely high. An analysis of the climate elements revealed the following: a) the extreme low temperature changed the most, i.e., it was two times higher than the base value of the climate extreme low temperature; b) average temperature indicators were also higher than the benchmark but with little deviation; c) average wind speed was lower than the climate base value after 2009; and d) extreme high temperature and precipitation events occurred around the greatest deviations from the base value. Generally, in the studied years, the current climate natural capacity fluctuated in Shanghai City, occasionally with acute volatility, which indicated that its climate system was clearly vulnerable. In addition, the extreme low temperature, average temperature, and average wind speed all changed considerably and were the main factors that affected the climate carrying capacity of Shanghai City.

4.2 Urban climate stress

The urban climate stress indicators of Shanghai City showed a trend of continuous growth (Fig. 2). The indicator layer analysis revealed that the rapid growth of urbanization of Shanghai City, in response to its socioeconomic development, had led to serious irreversible change to the underlying surface, e.g., the expansion of housing areas, increase in the number of high-rise buildings, and the expansion of the road network, which had adverse effects on the urban climate. In addition, Shanghai City had consumed considerable quantities of energy to fuel its rapid socioeconomic development. Coal and oil had accounted for a high proportion of Shanghai City's overall energy consumption structure, which had led to the emission of large volumes of greenhouse gases. Carbon emissions per capita showed a trend with an M-shaped curve. Maximum emissions occurred in 2010, following which they reduced annually, although they remained higher than the levels in 2000. The increasing lev-

el of industrial production and emissions, and the large increase in the density of the urban population had increased pressure on the urban climate. The energy structure had become the main factor constraining Shanghai City’s socioeconomic development, and the adoption of clean energy sources was imperative.

4.3 Urban coordinated development ability

As can be seen in Fig. 2, the urban coordinated development ability in Shanghai City presented a steadily increasing trend during 2004–2013. In terms of environmental protection, good economic strength provided the financial support necessary for the appropriate investment and research. Furthermore, the government implemented a series of measures for managing the high levels of industrial energy consumption and pollution, constructed many environmental facilities, and improved the capability for handling waste gas, water, and residues. All of these measures effectively reduced the pressure on the environment. The increase of green area per capita was another measure that improved climate suitability. The proportion of GDP attributable to tertiary industry had increased annually, showing that managers of Shanghai City recognized the impact of the industrial structure on climate and began to pay attention to the rationalization of the industrial structure and its diversity. Generally, the urban coordinated development capacity showed a rising trend; however, its rate of increase had yet to catch up with the speed at which urban development affected climate pressure.

4.4 Climate carrying capacity

The climate carrying capacity indicator of Shanghai City during 2004–2013 showed a trend of greater fluctuation. The indicator decreased slowly to a minimum value in 2007, and then grew quickly to the highest value in 2009, following which the volatility diminished (Fig. 3). Overall, the climate carrying capacity was far lower than the benchmark value. Comprehensive analysis of Fig. 1 and Fig. 2 revealed that the trends of the indicators of the climate carrying capacity and the climate natural capacity change were opposite. In addition, it indicated that the climate carrying capacity was greatly influenced by the climate natural capacity changes in Shanghai City. The climate carrying capacity during 2004–2013 was less than half that of the base year, which indicated that the climate situation was not optimistic. This also correlated with increases in the number of extreme climate events and in the frequency of the five islands effects (i.e., heat island, wet island, dry island, rain island, and turbidity island) caused by climate overload in recent years (Shi 2011). Although the urban coordinated development ability showed steady growth, urban climate stress was also increasing and it did not show signs of slowing. Furthermore, because of climate vulnerability, the climate carrying capacity showed an increase in the intensity of change. Recently, Shanghai City has begun to optimize its development

model to improve its climate situation. It has considered the influence of climate on socioeconomic development, and taken measures regarding its resources, environment, economy, and social development to address the ability of the coordinated development of the city and to reduce the pressure on climate. All of these measures will help improve the Shanghai City’s climate carrying capacity.

4.5 Influencing factors of climate carrying capacity

The influencing factors of climate carrying capacity were analyzed by principal component analysis with SPSS statistical software. Table 2 shows the resulting eigenvalues and contribution rates of the principal components. The greater the contribution rate, the stronger the principal component contained in the original variable information. When extracting principal components, two requirements should be satisfied concurrently: the first is that the eigenvalues should be more than 1 and the other is that the cumulative contribution rate should be more than 85% (Zhang 2016). The eigenvalues of the first five principal components were all more than 1 and their cumulative contribution was 91.86% of the total resources of the principal component analysis. Thus, the first five principal components could be used to reflect the original variable information (see Table 2). Principal component loadings reflect the relationship between the original variables and the principal component, which represents the weight of each original variable in the principal component. Higher absolute values of the load indicate that the corresponding variable is more closely related to the principal component. According to the principal component analysis of the influencing factors of climate carrying capacity change (Fig. 4), the loads of A9 (Urban population density), A12 (Per capita GDP), A13 (Energy consumption per unit GDP), A15 (Total industrial output value), A21 (Investment in environment protection), A22 (Spending on science and technology), and A23 (Green area per capita) were all greater than the other indicators for the first

Table 2 Eigenvalues and principal component contribution rate

Principal component	Eigenvalues	Contribution rate (%)	Cumulative contribution rate (%)
1	13.787	57.446	57.446
2	2.557	10.656	68.102
3	2.398	9.99	78.092
4	1.816	7.566	85.658
5	1.489	6.206	91.864
6	0.896	3.735	95.599
7	0.746	3.109	98.708
8	0.235	0.978	99.685
9	0.075	0.315	100
10	0	0	100
⋮
24	0	0	100

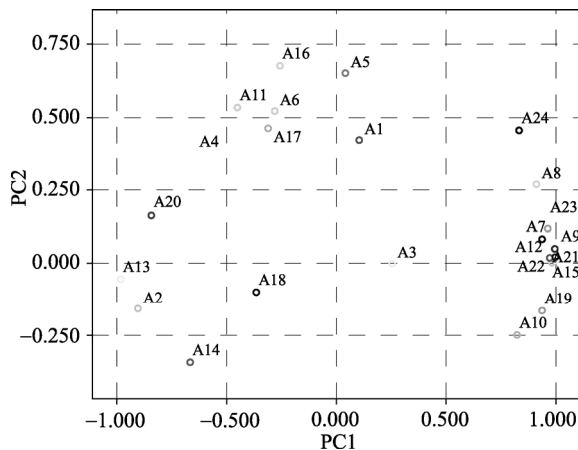


Fig.4 Plot of the first two PC loading vectors

principal component. Considering that socioeconomic development factors and urban coordinated development ability factors accounted for the majority of these factors, it could be seen that close relationships existed among the socioeconomic development factors, urban coordinated development ability factors, and first principal component. The loads of A5 (Extreme low temperature) and A16 (Average yield per unit area) were larger for the second principal component. From the above analysis, it could be concluded that the influences of urban coordinated development factors and socioeconomic development factors were greater on the climate carrying capacity than on the climate natural capacity, which shows that humans could adaptively utilize the climate resource.

5 Conclusions

In this study, the concept of climate carrying capacity was analyzed; then, an indicator system based on the three aspects of current climate natural capacity, urban climate stress, and urban coordinated development ability was established. The rule layer indicators were calculated using the Nemerow Indicator method and a comprehensive assessment method based on entropy weight. Subsequently, a comprehensive function was constructed to evaluate the climate carrying capacity. Shanghai City was used as a case to quantitatively analyze the size and the change trend of the climate carrying capacity during 2004–2013 and the following conclusions were derived.

(1) The climate carrying capacity value of Shanghai City during 2004–2013 was lower than the benchmark climate carrying capacity, and it fluctuated because of the significant influence by the current climate natural capacity. The climate stress and urban coordinated development capacity indicators increased steadily, but the growth rate of the urban coordinated development indicator was less than the growth rate of urban climate stress, which showed that socioeconomic development of Shanghai City had not reached a sustainable state. Overall, the climate carrying capacity was far lower than the benchmark value and it had been in a

state of fluctuation mainly due to the effect of current climate situation. In order to improve the climate carrying capacity, efforts to adjust the energy and industry structures need to be increased, investment in science and technology needs to be strengthened, and clean production and clean energy technologies must be implemented.

(2) According to a principal component analysis, seven factors of urban population density, per capita GDP, energy consumption per unit GDP, total industrial output value, investment in environment protection, spending on science and technology, and green area per capita were main influential factors of climate carrying capacity. This indicated that urban coordinated development and socioeconomic development had greater impact on the climate carrying capacity than on the climate natural capacity, which showed that humans could adaptively utilize the climate resource.

(3) The application process of the proposed method was verified as feasible. The positive indicator of climate carrying capacity was introduced to characterize the climate carrying capacity quantitatively. This assessment method was simple and easy to operate. This method could be used to describe the temporal changes of the climate carrying capacity of a city and to screen regional climate problems associated with urban development and function. A climate carrying capacity assessment could be used as the basis for a climate early warning system, and provide a technical reference for the formulation of a climate security management mechanism in China.

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城市气候承载力量化评价—以上海市为例

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摘要: 为了开展气候风险管理, 近期学者们提出了气候承载力的概念。本文在分析气候承载力的概念内涵及其影响因子的基础上, 从当前气候天然容量, 城市气候压力和城市协调发展潜力 3 个方面构建城市气候承载力综合评价指标体系。以上海市为例, 采用构建的城市气候承载力评价方法分析上海市 2004–2013 年气候承载力变化特点, 并利用主成分因子分析法确定气候承载力的主要影响因子。分析结果如下: (1) 当前气候天然容量指数表明上海市的气候条件劣于基准年, 在研究期间呈波动状态; (2) 城市气候压力和城市协调发展能力呈稳步增长状态, 但协调发展能力的增长速度低于城市气候压力的增长速度; (3) 总体来说, 研究期间上海市气候承载力远低于基准年, 且气候承载力值因受气候条件变化影响较大而处于较大波动状态; (4) 基于主成分因子分析方法确定城市人口密度、人均 GDP、单位生产总值能耗、工业总产值、环境保护投资、科技经费支出以及人均绿地面积为主要影响因子。结果表明, 该气候承载力评价方法是可行的, 它可以描述某一城市气候承载力在时域上的变化, 也可以对区域气候承载力开发利用过程中存在的问题进行甄别, 并可作为气候预警响应的依据, 为我国建立气候安全管理机制提供技术参考。

关键词: 气候承载力; 量化评价; 城市气候; 上海市