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Assessment and Future Scenario Estimation of Climate Carrying Capacity in the Beibu Gulf Urban Agglomeration of Guangxi, China

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Abstract: To enhance urban resilience to climate change in the future, this study quantitatively assesses the climate carrying capacity of the Beibu Gulf Urban Agglomeration (BGUA) in the Guangxi Zhuang Autonomous Region from 2000 to 2020 and in a future projected study from 2021 to 2060. The data used includes real-time data from the National Meteorological Observatory, prediction data from the National Climate Center's global climate model BCC-CSM2-MR under different Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5), and socio-economic development data. The assessment is conducted using four criteria dimensions: climate natural capacity (CNC), extreme climate event pressure (ECP), urban climate pressure (UCP), and urban coordinated development capacity (UCC). The results indicate that from 2000 to 2020, there was a significant interannual fluctuation in the CNC and ECP in the BGUA. The UCP and the UCC showed an increasing trend, while the overall climate-carrying capacity of the BGUA showed a fluctuating decrease. It is estimated that the climate carrying capacity will exhibit a non-significant decreasing trend from 2021 to 2060, with the capacity in the period from 2021 to 2040 generally higher than that in the period from 2041 to 2060 and the SSP2-4.5 scenario higher than the SSP5-8.5 scenario overall. Currently and in the future, the climate-carrying capacity of the BGUA is primarily influenced by normal climate conditions and extreme events such as strong winds and temperature extremes. With the passage of time, climate instability will increase. Under the planned implementation of China's carbon peak and carbon neutrality pathway, the rate of increase in the capacity for coordinated urban development is expected to surpass the rate of increase in urban climate pressure. Industrial production and energy consumption are the main drivers of future urban climate pressure growth.

Key words: urban; climate carrying capacity; assessment; estimation; Beibu Gulf; Guangxi

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1 INTRODUCTION

There exists a close and intricate interplay between urbanization and climate change. The greenhouse gas emissions from urbanization are a primary driver of global climate change (IPCC [1]). Simultaneously, the global effects of climate change, such as rising temperatures and increased frequency and intensity of extreme weather events, pose significant climate risks to cities. Urban areas characterized by high population density, limited natural resources, and fragile ecosystems are particularly vulnerable to the adverse impacts of climate change. These highly urbanized regions face both present-day and

potential future risks associated with climate change. As urbanization progresses and the population continues to grow, the climate change risks confronting cities are anticipated to become even more severe (IPCC [1]; Zhai et al. [2]; Zheng et al. [3]). Given that cities are sensitive to the impacts of climate change, it is imperative to study their capacity to withstand these changes and how they can effectively respond to and adapt to the changes in the future.

The Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6 SYR) (IPCC [4]) underscores the escalating impact of extreme weather events and the potential consequences of climate change on various urban infrastructures such as transportation, water supply, sanitation, and energy systems (Wright et al. [5]; Neumann et al. [6]; Pašičko et al. [7]; Duan et al. [8]). Vulnerable regions with weaker infrastructure are particularly susceptible to these impacts. The intricate and multifaceted dynamic relationships between urban systems and climate systems mean that climate change can directly influence urban functionality, and in turn, urban areas directly affect the climate (IPCC [4]; Wang et al. [9]; Shi et al. [10]; Mu et al. [11]). Climate-carrying capacity provides a comprehensive measure of these complex

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Biography: LI Yan-jun, engineer/MS, primarily undertaking research on climate change monitoring, impact assessment, and estimation

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interactions. It signifies the ability of climate resources in a given region over a specific period, including factors like temperature, precipitation, and wind, to support sustainable socioeconomic development. It serves as a description of the interplay between socioeconomic systems and climate systems (Yu et al. ^[12]; Yan et al. ^[13]; UNESCO ^[14]; Arrow et al. ^[15]). The concept of carrying capacity, originally rooted in mechanics, denotes the maximum load a structure can bear without any damage. Over time, this concept has been widely extended to various fields, including ecological carrying capacity, resource (e.g., water resources, atmospheric environment, land) carrying capacity, and tourism carrying capacity (Zhao et al. ^[16]; Lin ^[17]; Liu and Li ^[18]; Piipponen et al. ^[19]; Hu et al. ^[20]). A related field is climate production potential, which primarily explores the interrelationships between climate resources, agricultural production, and population dynamics (Xu et al. ^[21]; Li et al. ^[22]; Lu et al. ^[23]; Van Oort and Zwart ^[24]). Research on climate carrying capacity currently encompasses both qualitative and quantitative approaches, with quantitative assessment based on evaluation systems being the more widely applied and accepted method. Quantitative assessments have revealed that the climate-carrying capacity of economically developed first- and second-tier cities such as Beijing, Shanghai, Nanning, and Nanchang could be not promising (Yan et al. ^[13]; Yue et al. ^[25]; Li et al. ^[26]; Wu et al. ^[27]). In contrast, economically less developed fourth-tier cities like Baise and Nanchong exhibit relatively good climate-carrying capacity (Li et al. ^[28]; Zhao et al. ^[29]). Presently, research on climate-carrying capacity primarily focuses on historical and current assessments, with limited studies on forecasting future changes in climate-carrying capacity.

Future climate change is characterized by complexity and uncertainty. Numerous scholars have conducted climate projection studies for the Asian and Chinese regions under different greenhouse gas emission scenarios. These studies have consistently shown that the projected increases in average temperatures for Asia and China will exceed the global average under the same Representative Concentration Pathway (RCP) scenarios or warming thresholds (Chen et al. ^[30]; Xu et al. ^[31]). Additionally, the rate at which China's annual average surface temperature is projected to rise above certain thresholds will be faster than the global average across various scenarios, with higher levels of uncertainty (Zhang et al. ^[32]). The Coupled Model Intercomparison Project (CMIP) is an international collaboration to address key issues in climate research by sharing simulation results from multiple global climate models. It serves as a crucial basis for the reports by the Intergovernmental Panel on Climate Change (IPCC). China's National Climate Center's global climate model, BCC-CSM2-MR, participated in the Sixth Phase of the CMIP (CMIP6). This model exhibited significant improvements over its earlier version, BCC-CSM1.1m. It demonstrated higher spatial correlation coefficients with observed precipitation

patterns in China and better approximation of observed precipitation in southeastern China (Xin et al. ^[33]; Wu et al. ^[34]). Furthermore, in simulating extreme precipitation in Shenzhen, a city in southern China, it outperformed other CMIP6 climate models in terms of elements such as precipitation amount, duration, and the number of heavy rainfall days (Shao et al. ^[35]). The model also demonstrated good performance in simulating China's spatial distribution and variability of land surface variables, including surface temperature and soil moisture (Tan et al. ^[36]). These achievements suggest that the model has reasonable predictive capabilities for precipitation and temperature in southern China. Researchers from various fields have utilized the results from this model in their applied studies, including estimating future losses due to extreme precipitation disasters (Liu et al. ^[37]), characterizing precipitation heteroscedasticity under climate change in China (Qian et al. ^[38]), studying changes in Arctic sea ice extent and temperature (Ren et al. ^[39]; Zhao et al. ^[40]), and assessing the impact of different climate change scenarios on runoff (Wen et al. ^[41]) and drought process (Luo et al. ^[42]). These studies have generally yielded favorable simulation results.

In 2022, China released the "National Strategy for Climate Change Adaptation 2035" (Ministry of Ecology and Environment of the People's Republic of China ^[43]), which emphasized the importance of conducting in-depth research on climate carrying capacity, strengthening regional climate adaptation actions, and deepening climate-adaptive city pilot projects. China's "14th Five-Year Plan" for social and economic development specifically highlights the need to study the impacts of climate warming on vulnerable regions and enhance climate change adaptation capabilities (Xinhua News Agency ^[44]). Therefore, undertaking research on urban climate carrying capacity assessment and prediction is important for current urban adaptation efforts and for enhancing cities' ability to cope with climate change and sustainably develop in the future.

The BGUA is a key region for deep cooperation between China and the Association of Southeast Asian Nations (ASEAN). It is located at the intersection of South China and Southwest China and serves as a vital gateway to Southeast Asia, with the advantage of open coastal and border regions (National Development and Reform Commission ^[45]). It spans across the Guangxi Autonomous Region, Guangdong Province, and Hainan Province. The BGUA in Guangxi includes six cities: Nanning, Beihai, Qinzhou, Fangchenggang, Yulin, and Chongzuo (see Fig. 1). The total population of this agglomeration exceeds 11.5 million, with a regional GDP of over 952.5 billion RMB. The BGUA is also a key area for high-quality development in Guangxi, serving as a demonstration zone for Guangxi's development (National Development and Reform Commission ^[46]). The region is vulnerable to meteorological disasters (Li ^[47]; Yan et

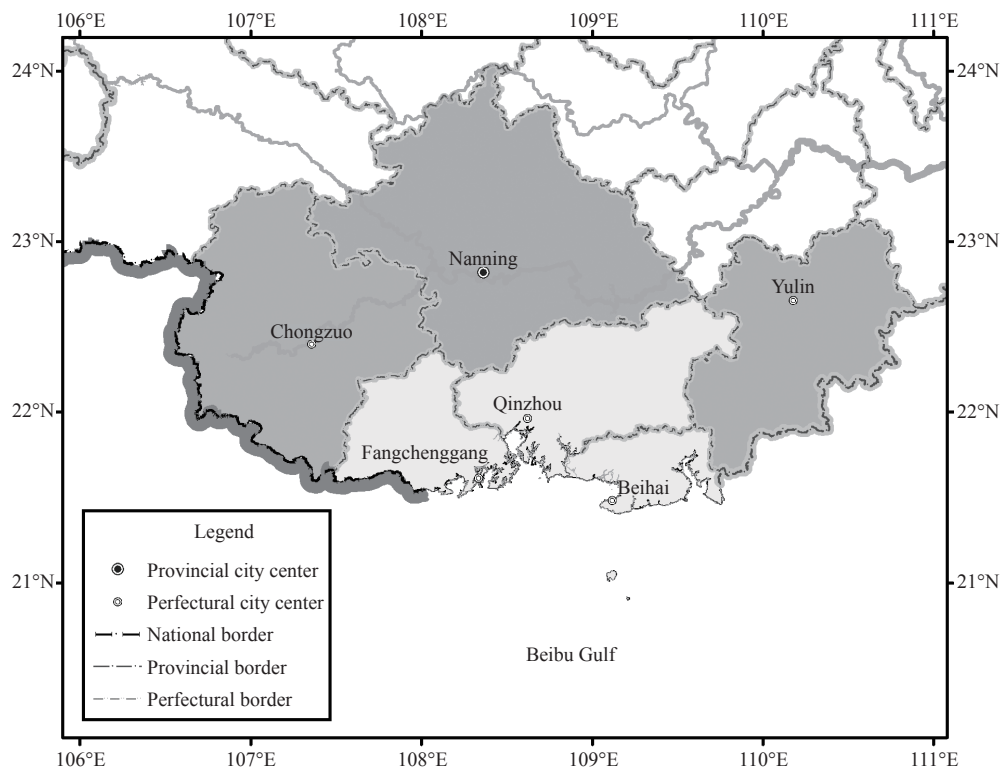


Figure 1. Schematic map of the BGUA in Guangxi.

al. [48]), and it faces higher climate change risks due to relatively weak infrastructure and economic development (Chen and Wang [49]; Liu and Wang [50]).

Previous studies have conducted quantitative assessments of climate-carrying capacity for some cities within the Beibu Gulf region (Li et al. [26]; Wu et al. [51]). These studies provided insights into the current climate-carrying capacity of individual cities, but they used different sets of indicators, making it challenging to make precise comparisons. Moreover, they should have studied the agglomeration as a whole, making it possible to assess and predict the climate-carrying capacity of the entire urban agglomeration. Therefore, this study selects the BGUA in Guangxi as its research focus. Using an indicator system, it will first conduct a quantitative assessment of the agglomeration's climate-carrying capacity from 2000 to 2020. Then, it will use quantitative estimates based on data from the National Climate Center's global climate model, BCC-CSM2-MR, which participated in CMIP6, and government targets for socio-economic development planning. This study aims to provide relevant authorities with references for scientific decision-making in addressing climate change and offer a pathway towards achieving "carbon neutrality" and "carbon peak" goals in urban development.

2 DATA AND COMPUTATIONAL METHODS

2.1 Data and processing

2.1.1 METEOROLOGICAL DATA

Annual average temperature, annual precipitation, annual sunshine hours, annual high-temperature days,

annual low-temperature days, annual heavy rainfall days, annual very heavy rainfall days, annual longest consecutive days without rain, annual days without rain, and annual strong wind days were observed at six national meteorological stations in Nanning, Beihai, Qinzhou, Fangchenggang, Yulin, and Chongzuo from 1975 to 2020. The data from 2000 to 2020 was selected for the quantitative assessment of carrying capacity. Climatic averages were calculated based on the 30-year average values from 1981 to 2010.

2.1.2 ESTIMATION DATA

For the assessment, data from the global climate model BCC-CSM2-MR, which is part of China's participation in the CMIP6, were used. The model provided simulated and projected daily data from 1975 to 2100 under RCP4.5 and RCP8.5 Scenarios. The data had a horizontal resolution of $1.125^\circ \times 1.125^\circ$. Grid-point data closest to the latitude and longitude of the national meteorological stations within the BGUA were extracted to represent each city. Various meteorological parameters, including annual average temperature, annual precipitation, high-temperature days, low-temperature days, heavy rainfall days, longest consecutive days without rain, and strong wind days, were calculated based on these model data. Systematic bias correction was applied to the model simulation results using observed data from the corresponding national meteorological stations for the period from 1975 to 2020. The estimated meteorological data were then derived from the corrected values.

The moderate emissions scenario (SSP2-4.5) and the high emissions scenario (SSP5-8.5) were used for

estimation. Both of them are from the Shared Socioeconomic Pathways (SSPs), which were developed by the IPCC based on the Representative Concentration Pathways (RCPs). The SSP2-4.5 (SSP5-8.5) scenarios represent distinct socioeconomic pathways and correspond to 65–85 (104–126) Gt CO₂ emissions by the year 2100 (IPCC [52]). As of 2023, the global average temperature has already risen by 1.45 °C, and the warming in China is higher (Chen et al. [30]; Xu et al. [31]; WMO [53]). It is very possible that the warming in China will be up to 3.9°C–6.0°C in 2100 (Deng et al. [54]). Hence, the SSP2-4.5 and SSP5-8.5 Scenarios are more realistic and achievable than other scenarios.

2.1.3 HISTORICAL SOCIOECONOMIC DEVELOPMENT DATA

Historical socioeconomic development data were obtained from the corresponding annual editions of the “Guangxi Statistical Yearbook” for the respective years. Socioeconomic projection data were sourced from several documents, including the “14th Five-Year Plan for National Economic and Social Development and the Outline of Long-term Goals for 2035” for the Guangxi Autonomous Region (National Development and Reform Commission [46]), as well as the cities of Nanning, Beihai, Qinzhou, Fangchenggang, Yulin, and Chongzuo. Additionally, data from the “National Land Spatial Plan (2021–2035)” and the “Research Report on Carbon Neutrality in China before 2060” (GEIDCO [55]) were used for socioeconomic development projections.

2.2 Climate-carrying capacity assessment indicator system construction

2.2.1 CALCULATION OF CLIMATE CARRYING CAPACITY FOR THE BGUA

This paper follows the construction method proposed by Yan et al. [13] and an improved indicator system from Li et al. [26] and Li et al. [28], consisting of four evaluation levels and 25 indicators (Table 1).

Based on the definition of climate carrying capacity, the formula for calculating urban climate carrying capacity is as follows:

$$CCC = \frac{UCC}{CNC \cdot ECP \cdot UCP} \quad (1)$$

where CCC represents the climate-carrying capacity of a specific city. UCC stands for the urban coordinated development capacity and reflects the ability of the socio-economic system to adapt to and mitigate the impacts of climate change. CNC refers to the climate natural capacity, an indicator that assesses the magnitude of abnormal fluctuations in a city's climate. ECP represents the extreme climate event pressure; it reflects the magnitude of pressure on a city's climate system caused by extreme climate events that occurred in a given year. UCP stands for urban climate pressure and assesses the negative impacts of economic development and human activities on the climate system.

From the formula, CNC, ECP, and UCP are inversely proportional to CCC. By contrast, UCC is directly proportional to climate-carrying capacity. A higher CCC

value indicates a stronger climate-carrying capacity in that region.

Because urban size and development status are generally measured by population and economic level (Qi et al. [56], Sun and Liu [57]), this paper constructs the climate-carrying capacity of the urban agglomeration based on the proportion of the permanent population and regional GDP for the six cities.

The formulas for calculating the comprehensive value of climate carrying capacity for the BGUA are as follows:

$$CCC = \sum_{i=1}^n W_i CCC_i \quad (2)$$

$$W_i = \frac{1}{2} \left(\frac{P_i}{\sum_{i=1}^n P_i} + \frac{G_i}{\sum_{i=1}^n G_i} \right) \quad (3)$$

where CCC represents the climate-carrying capacity of the Beibu Gulf Urban Agglomeration. CCC_i represents the climate carrying capacity of each city, where $i = 1, 2, 3, \dots, n$, and $n = 6$ represents the six cities in the Beibu Gulf area. W_i represents the weight coefficient for each city. P_i represents the permanent population of each city. G_i represents the regional GDP of each city. Since the reference year for estimation is 2020, the weights for each city are determined based on the proportion of permanent population and regional GDP for the six cities in 2020. The calculated weights for each city are as follows: Nanning 0.550, Beihai 0.130, Qinzhou 0.125, Yulin 0.075, Fangchenggang 0.060 and Chongzuo 0.060.

2.2.2 INDICATOR LEVEL CALCULATION

CNC objectively estimates the trend in the climate's state by calculating the deviation of climate elements from their annual averages. The calculation formula is as follows:

$$CNC = \frac{\sum_{i=1}^n |f_{ij}|}{n} \quad (4)$$

where f_i represents the standardized values of the CNC evaluation indicators listed in Table 1, $i = 1$ to n , and n denotes the total number of CNC evaluation indicators. j represents the years for which the calculations are made.

The calculations for ECP, CCP, and CDA all use the entropy weight method (Wang et al. [58], Zou et al. [59], Guiaşu [60]). The formula for these calculations is as follows:

$$S = \sum_{i=1}^n f_i Q_i \quad (5)$$

where S represents the indicator level (ECP, UCP, and UCC). f_i represents the standardized values of the evaluation indicators for a given year, where $i = 1$ to n , and n is the total number of evaluation indicators at that level. j represents the years for which calculations are made. Q_i represents the weight of evaluation indicator i . The entropy weight method objectively assesses the degree to which each indicator deviates from the average state. The greater the dispersion of an indicator is, the greater its

Table 1. Quantitative evaluation and estimation indicator system for climate carrying capacity of the BGUA.

Index	Indicator	Units
CNC	Annual precipitation**	mm
	Annual mean wind speed	m s ⁻¹
	Annual sunshine hours	h
	Annual average temperature**	°C
ECP	Annual high-temperature days**	d
	Annual low-temperature days**	d
	Annual heavy rainfall days**	d
	Annual very heavy rainfall days	d
	Annual longest consecutive days without rain*	d
	Annual days without rain	d
	Annual strong wind days**	d
UCP	Urban per capita housing area	m ² person ⁻¹
	Current urban land area for construction**	km ²
	Road mileage	km
	Urban population density	10,000 person km ⁻²
	Resident population*	10,000 person
	Number of civilian vehicles	ten thousand vehicles
	Per capita daily comprehensive domestic water consumption	t person ⁻¹
	Per capita GDP	yuan
	Energy consumption per unit of production.	tce 10,000 yuan ⁻¹
	Energy consumption per unit of GDP*	tce
	Energy consumption elasticity coefficient	
	Industrial production	10,000 yuan
	Value-added of industrial enterprises above designated size*	100 million yuan
UCC	Engel coefficient of urban households	%
	Total electricity consumption**	100 million kilowatt-hours
	Regional GDP*	100 million yuan
	Environmental protection investment to regional gross domestic product ratio	
	R&D expenditure to regional GDP ratio	
	R&D expenditure*	100 million yuan
	Per capita green space area	Hectares per ten thousand people
	Tertiary industry share	%
	Forest coverage rate*	%

* Note: ** indicates that an indicator serves as both an evaluation and estimation metric, * indicates that an indicator is used as an estimation metric, and the rest are used for evaluation.

weight is. The average values of each indicator level (i.e., CNC, ECP, UCP, and UCC) for the six cities are taken to represent the values for that indicator level in the BGUA.

2.3 Methodology for climate carrying capacity scenario estimation

Using 2020 as the baseline year, this study estimates and compares the climate-carrying capacity scenarios for the BGUA from 2021 to 2060 based on the products of the BCC-CSM2-MR model for both moderate and high emission scenarios. In the estimation process, calculations for climate carrying capacity and indicator levels still follow Formulas 1–5. Given the limited availability of model products and socioeconomic estimation data, the evaluation system for climate carrying capacity in this estimation is adjusted based on the quantitative evaluation system. This involves removing or replacing indicators based on the available data, to

obtain estimated indicators. The estimated indicators encompass four criteria dimensions, comprising 15 indicators (see Table 1).

Based on the results of the BCC-CSM2-MR model, data from two scenarios, namely, the SSP2-4.5 and the SSP5-8.5, are selected for calculations within the CNC and the ECP. The CNC utilizes two indicators: annual precipitation and annual average temperature, reflecting basic precipitation and temperature conditions. Due to the significant uncertainty in rainfall forecasts, the ECP excludes the indicators for annual very heavy rainfall days and annual no-rain days, retaining the indicators for annual heavy rainfall days and the longest consecutive days without rain. This paper presents two different estimation results for the SSP2-4.5 and SSP5-8.5 Scenarios.

The data for the UCP and the UCC indicators are sourced from various government departments' planning

documents and socioeconomic estimation reports. We have only set one ideal scenario in this estimation to achieve carbon peaking before 2030 and carbon neutrality by 2060. This scenario aligns with the socioeconomic development path under the IPCC's SSP2-4.5 Scenario. In the estimation process, the UCP and the UCC evaluation indicators are either removed if they are not estimated in various development plans or replaced with similar indicators (see Table 1). Since the data available do not provide specific annual estimation data but rather estimation values for the target years (2035 and 2060) within planning documents, we have assumed linear changes in the annual values of each indicator between the base year and the target year, reaching the estimated values by 2035. Data for the years 2020–2035 is sourced from the “14th Five-Year Plan for National Economic and Social Development and the Outline of Long-term Goals for 2035” and the “National Land Spatial Plan (2021–2035).” For 2060, socioeconomic development estimations are set according to the overall trends in China, while target data is based on the “Research Report on Carbon Neutrality in China Before 2060.” By 2060, the Chinese population is projected to decrease slightly, with the GDP roughly four times that of 2020 and total electricity consumption approximately double that of 2020 (GEIDCO [55]). Given data uncertainties, annual estimations beyond 2035 are not further subdivided, and the same estimation values are used for the years 2036–2060. In this study, the focus is on estimating and analyzing the period of 2021–2040, while the results for 2041–2060 are the average value of 20 years.

3 EVALUATION OF CLIMATE CARRYING CAPACITY IN THE BEIBU GULF URBAN AGGLOMERATION FROM 2000 TO 2020

3.1 Characteristics of climate carrying capacity changes in the urban agglomeration

A higher CCC value indicates a greater climate-carrying capacity. From 2000 to 2020, the CCC of the BGUA exhibited a fluctuating downward trend (see Fig. 2). The highest value was observed in 2006, while the lowest was recorded in 2019. There were 11 years where CCC values exceeded the average value for the 21 years,

with 6 of those years having CCC values higher than the baseline year (2000). During the years 2004–2007, the CCC in the BGUA was relatively good, consistently exceeding the average by more than 40%. In contrast, during the years 2018–2020, the BGUA experienced continuous low CCC values, falling below the average by more than 50%. This indicates that the long-term CCC trend in the BGUA over these 21 years could be not optimistic as climate-carrying capacity gradually declined.

3.2 Characteristics of climate natural capacity and extreme climate event pressure

From 2000 to 2020, against the backdrop of climate warming and the influence of climate anomalies and extreme weather events, the CNC and the ECP curves exhibited strong interannual fluctuations (see Fig. 2). During the years 2004–2007, when CCC was in good condition, both CNC and ECP values were relatively low, indicating stable climatic conditions in the urban agglomeration with fewer occurrences of extreme climate events. Over the 21 years, CNC values were higher than the baseline year of 2000 for 20 years, with 11 years being higher than the 21-year average. This suggests that the overall climate conditions in the BGUA were not stable. From 2015 to 2020, CNC values consistently exceeded the 21-year average, leading to a continuous decline in CCC. This was due to significant anomalies in annual average wind speed and annual average temperature in all five cities except for Qinzhou. Qinzhou, on the other hand, experienced significant anomalies in annual average temperature and annual precipitation. When statistically analyzing the top two indicators that had the greatest impact in each city (i.e., those with the highest correlation coefficients), it was found that the most frequently occurring indicators were annual average wind speed and annual average temperature. Additionally, the CNC in Nanning, Beihai, Fangchenggang, and Chongzuo was most heavily influenced by annual average wind speed, Qinzhou was most heavily influenced by annual average temperature, and Yulin was most heavily influenced by annual sunshine hours.

Over the 21 years, the ECP in the BGUA was higher than the baseline year of 2000 for 13 years, with 5 years

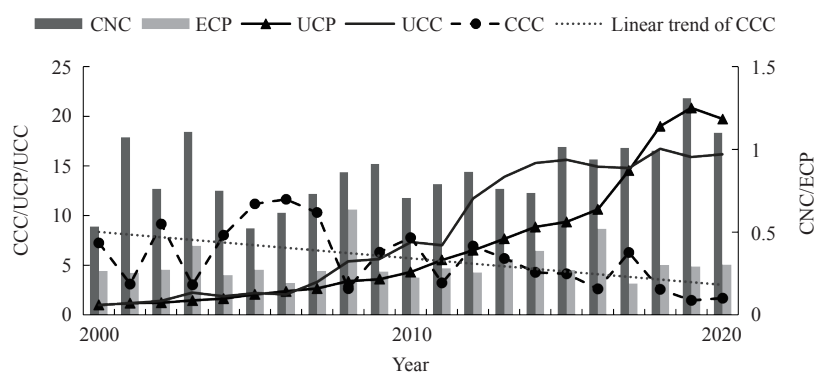


Figure 2. Changes in climate carrying capacity and various indicators in the BGUA from 2000 to 2020.

surpassing the 21-year average. This indicates that extreme climate events occurred more frequently and with greater intensity. Analyzing the highest ECP year in 2008, it was found that four cities experienced the highest number of low-temperature days and the longest consecutive days without rain over 21 years, while three cities had the highest number of heavy rainfall days. These factors contributed to the peak ECP value. When statistically analyzing the top two indicators that had the greatest impact on ECP in each city, we found that low temperature and heavy rainfall events were the most frequently occurring indicators. Additionally, the main extreme climate events affecting each city varied. Beihai, Qinzhou, Fangchenggang, and Chongzuo were most sensitive to extreme low-temperature events, Nanning was most heavily affected by extreme heavy rainfall events, and Yulin was most sensitive to drought (i.e., annual days without rain).

In summary, from 2000 to 2020, due to significant fluctuations in annual average wind speed and annual average temperature, the high frequency and intensity of extreme low-temperature and heavy rainfall events, and the impact of other extreme weather events, the overall climate conditions in the BGUA moved towards instability. There was increased pressure from extreme climate events, higher climate risks, and a negative impact on the urban climate carrying capacity.

3.3 Characteristics of urban climate pressure and urban coordinated development capacity changes

As shown in Fig. 2, the UCP and the UCC curves exhibited a stable upward trend. Since the beginning of the 21st century, the BGUA has experienced periods of rapid socioeconomic development, followed by a slowdown and a stable period (Qin [61]). Consequently, both the UCP and the UCC curves, which reflect urban climate development pressure and coordination capacity, have shown rapid growth along with the development of economic strength. However, the CCC continued to decline, indicating that the negative effects generated by the UCP, primarily driven by extensive high-energy consumption growth, outweighed the coordinating support capacity provided by the UCC. Therefore, under the combined influence of the socioeconomic and climate systems, climate carrying capacity was continually compressed in the face of climate instability and increasing frequencies of extreme climate events. The climate-carrying capacity evaluation indicators used in this study effectively reflect this characteristic.

The evaluation conclusions presented above are generally consistent with previous research findings for Nanning, Beihai, Qinzhou, and Fangchenggang (Li et al. [26]; Wu et al. [51]). The climate-carrying capacity of the BGUA in Guangxi has gradually decreased since the beginning of the 21st century. Simultaneously, it is faced the pressure of socioeconomic development and the impacts of unstable climate and extreme events against the background of global warming.

4 FUTURE SCENARIO ESTIMATION OF CLIMATE CARRYING CAPACITY IN THE BEIBU GULF URBAN AGGLOMERATION OF GUANGXI

The simulation effect of the BCC-CSM2-MR model on climate elements in the BGUA is examined by using the observational data of the BGUA from 1975 to 2014. Although there are some deviations between the model simulated and observed values, and the correlation varies, the long-term temperature and precipitation trends are basically simulated successfully. The model performs well in simulating the average temperature, high-temperature days, and strong wind days in some cities in the BGUA. Overall, the BCC-CSM2-MR model is reliable for predicting future changes in the BGUA.

4.1 Estimation of climate natural capacity and extreme climate event pressure

Future CNC estimation is conducted using the annual average temperature and annual precipitation indicators. As shown in Fig. 3, from 2021 to 2060, the average temperature in the BGUA shows an increasing trend under both scenarios. In the SSP5-8.5 Scenario, the warming rate (approximately $0.5^{\circ}\text{C} (10 \text{ years})^{-1}$) is faster than that in the SSP2-4.5 Scenario (approximately $0.4^{\circ}\text{C} (10 \text{ years})^{-1}$). By 2060, under the moderate and high emission scenarios, the average temperature in the BGUA is projected to increase by approximately 1.7°C and 2°C , respectively, compared to those of the year 2020.

The trend in annual precipitation from 2021 to 2060 in the BGUA is less pronounced. However, in the high-emission scenario, there is a larger fluctuation in annual precipitation compared to the moderate emission scenario, indicating more frequent or intense extreme precipitation events. From 2021 to 2060, there is a noticeable interannual variation in the CNC in the BGUA. CNC values are generally higher under the high emission scenario compared to the moderate emission scenario, and both scenarios show a significant increasing trend (see Fig. 4). When comparing the two decadal means (see Table 2), it is observed that under the moderate emission

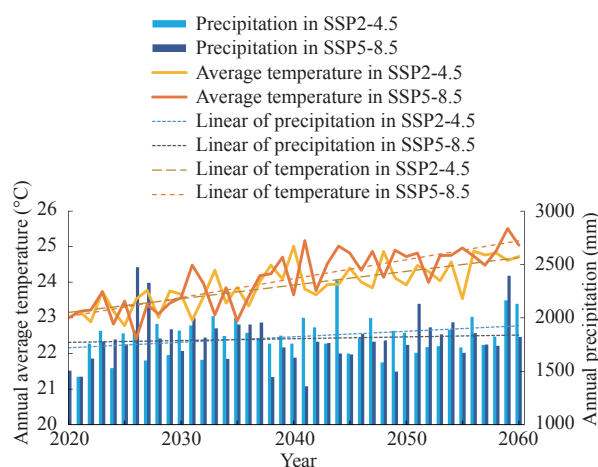


Figure 3. Estimating annual average temperature and precipitation in the BGUA from 2021 to 2060.

scenario, the CNC values for the periods 2021–2040 and 2041–2060 are lower by 0.08 and 0.53, respectively, compared to those of the high emission scenario. This indicates smaller fluctuations and greater stability under the moderate emission scenario, suggesting that the climate system is more stable under this scenario until 2060. Additionally, in both emission scenarios, the climate conditions from 2021 to 2040 are more stable, with smaller CNC mean values compared to those during the period from 2041 to 2060. This suggests that, in the context of warming, the risk of climate instability increases gradually with time under both moderate and high emission scenarios. Under the high emission scenario, the BGUA faces more significant climate changes. In both scenarios, the six cities in the Beibu Gulf have higher deviations of annual average temperature from the climate average than annual precipitation, which exerts a greater impact on the CNC. This indicates that the changes in annual average temperature due to climate warming are the main reasons for climate system instability.

Based on five indicators: annual high-temperature days, annual low-temperature days, annual strong wind days, annual heavy rainfall days, and annual longest consecutive days without rain, extreme climate events are estimated by using Formula 5. There are notable interannual variations in the ECP for the BGUA from 2021 to 2060 (Fig. 5). The linear trend is not significant, and the ECP values are generally higher under the high emission scenario than the moderate emission scenario. Calculating decadal means (Table 2) also reveals that ECP values are higher for 2021–2040 and 2041–2060 under the SSP5-8.5 Scenario than the SSP2-4.5 Scenario. This indicates that under the high-emission scenario, the frequency and severity of extreme climate events are higher in the BGUA. However, in both emission scenarios,

the ECP values for 2021–2040 are slightly higher than those for 2041–2060, suggesting a slightly higher risk of extreme climate events occurring during the 2020–2040 period. This may be related to the socioeconomic development path with moderate greenhouse gas emissions, where global carbon peak emissions are expected to occur around 2030, leading to the highest global warming rates and greater climate instability during the transition. The weighting of indicators varies across cities: Nanning, Qinzhou, and Chongzuo have the highest weights for strong wind days and low-temperature days, while Beihai and Fangchenggang have the highest weights for high-temperature days and low-temperature days, and Yulin has the highest weights for strong wind days and the longest consecutive days without rain. In summary, strong wind days, low-temperature days, and high-temperature days contribute the most to the ECP values for the BGUA. This suggests that in the coming 10–50 years, apart from events like heavy rainfall and flooding, drought, etc., policymakers should also pay close attention to the risks associated with extremely strong winds, extremely low temperatures, and extremely high temperatures.

4.2 Estimation of urban climate pressure and urban co-ordinated development capacity

Based on the planning data for Guangxi and the six cities in the Beibu Gulf from 2021 to 2025 and the long-term goals for 2035 and 2060, the UCP and the UCC estimation curves are plotted (Fig. 6). From 2021 to 2035, both the UCP and the UCC in the BGUA are projected to show an upward trend. By 2035, the UCP is approximately six times that of 2020, and the UCC is approximately 17 times that of 2020 (see Fig. 3). Even in the ideal scenario, the UCP exhibits some degree of growth, but the development rate of UCC is significantly higher than that of UCP. The growth of UCP is relatively gradual,

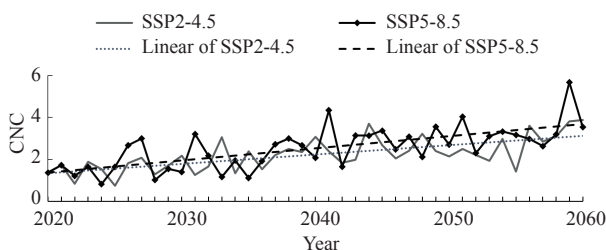


Figure 4. Estimation of climate natural capacity in the BGUA from 2021 to 2060.

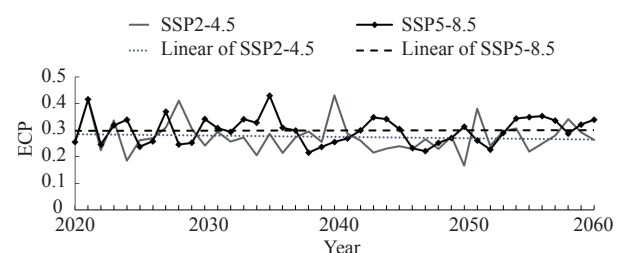


Figure 5. Estimation of extreme climate event pressure in the BGUA from 2021 to 2060.

Table 2. Estimated decadal mean values of various indicator levels and climate carrying capacity for the Beibu Gulf Urban Agglomeration.

	2021–2040 annual mean		2041–2060 annual mean	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
CNC	1.83	1.91	2.65	3.18
ECP	0.29	0.30	0.26	0.30
UCP		3.02		8.67
UCC		5.93		25.37
CCC	4.90	3.85	3.31	2.56

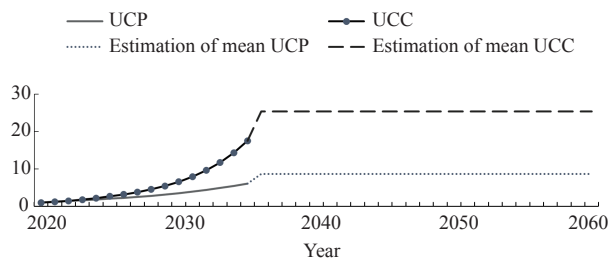


Figure 6. Estimation of urban climate pressure and urban co-ordinated development capacity in the BGUA from 2021 to 2035 and 2060.

indicating that the transformation of economic and social development to reduce energy consumption, as per the planned development, is effective. Analysis of the indicators reveals that the primary contributors to UCP growth are industrial added value, total electricity consumption in society, and regional GDP. UCC growth, on the other hand, primarily relies on increased research and development expenditure. Industrial production and energy consumption may become the main socioeconomic factors constraining the climate-carrying capacity of the BGUA in the future. Increasing investment in scientific research, transitioning and upgrading green industries, and improving energy efficiency can greatly alleviate this issue.

4.3 Future scenario estimation of climate carrying capacity

Based on the carrying capacity estimation curve (Fig. 7), from 2021 to 2060, there are noticeable interannual variations in CCC for the BGUA under both scenarios, showing a slightly decreasing trend that is not significant. An analysis of the correlation coefficients between various indicator levels and CCC reveals that from 2021 to 2035, CCC is primarily influenced by CNC and ECP, with UCP and UCC having relatively smaller impacts. From 2036 to 2060, since UCP and UCC are fixed using the estimated values for 2060 (as shown in Fig. 6), changes in CCC are primarily driven by natural climatic factors. Therefore, the climate-carrying capacity of the BGUA is primarily constrained by natural climatic factors.

Under the SSP2-4.5 Scenario, the overall CCC is higher than the CCC under the SSP5-8.5 Scenario (see Fig. 7). In the SSP2-4.5 Scenario, over 40 years, the CCC is higher than the estimated baseline year of 2020 for 19 years. There are concentrated high values in 2022–

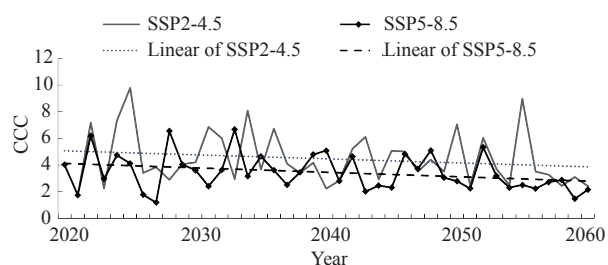


Figure 7. Estimation of climate carrying capacity for the BGUA from 2021 to 2060.

2025, 2031–2036, and 2042–2046, with these periods exceeding 20% of the baseline year of 2020. The highest CCC value occurs in 2025, reaching 2.4 times that of 2020. Under the SSP5-8.5 Scenario, the CCC is higher than that in the estimated baseline year 2020 for 13 years, but the high values are scattered. The highest CCC value occurs in 2033, reaching 1.7 times that of 2020. However, regardless of the emission scenarios, the CCC is lower than the baseline year 2020 in more than half of the estimated years. This indicates that even under the ideal emission scenario, the climate-carrying capacity of the BGUA remains challenging in the context of climate change.

Analyzing the decadal changes from 2021 to 2040 and from 2041 to 2060, the average CCC for the BGUA under both moderate and high emission scenarios is higher in the 2021–2040 period compared to that in the 2041–2060 period by 1.59 and 1.29, respectively (see Table 2). This is consistent with the previous year-by-year analysis, indicating that the climate-carrying capacity of the BGUA will gradually decrease in the future. Under the current social development planning goals, this decline is primarily due to climate change-induced climatic instability (increasing the CNC values) and the frequent occurrence of extreme climate events (large fluctuations in the ECP values). Additionally, part of the reason comes from the climate development pressure of the urban agglomeration (increasing the UCP values). Although the coordinated development capacity (UCC values) is rapidly increasing with technological development, it is still insufficient to balance the combined impacts of the former factors. Therefore, more robust measures and longer-term strategies are needed to maximize the role of urban agglomeration's coordination capacity in mitigating the adverse effects of climate change.

5 CONCLUSION AND DISCUSSION

In this paper, we employed an urban climate-carrying capacity evaluation system to quantitatively assess the climate-carrying capacity of the BGUA during the early 21st century (2000–2020). We also conducted climate-carrying capacity projections based on the BCC-CSM2-MR model under middle and high scenarios and planned socioeconomic development pathways. The obtained results are as follows.

From 2000 to 2020, the BGUA's climate-carrying capacity fluctuated downward, indicating a gradual decline in the agglomeration's capacity to sustain urban development. This decline is primarily attributed to factors related to climate conditions and extreme events.

According to the projections for the period from 2021 to 2060, the comprehensive climate carrying capacity of the BGUA displays noticeable interannual variations, with an overall trend of moderate decline. The climate carrying capacity during the years 2020–2040 is generally better than that during 2041–2060, and it is also better under the moderate emission scenario compared to the high emission scenario. The climate carrying capacity of the BGUA is

primarily influenced by natural climate factors, and it is particularly sensitive to changes in average climate conditions as well as extreme events such as strong winds, high temperatures, and low temperatures.

From 2021 to 2060, under the high emission scenario, both the climate natural capacity and extreme climate event pressure are generally higher than those under the moderate emission scenario. This indicates that high emissions will lead to more unstable climate conditions and a higher frequency of extreme climate events. Under both emission scenarios, the instability of climate conditions is expected to increase over time.

According to China's development plan for achieving carbon peaking and carbon neutrality, by actively controlling carbon emissions and choosing a path of low energy consumption and sustainability, the urban climate pressure and urban coordinated development capacity of the BGUA are projected to continue increasing from 2021 to 2060. Nevertheless, the growth in urban coordinated development capacity is expected to be greater. Industrial production and energy consumption remain the primary factors contributing to the growth in urban climate pressure. Increasing investment in research and development can be beneficial in enhancing urban coordinated development capacity.

This study relied on a single climate model for estimating climate capacity and extreme events. Additionally, due to the inherent unpredictability in climate modeling, the estimates for climate natural capacity and extreme climate event pressure are subject to considerable uncertainty (Zhang and Chen^[62]; Liang et al.^[63]; Du et al.^[64]). Limited data availability constrained the assessment of urban climate pressure and urban coordinated development capacity to only one ideal scenario. This limitation means that the estimates may lean towards an overly optimistic view. Moreover, some indicators do not exhibit significant changes over the forecast years, and therefore, the impact of certain individual indicators on the final results is limited. For example, forest coverage in the urban coordinated development capacity is already ideal for most cities in the BGUA and is not likely to grow much in the upcoming decades. Thus, this indicator has a minor impact on the results. Future research could consider using multiple models and employing socioeconomic development models. Furthermore, interdisciplinary collaboration could facilitate access to more accurate and comprehensive socioeconomic data, enhancing the scientific robustness of the estimates.

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