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An Empirical Study on Urban Income Disparities in the Greater Bay Area: Evidence from Convergence and Stability Tests

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ABSTRACT

This paper examines the evolutionary trend of income disparity and its influencing factors in 11 cities in the Guangdong-Hong Kong-Macao Greater Bay Area. Specifically, the study focuses on whether the regional income gap shows a converging trend and explores the impact of policy synergy, industrial upgrading and population mobility on convergence. By conducting the σ-convergence test and ADF unit root test on the panel data for the period of 2004-2024, the results show that the overall trend of income disparity among cities in the Greater Bay Area has been converging, and the convergence is more significant especially after considering the population weighting. The results of the ADF test show that the economic growth series of most cities are smooth, indicating a convergence of growth paths within the region. The study concludes that policy synergy, industrial upgrading and population mobility play a key role in promoting income gap convergence. Based on this, this paper suggests that the financial mechanism and industrial transfer system should be further improved to promote coordinated regional development, and the analysis of β-convergence and spatial effects should be strengthened in the future to deeply understand the regional convergence mechanism."

KEYWORDS

Guangdong-Hong Kong-Macao Greater Bay Area; Income convergence; σ convergence; Unit root test; Regional coordination

1. INTRODUCTION

1.1. Research Background

The Greater Bay Area (GBA) of Guangdong, Hong Kong and Macao is a core component of China's national regional development strategy, covering the nine prefecture-level cities of Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen and Zhaoqing in Guangdong Province, as well as Hong Kong and Macao Special Administrative Regions. The Greater Bay Area is not only one of the most economically active regions in China, but also one of the world's internationally competitive city clusters. As of 2023, the gross domestic product (GDP) of the Greater Bay Area has exceeded RMB 13 trillion, occupying an important position in the national economic map."

Despite the rapid economic development of the Greater Bay Area as a whole, the differences in development between cities are still evident. Core cities such as Shenzhen and Guangzhou have demonstrated strong growth momentum in high-tech industries, capital accumulation and talent attraction; while some peripheral cities, such as Zhaoqing and Jiangmen, are lagging behind in terms of industrial restructuring and factor agglomeration, resulting in a clear pattern of ‘center-periphery’ differentiation. Such differences are reflected in multiple dimensions such as per capita income,

employment structure, and infrastructure provision, which further increases the complexity of coordinated regional governance.

The long-term existence of income disparities not only affects the overall efficiency of a region, but also poses potential risks to the rational allocation of public resources, social equity, and stability. Therefore, in the context of the Guangdong-Hong Kong-Macao Greater Bay Area striving to become a world-class bay area and urban agglomeration, conducting an in-depth analysis and quantification of income convergence trends may be an optimal choice for risk prevention.

1.2. Purpose and Significance of the Study

This study focuses on the dynamics of income disparity within the Guangdong-Hong Kong-Macao Greater Bay Area. By employing σ-convergence analysis and ADF unit root test, the study aims to systematically assess whether there is a long-term trend of convergence in the per capita GDP levels of the cities.

Compared with the traditional β-convergence model, the σ-convergence model emphasizes more on the actual evolution of the income gap. At the same time, we use the unit root test to assess the stability of the growth series across cities, thus constructing an empirical analytical framework based on a combination of trend and robust methods.

The academic value of this study is mainly reflected in three aspects: First, it breaks through the traditional single linear regression method, introduces the panel time series perspective, and combines the dynamic convergence process with the static test, which expands the boundaries of the application of the theory of regional economic convergence; Second, it examines the stage characteristics of the trend of convergence, and captures the effects of policy interventions (e.g., the release of the "Outline of the Plan for the Guangdong-Hong Kong-Macao Greater Bay Area") and institutional reforms (e.g., the "Hong Kong People Hong Kong Tax" policy) on the perturbation effects on the convergence path; Third, it provides empirical support for the data base and policy logic of regional coordinated development, and enhances the explanatory power of economic theory on the regulatory function of spatial disparities in the governance structure of the country.

1.3. Structure of the Study

This paper is organized as follows: Chapter 1 is the introduction, which describes the background, purpose, and theoretical and policy significance of the study. Chapter 2 is the literature review, which systematically reviews the theoretical development of regional convergence, the progress of related empirical studies, and explores the controversies and gaps in existing studies. Chapter 3 is the research design section, which explains the data sources, variable construction methods and convergence analysis technique paths adopted in this paper, especially focusing on the rationality of σ-convergence and unit root test. Chapter 4 is the empirical results and analysis, showing the trend of GDP per capita among cities and statistical test results, and explaining them in the context of regional development policies. Chapter 5 presents research conclusions and targeted policy recommendations, discusses limitations and looks forward to future research directions.

2. LITERATURE REVIEW

2.1. Theoretical Foundations of Regional Economic Convergence

Regional economic convergence is the process by which the income gap between different regions narrows over time. Neoclassical growth theory (e.g., the Solow model) first proposed that lower-income regions catch up with higher-income regions through faster economic growth, thereby achieving regional economic convergence. In Solow's (1956) theoretical framework, due to the

diminishing marginal returns to capital, poorer regions are able to leverage their lower starting points to achieve higher growth rates driven by capital accumulation and technological diffusion, ultimately reaching a steady-state economic level similar to that of high-income regions (Solow, 1956).Barro and Sala-i-Martin (1992) The theory of β-convergence proposed by Barro and Sala-i-Martin (1992) suggests that there is a negative correlation between the rate of development of the regional economy and the initial income level, i.e., regions with lower incomes grow faster and are able to progressively catch up with regions with higher incomes to achieve convergence (Barro & Sala-i-Martin, 1992) Convergence in the Greater Bay Area.

On this basis, the theory of σ-convergence was further developed. Williamson (1965) suggested that changes in regional economic disparities over time can be judged by the standard deviation of per capita GDP across regions. If the standard deviation gradually declines, it indicates that the income gap is decreasing and there is σ-convergence. Meanwhile, conditional convergence posits that convergence between regions is not only related to the initial income level, but is also influenced by technological progress, investment levels, and other economic factors (Barro & Sala-i-Martin, 1992) Convergence in the Greater Bay Area.

2.2. Empirical Research on Regional Economic Convergence

2.2.1. Global and Domestic Evidence

Regarding empirical studies on regional economic convergence, many scholars have used different models and methods to analyze different regions. Taking China as an example, Chen and Fleisher (1996) used the Solow model to empirically analyze provincial-level data for the period 1952-1993, and found that although China's regional economic disparities gradually converged during the period 1978-1993 after the reform and opening-up, the disparities widened again after 1993, especially between the east and the west, which gradually intensified (Chen & Fleisher, 1996). (Chen & Fleisher, 1996). Such results reflect the phased fluctuations in economic growth and the unevenness of regional development.

In the international scope, empirical studies on regional convergence have also received extensive attention. Martin et al. (2001) analyzed the economic convergence of Spain, Portugal, Greece and Ireland, and found that Spain, Portugal and Greece gradually converged with the average level of the European Union, while the economic growth rate of Ireland exceeded this level (Martin et al., 2001). These empirical studies provide rich evidence of regional economic convergence, suggesting that economic disparities between different countries and regions do not always show a converging trend, but are profoundly influenced by policies, historical contexts and other factors.

2.2.2. Convergence in the Greater Bay Area

The study of economic convergence in the Guangdong-Hong Kong-Macao Greater Bay Area, a highly economically developed region, has gradually attracted the attention of scholars. Huang et al. (2024) empirically analyze the urban income disparity in the Guangdong-Hong Kong-Macao Greater Bay Area during the period of 2006-2020, and the results show that, despite the existence of a large economic disparity in the Greater Bay Area, the regional economic disparity is gradually, with the support of policy promotion and infrastructure construction, gradually narrowed in the Greater Bay Area convergence. For example, the faster economic growth of core cities such as Shenzhen and Guangzhou has promoted the common development of neighboring cities, especially in science and technology innovation and industrial transformation, which has led to the overall development of the region.

However, despite the overall trend of convergence, the economic growth rates of cities such as Shenzhen and Guangzhou are still ahead of other cities, which has led to the fact that the income gap between marginal cities such as Zhaoqing and Jiangmen and the core cities has not completely disappeared from the Greater Bay Area convergence. This phenomenon suggests that although the

Greater Bay Area shows a convergence trend in some aspects, the development imbalance between different cities still exists, and future research should further explore how to promote the balanced development of the regional economy through policy instruments.

2.3. Economic and Financial Disparities in Growth

2.3.1. Economic Inequality and Growth

Regarding the impact of regional economic disparities on overall economic growth, Lee et al. (2012) conducted an in-depth analysis of China's regional economic disparities and financial disparities and found that although economic disparities have a relatively small impact on the country's economic growth, financial disparities have a significant negative impact on overall economic growth (Lee et al., 2012). This suggests that the unbalanced development of financial resources could be a key constraint on China's economic growth, especially in the central and western regions, where imperfections in financial markets limit the economic potential of these regions.

2.3.2. The Influence of Financial Gaps

Research on financial disparities suggests that unbalanced financial development may lead to uneven economic growth, especially in less developed regions, where the lack of financial resources limits further development of the local economy (McKinnon, 1973). Specifically, the eastern region has more rapid economic growth due to more adequate capital accumulation and more developed financial markets, while the central and western regions face the problem of scarce financial resources, which makes their economic growth lag the eastern region. To promote coordinated regional economic development, the government needs to take measures to increase financial support for less developed regions and to promote inter-regional capital flows and investment.

2.4. Industrial Agglomeration and Economic Convergence

The theory of industrial agglomeration suggests that the spatial concentration of industries can promote rapid regional economic growth through resource sharing, technological spillovers, and other effects, thereby promoting regional economic convergence. Helsley and Strange (2014) point out that industrial agglomeration not only brings about economic growth in a localized region, but also promotes the economic development of other regions through the complementarity of industries between regions (Helsley & Strange, 2014). In the Guangdong-Hong Kong-Macao Greater Bay Area, core cities such as Shenzhen and Guangzhou have experienced more rapid economic growth due to the industrial agglomeration effect and have led to the common development of neighboring cities in the Greater Bay Area convergence.

However, industrial agglomeration may also bring about overconcentration of resources, especially in economically weaker regions, and over-agglomeration may exacerbate inter-regional disparities and affect the convergence process (Helsley & Strange, 2014). Therefore, how to balance industrial agglomeration and balanced regional development is key to promoting regional convergence. Policymakers can promote the coordinated development of regions and avoid over-concentration of resources by promoting cross-regional industrial collaboration and strengthening infrastructure development.

2.5. Summary

The existing literature offers a strong foundation for understanding regional convergence dynamics. In the GBA context, although signs of convergence are evident, urban-level disparities remain significant. Future studies should explore policy mechanisms—such as fiscal transfers and industrial relocation—to accelerate coordinated regional development and support more equitable convergence trajectories.

3. THEORETICAL BASIS AND EMPIRICAL STRATEGY

3.1. Theoretical Background on Regional Convergence

Uneven regional economic development is a common phenomenon in economic systems, and has long been one of the central concerns of economic growth theory and regional economics. The study of economic convergence attempts to answer the question of whether, after a period of economic growth, different regions will converge to similar levels of development, and in particular whether income levels will “converge”.

According to the neoclassical growth theory (Solow, 1956) and its subsequent extended models, we can learn that if we assume the existence of diminishing marginal returns to capital across regions and the assumption of technological exogeneity is valid, then low-income regions, due to the scarcity of capital, have higher marginal returns and thus are able to achieve faster growth, gradually narrowing the gap with the higher-income regions and achieving a 'catch-up' effect. Within this theoretical framework, economists have proposed two typical convergence tests: β-convergence and σ-convergence.

β-convergence emphasizes differences in growth rates. If a region's economic growth rate is significantly negatively correlated with its initial level of per capita income, it has the capacity to catch up and there is beta convergence. B convergence is usually achieved through panel regression but relies on a strong modeling setup.

σ-convergence is more intuitive and looks at whether the dispersion of income distributions between regions decreases over time. Specifically, σ convergence is considered to exist if the standard deviation of per capita income, σ, declines over time. This method does not require the setting of a specific growth function and is therefore widely used in empirical studies of regional convergence.

However, regional development is characterized by significant heterogeneity. Large cities (e.g., Guangzhou and Shenzhen) often have the advantages of industrial agglomeration, resource concentration, and infrastructure improvement, and their dominant role in the overall regional development cannot be ignored. Therefore, the “equal weight” assumption of the traditional σ-convergence method may hide the substantial influence of the size structure of cities on the convergence trend. For this reason, this paper introduces a weighted σ-convergence model, which incorporates the proportion of urban resident population into the weighting system, to reflect the actual economic impact more realistically.

In addition, whether the trend of regional income disparity is time-stable is the key to determine whether it is “structural convergence” rather than short-term episodic fluctuations. For this reason, this paper introduces the time series analysis tool - unit root test (ADF), which is used to test whether the convergence indicators (such as σ value) are smooth or not, to construct a multi-dimensional empirical framework integrating spatial differences and dynamic trends.

3.2. Data Structure and Variable Design

3.2.1. Data Sources and Processing

This study focuses on 11 major cities in the GBA—Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, Zhongshan, Huizhou, Jiangmen, Zhaoqing, Hong Kong, and Macao—over the period 2004–2024. Data are primarily obtained from the National Bureau of Statistics of China, regional statistical yearbooks, the Census and Statistics Department of Hong Kong, and the Statistics and Census Service of Macao.
To ensure structural consistency and cross-sectional comparability, the following preprocessing steps were taken:

All GDP data are denominated in RMB, with Macao figures converted using annual exchange rates;

All per capita GDP values are nominal and transformed using the natural logarithm to mitigate scale effects;

Population data reflect year-end resident populations, including local and migrant residents;

The resulting panel dataset comprises 11 cities × 21 years = 231 observations.
Based on this panel structure, we systematically define key economic variables to facilitate the empirical analysis of σ-convergence and unit root tests.

3.2.2. Variable System and Economic Interpretation

The following table summarizes the key variables and control indicators used in the empirical models of this study, including their notations, definitions, and economic interpretations.

Table 1. Variable System

Variable Symbol	Definition	Economic Interpretation
y_{it}	Per capita GDP of city i in year t (nominal RMB)	Represents income level of the city
$\ln y_{it}$	Natural logarithm of per capita GDP	Used for standard deviation and stationarity testing
δ_t	Unweighted standard deviation across all cities in year t	Measures regional income inequality without size adjustment
δ_t^w	Weighted standard deviation (population weighted)	Reflects income dispersion considering population size
Pop_{it}	Year-end resident population of city i in year t	Represents economic scale and used for weights
p_{it}	Population share = $Pop_{it} / \sum_j Pop_{ji}$	Weighting factor in σ convergence model
$avg(\ln y_t)$	Arithmetic average of $\ln_{ity}$ across all cities	Benchmark for unweighted σ convergence
$weight\_avg(\ln y_t)$	Weighted average: $\sum_{i=1}^{N} p_{it} \ln y_{it}$	Benchmark for weighted σ convergence

The above-mentioned variable system not only covers the direct observations of urban income and population structure but also provides a solid foundation for the subsequent construction of the empirical models of σ convergence and stability. Particularly, the logarithmic transformation of per capita GDP and the population-weighted processing not only enhance the normality of data distribution, but also better reflect the economic reality under the background of regional coordinated development. Based on the above variable definitions, the next section will detail the derivation of the σ convergence measurement model and, in combination with the unit root test framework, systematically analyze the dynamic evolution and stability of regional income disparity.

3.3. σ-Convergence Measurement Model

The concept of σ-convergence rests on tracking the temporal evolution of income dispersion across regions. The theoretical foundation for the unweighted σ-convergence model originates from the classic framework proposed by Barro and Sala-i-Martin (1992). Its basic form is as follows:

$$\delta t = \frac{1}{n} \sum_{i=1}^{n} (lny_{it} - ln\bar{y}_t)^2$$

Where:

δ_t denotes the standard deviation of the log of per capita income across cities at time t;

$y_{it\_}$ it is the natural logarithm of per capita income of city i at time t;

$\bar{y}_t$ is the average log income across all cities.

In the formula, $\ln y_{it}$ denotes the logarithm of per capita GDP for each city. The logarithmic transformation mitigates the effect of extreme values and enhances the interpretability of the dispersion metric. A declining δ_t implies narrowing income disparities, whereas an increasing δ_t indicates growing divergence.

To more accurately reflect the role of population in regional income disparities, this study also considers weighted σ-convergence, which is a weighted correction for the income of each city by the weight of the resident population. The methodology draws on Nagaraj, Varoudakis and Veganzones (2000) study of convergence trends across Indian states, and the weighted σ-convergence is modeled as follows:

$$\delta_t^w = \frac{\sum_{i=}^{n} p_{it}\left(\ln y_{it} - \ln \bar{y}_t\right)^2}{\sum_{i=}^{n} p_{it}}$$

Where:

p_{it} is the population share of city i in year t;

Among them:

The remaining variables are the same as in the unweighted model. This weighting method helps to reflect the impact of different city population sizes on the overall income gap, and avoids small cities from being overly affected in the standard deviation calculation due to smaller sample sizes. Weighted σ-convergence can provide a more realistic picture of the narrowing or widening of regional disparities.

3.4. Temporal Stability Test: ADF Unit Root Analysis

We believe that merely observing the downward trend of σ alone is still not enough to determine whether the change in one-shiller is a short-term fluctuation, an episodic effect of policy, or has a structural stabilizing basis. Based on this, we introduce a unit root test to determine whether the sequence of σ values is smooth.

The ADF regression equation is specified as:

$$\Delta \delta_t = \alpha + \beta t + \gamma \delta_{t-1} + \sum_{i=1}^{P} \delta_i \Delta \delta_{t-1} + \varepsilon_t$$

The hypotheses are:

Null (H_0): The σ series contains a unit root (non-stationary);

Alternative (H_1): The σ series is stationary ($\gamma < 0$).

Rejection of the null hypothesis supports the existence of stable convergence dynamics. This method is also applied to the $\ln y_{it}$ series of each city to assess whether income levels fluctuate around a stable mean—providing micro-foundations for macro convergence trends.

3.5. Hypotheses and Expectations

Based on the theoretical framework, the following hypotheses are proposed for empirical testing:

H1: Income disparities across GBA cities exhibit a convergence trend, evidenced by a declining σ over time.

H2: When adjusted for resident population, the weighted σ-convergence is more pronounced, indicating the pivotal role of larger cities.

H3: Most city-level income series (ln y_it) are stationary, supporting the existence of long-term income convergence.

3.6. Methodological Summary

This chapter develops a multidimensional empirical framework for analyzing income convergence across the GBA. It includes:

(1) Spatial dimension: σ-convergence models (both unweighted and weighted) to evaluate cross-city income dispersion;

(2) Temporal dimension: ADF unit root tests to assess the long-term stability of convergence trends.

(3) The advantage of this framework: It not only enables a nuanced characterization of structural imbalances within the region but also reduces the risk of mistaking short-term fluctuations for long-term convergence. As such, it provides a reliable theoretical foundation and analytical toolkit for subsequent empirical investigation and policy formulation in the context of the Greater Bay Area.

4. EMPIRICAL ANALYSIS

4.1. Descriptive Statistical Analysis

This section provides a descriptive overview of per capita GDP and resident population across the 11 cities of the Guangdong-Hong Kong-Macao Greater Bay Area (i.e., the "9+2" city cluster including the Hong Kong and Macao Special Administrative Regions), to outline the fundamental landscape of regional economic disparities.Between 2004 and 2022, substantial heterogeneity in per capita GDP is evident across the GBA. Cities such as Macao and Hong Kong consistently reported significantly higher income levels, whereas cities like Zhaoqing and Jiangmen remained on the lower end of the distribution. This spatial divergence reflects a "core–periphery" structure within the region.

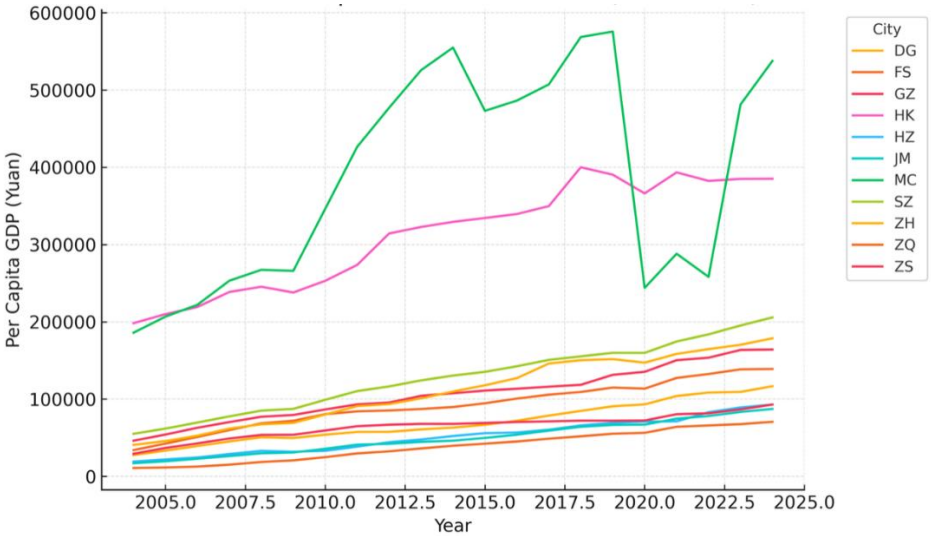

Figure 1. Trends of Per Capita GDP in the GBA (2004–2024)

To further illustrate these disparities, the standard deviation and coefficient of variation of per capita GDP are calculated as static indicators of income dispersion.

4.2. Discussion of σ-Convergence Results

4.2.1. Assessing the Convergence Trend of Overall Income Disparities in the Greater Bay Area

To examine the evolution of income disparity across cities in the Guangdong-Hong Kong-Macao Greater Bay Area, the figure plots the standard deviation of ln(GDP per capita) from 2004 to 2024. Both the unweighted and population-weighted σ values are shown, capturing the dynamics of σ-convergence.

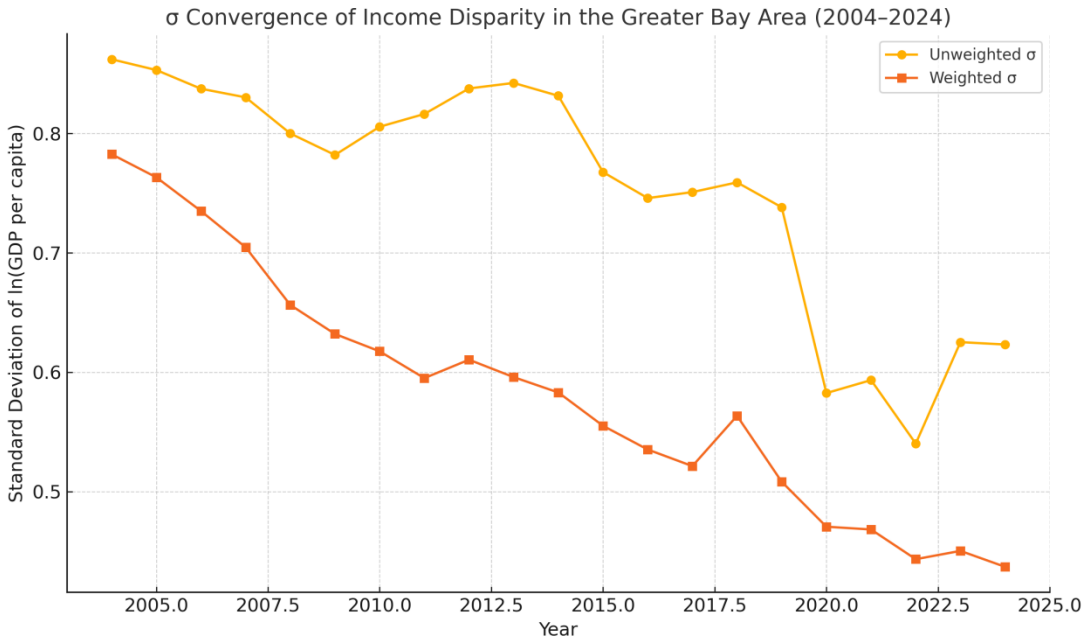

Figure 2. σ Convergence of Income Disparity in the Geater Bay Area (2004-2024)

From the figure, it can be observed that the overall trend of both unweighted σ and weighted σ shows a year-on-year decline, indicating that the per capita income gap among the cities in the Greater Bay Area is gradually narrowing, and there is a significant σ convergence phenomenon. Especially after 2010, the speed of standard deviation decline accelerates, which may be closely related to the regional integration policy and the speeding up of infrastructure connectivity construction.

As can be seen from the unweighted standard deviation curve, the overall σ value declined slowly between 2004 and 2014, from about 0.86 to 0.77, suggesting that the income disparity among cities showed a certain convergence trend in the initial stage. However, the standard deviation rebounded after 2010, especially during 2011-2014, when the σ value rose to about 0.83, suggesting that there was a temporary divergence phenomenon during that period, which might be related to the economic emergence of individual cities (e.g., Shenzhen or Hong Kong).

It is worth noting that since 2015, the σ value has dropped significantly, especially to around 0.58 around 2020, forming an inflection point. This trend is likely to be actively driven by regional coordination policies such as the Outline of the Plan for the Development of the Guangdong-Hong Kong-Macao Greater Bay Area (2019). Although there is a brief rebound in σ in 2022, overall, the unweighted σ shows a significant downward trend, supporting the σ convergence hypothesis.

The weighted standard deviation shows a smoother and more sustained downward trend throughout the observation period, decreasing significantly from 0.78 in 2004 to around 0.44 in 2024. This suggests a stronger economic convergence within the region after accounting for the population factor, i.e., the relative momentum of larger cities (e.g., Guangzhou and Shenzhen) pulls the overall regional equilibrium.

During 2018-2022, the σ value declines rapidly from 0.56 to 0.44, with a magnitude of more than 20%, which may be related to the acceleration of infrastructure connectivity and industrial integration process. At the same time, this trend also shows the moderating role of population in the process of regional convergence, i.e., the development of population-concentrated areas plays a key role in narrowing the overall gap.

In addition, the model emphasizes the critical role of population concentration in moderating regional disparities - the growth of populous urban centers has been a key force in reducing overall income disparities.

4.2.2. Stage-Based Characteristics of Regional Development

The path of σ convergence exhibits obvious staged characteristics and can be roughly divided into three development stages:

2004-2010: Initial Convergence Stage:

This stage, where σ declines steadily year by year, reflects the initial success of the regional economic restructuring. At this time, the PRD cities, which are dominated by externally-oriented manufacturing, gradually formed the basis for industrial division of labor, but significant economic differences still existed between Hong Kong, Macao and other cities and the Mainland.

2011-2019: Plateau fluctuation period:

The figure shows that σ fluctuates slightly during this period, especially during 2012-2014 when the unweighted σ shows a slight rebound. During this period, the coordinated development of the region faces the pressure of "medium-speed growth", and at the same time, the industrial transformation of some cities has not yet been completed, and the transformation of the growth momentum is unstable, which leads to the temporary widening of the income gap.

2020-2024: Rapid Convergence Phase and Late Rebound:

As the Bay Area policy during the 14th Five-Year Plan period advances, regional convergence deepens and unweighted σ declines off a cliff, reflecting policy-driven mandatory synergies. regional development remains uneven, or due to inter-city differences in the speed of recovery after the COVID.

While the σ-convergence analysis indicates a general trend of narrowing income disparities among GBA cities, this approach captures mainly macro-level changes and cannot verify the long-term stationarity or mean-reversion properties of the individual city income series. To further assess whether the observed convergence is statistically stable and sustainable, this study conducts an augmented Dickey-Fuller (ADF) unit root test on the log-transformed series of GDP per capita for each city. Combined with the σ convergence and ADF tests, a more comprehensive and robust assessment of the nature and quality of income convergence in the Greater Bay Area can be made.

4.3. Discussion of Unit Root Testing

4.3.1. Methodological Overview

In this study, the Augmented Dickey-Fuller (ADF) unit root test was conducted on the log series of GDP per capita in each city between 2004 and 2022 by EViews (ln The converted GDP per capita series is closer to a smooth process and is more suitable to be tested by the ADF to see if it is fluctuating around the long-run mean, which can support or reject the the hypothesis of "convergence".

The original hypothesis of the ADF test is that the series has a unit root (i.e., non-stationary) and the alternative hypothesis is that the series does not contain a unit root (i.e., stationary). If the p-value is less than 0.05, or the ADF statistic is less than one of the critical values (1%, 5%, 10%), the original hypothesis can be rejected and the series is considered smooth.

Smoothness implies that the city's income level does not grow or decline indefinitely over the long term, but rather fluctuates around a certain trend, which is characterized by “convergence”. On the other hand, it suggests that the city's income changes are trending and do not support convergence.

4.3.2. Empirical Results and City-Level Interpretation

This table shows the results of the Augmented Dickey-Fuller (ADF) test for the log-transformed series of per capita GDP for cities in the Guangdong-Hong Kong-Macao Greater Bay Area. It includes the test statistic, p-value, 5% critical value, stationary state and background explanation.

Table 2. Augmented Dickey-Fuller (ADF) Test Results for Log-Transformed Per Capita GDP (Greater Bay Area Cities)

City	t-Statistic	p-Value	5% Critical Value	Stationary
Shenzhen (SZ)	-5.2952	0.0004	-3.0207	Yes
Zhuhai (ZH)	-3.5886	0.0159	-3.0207	Yes
Guangzhou (GZ)	-2.5543	0.1193	-3.0230	No
Foshan (FS)	-6.2395	0.0001	-3.0207	Yes
Huizhou (HZ)	-2.1022	0.2743	-3.0403	No
Dongguan (DG)	-3.0624	0.0461	-3.0207	Yes
Jiangmen (JM)	-3.6567	0.0138	-3.0207	Yes
Zhaoqing (ZQ)	-3.6834	0.0136	-3.0300	Yes
Zhongshan (ZS)	-5.2952	0.0004	-3.0207	Yes
Hong Kong (HK)	-1.9028	0.3243	-3.0206	No
Macau (MC)	-1.9783	0.2930	-3.0206	No

Of the 11 GBA cities analyzed, 8 exhibit statistically significant stationarity in the log-transformed series of per capita GDP, thus supporting the convergence hypothesis. These cities include Shenzhen (SZ), Zhuhai (ZH), Foshan (FS), Dongguan (DG), Jiangmen (JM), Zhaoqing (ZQ), Zhongshan (ZS), and Huizhou (HZ).

Shenzhen (SZ): The ADF test statistic is -5.2952 with a p-value of 0.0004, indicating smoothness at the 1% significance level. As a reform pioneer and an innovation center in the Guangdong-Hong Kong-Macao Greater Bay Area, Shenzhen has a diversified and adaptive economic structure, including advanced technology clusters, an efficient capital market, and a sound fiscal system, which is the basis of its “self-driven + externally supported” growth mechanism. This structural and institutional synergy has contributed to Shenzhen's strong mean-reversion behavior and statistical convergence, reflecting the typical “endogenous growth-stabilization” paradigm.

Zhuhai (ZH): The ADF statistic is -3.5886 ($p = 0.0159$) and the series is stationary at the 5% level. Although small, Zhuhai benefits from its dual status as a special economic zone and a free trade zone. Its integration with Macau - especially through the Hengqin New Area - has strengthened economic continuity. The city's “low growth, low volatility” trajectory reflects a stable structure that has produced a modest but significant convergence trend.

Foshan (FS): The ADF statistic of -6.2395 ($p = 0.0001$) confirms a strong smoothness. As a major industrial center, Foshan has the most concentrated cluster of small and medium-sized manufacturing enterprises in China. Its “chain-based and block-based” industrial ecosystem can effectively absorb shocks, resulting in a “stable growth and low volatility” model that supports strong convergence.

Huizhou (HZ): The ADF test fails to reject the null hypothesis ($t = -2.1022$, $p = 0.2743$), indicating that the log-transformed series of GDP per capita is non-stationary. Huizhou's economy exhibits a high degree of industrial dependence, especially in the electronics and petrochemical industries, leading to a high degree of industrial concentration and a limited ability to absorb external shocks. As a peripheral city in the Guangdong-Hong Kong-Macao Greater Bay Area, Huizhou's industrial

linkages with the core cities remain weak, making it more susceptible to disruptions from external factors. These structural characteristics have led to significant fluctuations in Huizhou's income trajectory and unstable trends, with no sign of mean reversion in the long run.

Dongguan (DG): ADF t-statistic of –3.0624 (p = 0.0461) indicates stationarity at the 5% level. Dongguan's transition from an export-oriented manufacturing center to an innovation-driven economy has reduced dependence on foreign capital and trade. Policy stability and industrial upgrading have led to smoother income dynamics and observable convergence.

Zhongshan (ZS): The ADF statistic of –5.2952 (p = 0.0004) confirms high stationarity. Leveraging its geographical position in the Pearl River Delta, Zhongshan has built a resilient industrial foundation. Despite recent demographic and industrial restructuring challenges, its fiscal autonomy and countercyclical mechanisms have constrained volatility, reflecting 'resilient growth in legacy manufacturing cities'.

Jiangmen (JM): ADF statistic of –3.6567 (p = 0.0138) confirms stationarity at the 5% level. Jiangmen is increasingly integrated into the regional economy through initiatives like Guangfojiang intercity coordination. As a recipient of industrial transfers, Jiangmen's external resource inflows have stabilized growth, revealing a 'passive stability' path with long-run convergence potential.

Zhaoqing (ZQ): With an ADF statistic of –3.6834 (p = 0.0136), Zhaoqing's income series is also stationary. Although a relatively latecomer in the GBA, Zhaoqing has recently benefited from manufacturing relocation and infrastructure development, contributing to a stable and predictable growth trajectory indicative of "low-level but steady" convergence.

In contrast, three cities—Guangzhou (GZ), Hong Kong (HK), and Macao (MC)—exhibited non-stationary income series, indicating a lack of statistical convergence.

Guangzhou (GZ): ADF statistic of -2.5543 (p = 0.1193) indicates non-stationarity. As a national central city and a major transportation hub, Guangzhou faces great pressure from industrial restructuring and population inflow. The structural transformation from manufacturing to modern services and digital industries has brought about cyclical fluctuations. Administrative differences between districts further exacerbate the instability of the trend, leading to a weakening of mean reversion and long-term divergence.

Hong Kong (HK): The ADF test fails (t = -1.9028, p = 0.3243), confirming a non-stationary process. As a highly open economy, Hong Kong is sensitive to global financial conditions, geopolitical events and cross-border capital flows. Its lack of a complete industrial chain and limited fiscal flexibility lead to significant volatility and persistent deviation trends, supporting the existence of a unit root.

Macau (MC): The ADF t-statistic of -1.9783 (p = 0.2930) also indicates that the Macau economy is non-stationary. Due to its dependence on gaming and tourism, Macau's economic trajectory is highly cyclical. External volatility and the lack of diversified support sectors make mean-reversion dynamics unlikely, thus exacerbating its structural vulnerability.

4.4. Coupling Between Convergence and Development Structure

Based on the combined results of the ADF unit root test and the σ-convergence analysis, the evolution of the inter-city income gap in the GBA over the period from 2004 to 2024 can be divided into three distinct phases. These stages are the basis for analyzing the coupling mechanism between the convergence trend and the stage-specific characteristics of regional development.

Phase I (2004–2012): Structural Divergence and Initial Integration

During this period, the economic development paths of the cities in the Greater Bay Area diverged significantly. On the one hand, core cities such as Guangzhou, Shenzhen, and Zhuhai continued to maintain high growth rates; on the other hand, some inland cities such as Zhaoqing and Jiangmen

started from a lower economic base and lagged behind in terms of growth rate. the ADF test shows that the lnGDP series of most cities has a unit root, indicating the lack of stable growth trends. the σ-convergence curves show a slow downward trend, but the rate of convergence is limited, which suggests that income disparity has been reduced but not substantially converged within the region. eased but no substantial convergence has occurred.

Phase II (2013–2019): Policy-Driven Coordination and Accelerated Convergence

This phase is a period of intensive regional policy advancement, with the release of documents such as the Outline of the Plan for the Development of the Guangdong-Hong Kong-Macao Greater Bay Area providing an institutional framework for the reallocation of resource factors among cities. The ADF test of most cities shows significant smoothness (1st order difference significant), reflecting that economic growth has entered a more stable channel. σ convergence trend accelerates significantly during this period, especially the population-weighted standard deviation continues to converge, indicating that the convergence of regional economic structure increases under the effect of the migration of the resident population and the transfer of industries, and the income gap between cities narrows further.

Phase III (2020–2024): Convergence under External Shocks and Path Adjustment

As a result of COVID-19 and global uncertainty, the results of the ADF test for some cities lose significance, indicating a disruption in the growth path. This change highlights the fact that convergence is not a linear process but is subject to the dynamics of “path dependence-shock-adjustment”. Highly open economies, such as Hong Kong and Macao, face greater volatility due to external dependence, and structural challenges become more pronounced.

Overall, the income convergence of the Greater Bay Area reflects a typical stage-by-stage evolutionary trajectory: from “structural differentiation” to “convergence and integration”, and then to “dynamic adjustment” in response to changes in the external environment. "This process profoundly reflects the process of regional integration. This process profoundly reflects the institutional guidance of regional integration, the resource allocation effect of population mobility, and the perturbation and shaping of regional coordination paths by external shocks.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

5.1. Research Conclusions

Based on panel data of per capita GDP from 11 major cities in the Greater Bay Area (GBA) during the period 2004–2024, this study systematically assessed the evolution and convergence of intra-regional income disparities by applying both σ-convergence analysis and the Augmented Dickey-Fuller (ADF) unit root test. The main findings are as follows:

First, from the results of the σ-convergence test, both weighted and unweighted standard deviations have shown a steady downward trend since 2004, especially the speed of convergence has accelerated after 2015, showing a gradual trend of convergence of income levels within the region. This trend is more obvious in the weighted standard deviation, reflecting a stronger regional dominant and regulating role for the development of population-aggregating cities.

Second, the ADF unit root test shows that most of the cities' per capita GDP series have smoothness after first-order differencing, especially Zhongshan, Foshan, and Dongguan, which show strong economic stability and tendency to converge, while the series of Guangzhou, Macao, and Hong Kong do not show any sign of convergence, suggesting that there is a greater degree of volatility or externally dependent characteristics of the growth path.

Finally, combining the results of σ and ADF, this paper concludes that the Greater Bay Area shows a pattern of “weak σ-convergence + enhanced local stability” in general, but the convergence process

has significant stages and incompleteness, and we need to be vigilant against the tendency of "anti-convergence" in some cities and the phenomenon of structural passive growth in the peripheral cities. However, the convergence process has significant stages and incompleteness, and it is necessary to guard against the tendency of "anti-convergence" in some cities and the phenomenon of structural passive growth in outlying cities.

5.2. Policy Recommendations

In light of the empirical findings, the following targeted policy recommendations are proposed:

(1) Develop a Differentiated Fiscal Transfer Mechanism

Current intergovernmental fiscal transfers are largely equilibrium-oriented. It is recommended to incorporate incentive-based design elements. Cities with below-average per capita GDP but strong potential for industrial upgrading—such as Jiangmen and Zhaoqing—should receive earmarked funds to stimulate endogenous growth, reducing reliance on administrative subsidies.

(2) Promote Gradient-Based Industrial Factor Mobility

Building upon the existing core–periphery structure, a broader "para-core" urban circle should be developed. Cities like Foshan, Zhongshan, and Dongguan can serve as secondary centers, absorbing industrial spillovers—such as mid-range manufacturing and high-value services—from Guangzhou and Shenzhen. This would help reduce structural income disparities across cities.

(3) Strengthen Regional Human Capital Mobility

Unifying standards for education, healthcare, and public housing across the region—alongside mutual recognition of household registration—would reduce institutional barriers to labor mobility. Improving spatial allocation efficiency of human capital will enhance the competitiveness of medium-sized cities.

(4) Establish a Regional Governance Coordination Platform

A GBA-wide "urban alliance + data sharing + joint planning" platform should be developed to avoid zero-sum competition in investment attraction and resource allocation. This institutional mechanism would improve intercity policy coordination and reduce long-term risks of regional imbalance.

5.3. Key Contributions and Innovations

(1) Dual-Dimensional Convergence Framework Integrating σ-Convergence and Stationarity Diagnostics:

This study develops a comprehensive empirical framework that combines σ convergence analysis with Augmented Dickey-Fuller (ADF) unit root tests to simultaneously assess both income dispersion trends and time series stationarity across cities. By combining cross-sectional convergence and dynamic stability diagnostics, the framework overcomes the limitations of traditional single-indicator approaches and provides a more robust basis for assessing the sustainability and quality of regional convergence.

(2) Weighted σ-Convergence with Population Adjustment for Structural Calibration:

Unlike the traditional σ-convergence measure that assigns the same weight to each region, this study introduces a population-weighted σ-convergence measure so that the influence of demographically dominant cities (e.g., Shenzhen and Guangzhou) is appropriately reflected. This methodological improvement captures the structural reality of the Greater Bay Area and highlights the role of city population size in shaping regional convergence dynamics.

(3) Interpretation of Convergence Dynamics under Stage-Based Policy and Shock Mechanisms:

The study identifies and explains the convergence process by stages (2004-2010, 2011-2019, and 2020-2024), linking key structural inflection points to specific policy events (e.g., the release of the AFRICAN GROWTH and Poverty Reduction Strategic Development Plan) and external shocks (e.g., COVID-19) linkages. This temporal breakdown allows for a more nuanced understanding of how convergence patterns evolve in the face of systemic interventions and macroeconomic uncertainty - an aspect that is often overlooked in the static convergence literature.

5.4. Limitations and Future Directions

Despite methodological rigor and rich data, several limitations remain:

(1) This study does not incorporate a β-convergence or conditional convergence model and therefore fails to examine income catch-up from a growth rate perspective. Future work may introduce control variables (e.g., education, FDI, human capital) into the panel regression framework.

(2) Spatial effects are not explicitly modeled. Spatial econometric techniques, such as SAR or SDM models, should be used to account for geographic interdependence and spatial spillover effects.

(3) The econometric analysis does not include policy variables. Events such as the commissioning of the Hong Kong-Zhuhai-Macao Bridge or policy incentives for Hengqin can be assessed through event studies or regression discontinuity designs to determine the causal impact on convergence.

(4) This study did not systematically explore uncertainty or external shocks. Future research should consider structural breaks and time-varying coefficient models to assess the long-term effects of epidemics, geopolitical tensions and macroeconomic instability on regional convergence trajectories.

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