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The coupling relationship of urbanization and atmospheric environment in Shenzhen

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Abstract. This paper analyzes the relationship between urban development and air quality in Shenzhen using the Coupling Coordination Degree Model (CCDM). Results show that spatial urbanization has the greatest impact on urban development, while atmospheric pressure significantly affects air quality. From 2005 to 2006, the urbanization system experienced a decline in its comprehensive level, followed by a fluctuating increase between 2006 and 2015. Similarly, the comprehensive level of the atmospheric environment decreased from 2005 to 2007, followed by a fluctuating rise until 2015. The study also demonstrates that the contribution ratio between urbanization and atmospheric systems has only a slight effect on the Coupling coordination degree (CCD)'s values and trends. Over the period from 2005 to 2015, Shenzhen's coupling coordination degree transitioned from uncoordinated development to highly coordinated development. The findings underscore the importance of integrating long-term urban planning with environmental protection measures to achieve sustainable development.

Keywords: Urbanization, Atmospheric Environment, Coupling Model, Shenzhen, Environmental Protection.

1. Introduction

Urbanization fosters population growth, economic progress, and spatial expansion, but it also intensifies environmental challenges. Since the Reform and Opening-up in 1978, urbanization rate in China has surged from 18% to 65.22%, supported by extensive infrastructure development [1]. However, rapid urbanization has also exacerbated environmental problems, including water pollution, carbon storage decline [2], urban heat islands [3], and rising carbon emissions. By 2007, carbon emissions in China accounted for 13% of global carbon dioxide emissions, largely due to industrial growth [4] Globally, the relationship between urbanization and environmental pollution has garnered increasing attention [5]. While much research has focused on urbanization's impact on the ecological environment [6-7], fewer studies have systematically explored its effects on atmospheric conditions. For instance, Kalhor et al. highlighted the environmental, economic, and social problems resulting from urbanization in Iran [8], similar to challenges faced by Shenzhen. Other studies [9-10] were conducted based on the Environmental Kuznets Curve, which have shown that, during early urbanization, environmental degradation increases, but as economies develop, attention to environmental issues improves, often leading to better outcomes. Despite these findings, few studies have employed quantitative models like the

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Coupling Coordination Degree Model (CCDM) to assess the specific correlation between urbanization and atmospheric conditions.

This paper aims to address that gap by analyzing the coupling coordination between urbanization and atmospheric conditions in Shenzhen from 2005 to 2015.

Shenzhen, located in southern Guangdong province, has a subtropical monsoon climate with hot, humid summers, which favor the formation of secondary pollutants like ozone. As a Special Economic Zone since 1980, Shenzhen has undergone rapid urbanization, but this has also led to atmospheric pollution. By 2004, Shenzhen's SO_2 and NO_2 levels had risen to 24 μg/m³ and 72 μg/m³, respectively, negatively impacting air quality and living conditions [9,11]. However, significant improvements occurred after the implementation of environmental policies, including the Pearl River Delta Reform and Development Plan (2008–2020). By 2009, SO_2 levels dropped to 13 μg/m³ and NO_2 to 42 μg/m³. The 2020 Shenzhen Blue Sustainable Action Plan further reduced pollution, with SO_2 at 6 μg/m³ and NO2 at 23 μg/m³. Given these changes, this study uses the CCDM to examine the relationship between Shenzhen's urbanization and atmospheric environment from 2005 to 2015. Data from the Annual Report of Shenzhen show that, during this period, Shenzhen's permanent population grew from 8.28 million to 14.08 million, and its per capita GDP rose from 61,844 yuan to 135,271 yuan. Meanwhile, significant environmental improvements were observed: by 2015, SO_2, NO_2, and PM2.5 concentrations dropped significantly, and dust deposition rates decreased from 7.08 tons/km²/month to 3.00 tons/km²/month. The study aims to explore the dynamic relationship between urbanization and the atmospheric environment during Shenzhen's rapid urban development, offering insights into balancing economic growth and environmental protection. All data will be sourced from the Annual Report of Shenzhen and the Shenzhen Environmental Bulletin between 2005 and 2015.

2. Methodology

2.1. Index system

The urbanization and atmospheric environment index systems are distinct and analyzed separately. According to previous research [7,12], the urbanization system indicators are divided into four layers: demographic, economic, spatial, and social urbanization. In the atmospheric system, according to the PSR model, the indicators will be categorized into three layers atmospheric environment pressure' layer, reflecting the pressure caused by urbanization on the atmospheric environment; 'atmospheric environment state' layer, presenting the condition of atmospheric environment and 'atmospheric environment response' layer, reflecting the response of the local district due to the present condition of the atmospheric system. The system layers, subsystem layers, indexes and their weights are summarized in the Table 1 and Table 2.

Table 1. Urbanization index systems

System layer	Subsystem layer	Weight (%)	Index layer	Weight (%)
Urbanization system	Demographic urbanization	22.7	Non-Agricultural Population (10,000 people)	6.34
			Average Number of Employed Workers (10,000 people)	9.88
			Population Density (people/square kilometer)	6.48
	Economic urbanization	20.41	Per Capita GDP (Yuan/person)	6.18

DOI: 10.54254/2753-8818/75/2024.LA19358

Table 1. (continued).

			Average Wage of Employees (Yuan)	8.09
			Total Social Fixed Asset Investment (Billion Yuan)	6.14
	Spatial urbanization	44.28	Urban Green Space Area (Hectares)	20.17
			Per Capita Paved Road Area (square meters)	10.38
			Sales Area of Commercial Housing (10,000 square meters)	13.73
	Social urbanization	12.61	Total Retail Sales of Consumer Goods (Billion Yuan)	7.65
			Public Buses and Electric Cars per 10,000 People (standard units)	4.96

Table 2. Atmospheric environment index system

System layer	Subsystem layer	Weight (%)	Index layer	Weight (%)
Atmospheric environment system	atmospheric environment pressure	43.26	Industrial sulfur dioxide emission (tons)	31.64
			Industrial particulate matter emissions(tons)	11.62
	atmospheric environment state	34.29	Yearly Average Concentration of sulfur dioxide in the Air (ug/m3)	12.81
			Yearly Average Concentration of nitrogen dioxide in the Air (ug/m3)	21.49
	atmospheric environment response	22.45	Year-on-year reduction rate of sulfur dioxide emissions (%)	10.34
			Year-on-year reduction rate of nitrogen dioxide emissions (%)	12.11

In Table 1 and Table 2, all weights are calculated by entropy weight method.

DOI: 10.54254/2753-8818/75/2024.LA19358

2.2. Study method

In this study, the original index values are first standardized, followed by the calculation of weights using the entropy weight method and the weight of each index will be calculated. Next, the comprehensive evaluation index is calculated, and the CCDM is applied. The CCDM assesses the degree of interaction and synchronization between urbanization and atmospheric systems. It provides a quantitative measure to analyze the relationship between two complex systems by calculating coupling and coordination scores. The calculation of CCDM includes following steps: Standardization of indices. After calculating the standardized scores for each index, the comprehensive evaluation index is determined by aggregating the weighted values. Subsequently, the CCDM is employed to calculate the coupling degree between urbanization and the atmospheric environment, using the comprehensive indices as input.

2.2.1. The standardize of data

The handling of positive indexes:

$$x_{nj}^{*} = \frac{x_{nj} - x_{njmin}}{x_{njmax} - x_{njmin}} \tag{1}$$

The handling of negative indexes:

$$x_{nj}^{*} = \frac{x_{nj\,max} - x_{nj}}{x_{njmax} - x_{njmin}} \tag{2}$$

In the both two formulas, the x_{nj} means the original value of the j-th index in the n-th year; the x_{nj}^{*} means the standardized value of j-th index in the n-th year. The x_{njmax} and the x_{njmin} equals to the maximum index and the minimum value of j-th index. Both formulas are easy to calculate and implement. However, if there is any outlier dataset, a data point far from the normal range for example, the calculation and standardized data may be affected.

2.2.2. The handling of indexes' weights

The weight determination of the indexes will be processed using the entropy weight method. The advantage of the entropy weight method lies in its complete reliance on the intrinsic characteristics of the data, avoiding subjectivity in manual weight setting. However, its computational complexity and sensitivity to outliers are potential limitations.

$$p_{ij} = \frac{x_{nj}^{*}}{\sum_{n=1}^{m} x_{nj}^{*}} \tag{3}$$

$$e_j = -\frac{1}{\ln(m)} \sum_{n=1}^{m} p_{ij} \ln(p_{ij}) \tag{4}$$

$$w_{nj} = \frac{e_j}{\sum_{k=1}^{m} e_k} \tag{5}$$

According to the formula (3), (4) and (5), the m is the volume of the indexes; the p_{ij} equals to the proportion of the value of the specific index relative to the sum of all indexes' values; the e_j is the entropy value, reflecting the uncertainty of the information of the index; the w_{nj} is the weight of the particular index.

2.2.3. The comprehensive level index

The comprehensive index is a weighted sum of the individual standardized indicators, providing a simplified score from complex data.

$$X = \sum_{n=1}^{m} x_{nj}^{*} w_{nj} \tag{6}$$

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$$Y = \sum_{n=1}^{m} x_{nj}^{*} w_{nj} \quad (7)$$

Accordingly, the X and Y are the comprehensive level indexes, showcasing the overall rank of the urbanization or the atmospheric environment in specific year. Particularly, in this study, the X is the comprehensive level of urbanization, the Y is the comprehensive level of atmospheric environment.

2.2.4. The CCDM

The CCDM assesses the interaction and synchronization between urbanization and atmospheric systems by normalizing data, calculating weights, and determining comprehensive levels. The final coordination degree is then derived from these values to assess their interplay. However, such model can become complex with many interacting systems and may require sophisticated data analysis.

(1)The coupling degree

$$= \left\{ \frac{X \times Y}{\left(\frac{X+Y}{2}\right)^2} \right\}^{K} \quad (8)$$

In the formula (8), C denotes the coupling degree of the two systems, representing the interaction degree and the dependency degree of the urbanization system and the atmospheric environment system. Usually, the value of C ranges from [0,1]. The closer is the volume to 1, the higher the coupling degree is. K is the adjustment factor used to scale the coupling degree. In this study, based on previous researches [12], the value of K is set to 2.

(2) The comprehensive level

$$T = \alpha X + \beta Y \quad (9)$$

T is the comprehensive level of the two systems, reflecting the importance of each system in the coordination. α and β are the contribution weights of each system. Since the urbanization system and the atmospheric environment system are equally important in this study, the α and β will be equally set to 0.5.

(3) The CCD

$$D = \sqrt{C \times T} \quad (10)$$

D is the CCD (Coupling Coordination Degree), reflecting the coordination and the interaction of the two systems. The types and subtypes of coupling coordination and their characteristics are shown in the Table 3.

Table 3. Classification of coupling relation between urbanization and atmospheric environment

Coupling coordination degree (D)	Type	Subtype	characteristic
$0 < D \leq 0.3$	Severely uncoordinated	**0≤|X-Y|≤0.1**	Severely uncoordinated - Balanced development
		X-Y>0.1	Severely uncoordinated-atmospheric environment hindered
		X-Y<0.1	Severely uncoordinated-urbanization hindered
$0.3 < D \leq 0.5$	Basically uncoordinated	**0≤|X-Y|≤0.1**	Basically uncoordinated - Balanced development
		X-Y>0.1	Severely uncoordinated-atmospheric environment hindered
		X-Y<0.1	Basically uncoordinated-urbanization hindered

DOI: 10.54254/2753-8818/75/2024.LA19358

Table 3. (continued).

0.5 < D ≤ 0.8	Basically coordinated	**0≤|X-Y|≤0.1**	Basically coordinated - Balanced development
		X-Y>0.1	Basically coordinated - atmospheric environment hindered
		X-Y<0.1	Basically coordinated - urbanization hindered
0.8 < D ≤ 1	Highly coordinated	**0≤|X-Y|≤0.1**	Highly coordinated - Balanced development
		X-Y>0.1	Highly coordinated - atmospheric environment hindered
		X-Y<0.1	Highly coordinated - urbanization hindered

3. Results

3.1. The analysis of the index system and weight

Table 1 presents the weights of each subsystem layer in the urbanization index system. Spatial urbanization, with the highest weight (44.28%), reflects Shenzhen's heavy focus on infrastructure, emphasizing large-scale projects such as transportation and commercial development, which are essential to accommodating its rapidly growing population. Following spatial urbanization, the other subsystems—demographic urbanization (22.7%), economic urbanization (20.41%), and social urbanization (12.61%)—show relatively smaller impacts on the overall urbanization system. The high weight of spatial urbanization reveals that Shenzhen's urbanization heavily depends on infrastructure construction and urban expansion. In the Index layers, the Urban Green Space Area (20.17%), Sales Area of Commercial Housing (13.73%) and Per Capita Paved Road Area (10.38%) occupy the largest share, account for totally 44.28%. This is because the special administrative cities like Shenzhen usually emphasize the modernization and development of infrastructure. Large urban green space area, advanced transportation networks and modern architecture are prominent features of these urban areas, with significant investments especially in the construction of major transportation hubs such as ports, airports, and high-speed rail. Moreover, as larger population settling in, the demands of commercial housing usually increase, which makes the housing sale also important.

According to the atmospheric environment system in the Table 2, in the subsystem layers, the atmospheric environment pressure (43.26%) has the highest weight, followed by the atmospheric environment state (34.29%) and the atmospheric environment response (22.45%). This indicates that the urban pressure, the industrial emission especially, has the most influential impact on the atmospheric environment. In the index layer, the indicators with the highest contributions are Industrial Sulfur Dioxide Emission (31.64%), Yearly Average Concentration of nitrogen dioxide (21.49%), and Yearly Average Concentration of sulfur dioxide (12.81%), together accounting for 65.94%. This indicates that improving the atmospheric environment mainly involves reducing pollutant emissions and lowering their concentrations in the air, indicating that optimizing the atmospheric environment primarily involves reducing pollutant emissions and lowering their concentrations in the air.. In these indexes, two of them are indexes from the atmospheric environment state, one of them is from the atmospheric environment pressure, showcasing that the response to the atmospheric environment state is relatively scarce.

DOI: 10.54254/2753-8818/75/2024.LA19358

3.2. *The analysis of comprehensive level*

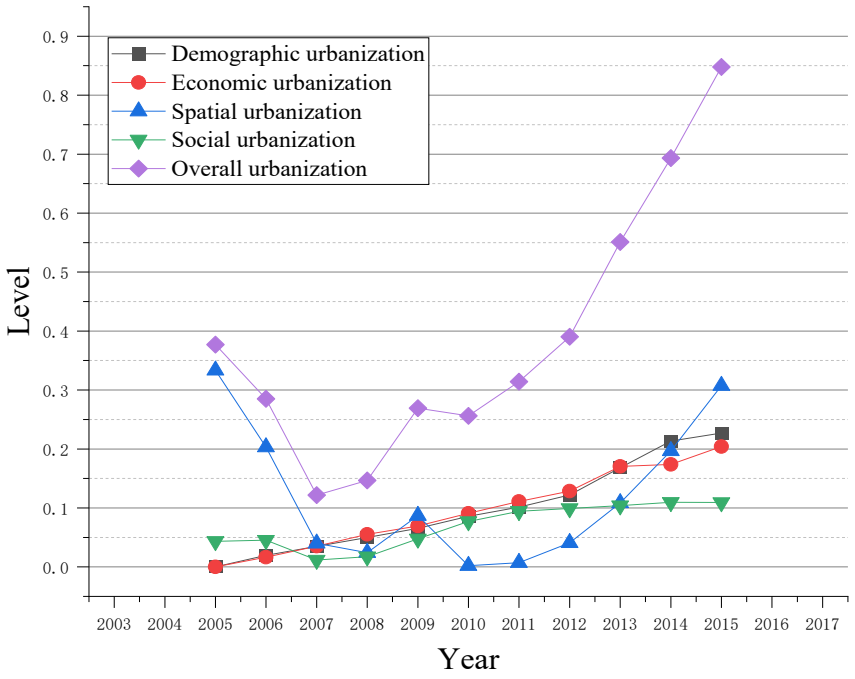


Figure 1. Comprehensive urbanization levels

Fig.1 demonstrates the comprehensive levels and evolution trends of the urbanization system and its subsystems. The comprehensive level is dimensionless and thus does not involve specific units. Fig.1 shows a decline in urbanization in 2005, largely attributed to economic readjustments following rapid expansion in the early 2000s. This decline was reversed with the implementation of new housing policies aimed at stabilizing population growth and housing prices. This trend was followed by a fluctuating increase between 2006 and 2015. According to the subsystems in Fig.1, in 2005, the comprehensive level of spatial urbanization is significantly greater than other three subsystem comprehensive levels. However, from 2005 to 2007, the comprehensive level witnessed a dramatic decrease from 0.3334 to 0.040119, mirroring the declining trend in the overall urbanization system, which indirectly proves that spatial urbanization has the greatest influence on the urbanization system. The trend shown in the spatial urbanization system is because, firstly, the declination of the sales' volume of commercial housing due to the increasing housing price in Shenzhen from 2004 to 2006; secondly, a massive population surged into Shenzhen from 2005 to 2007, the non-agricultural population increased from 1.8193 million to 2.1684 million, causing the declination of the per capita paved road area of Shenzhen, which declined from 14.37 square meters to 9.66 square meters. From 2007 to 2009, the comprehensive level of spatial urbanization increased significantly. This increase was driven by higher commercial housing sales, prompted by a surge in population. However, such process didn't continue in 2010 and caused the large -scale declination of spatial urbanization. From 2011 to 2015, the spatial urbanization increased gradually, this is because the implement of "*Outline of the Reform and Development Plan for the Pearl River Delta Region*" and "*Overall Plan for Comprehensive Reform in Shenzhen*", which intended to create 150 square kilometers of construction land through the redevelopment until of old urban area until 2015; construct a number of transportation infrastructures and achieve the incorporation of the Pearl River Delta Regions. The demographic urbanization and the economic urbanization increased gradually from 2005 to 2015, resulted from the "encourage the eastern region to take the lead in development" and the "actively and steadily promote urbanization" policies from the "*Outline of the Eleventh Five-Year Plan for National Economic and Social Development of the People's Republic of China*" and the "*Outline of the twelfth Five-Year Plan for National Economic and Social Development of the People's*

DOI: 10.54254/2753-8818/75/2024.LA19358

Republic of China" From 2005 to 2006, the social urbanization evolution trend was steady. From 2007 to 2008, affected by the economic crisis, the comprehensive level of social urbanization declined. From 2009 to 2015, after the China Central Economic Work Conference considered maintaining stable and rapid economic development as the top priority for economic work in 2009 and adopted a series of policy measures, quickly formed and fully implemented a comprehensive plan to effectively respond to the impacts of the international financial crisis, the comprehensive level in social urbanization increased.

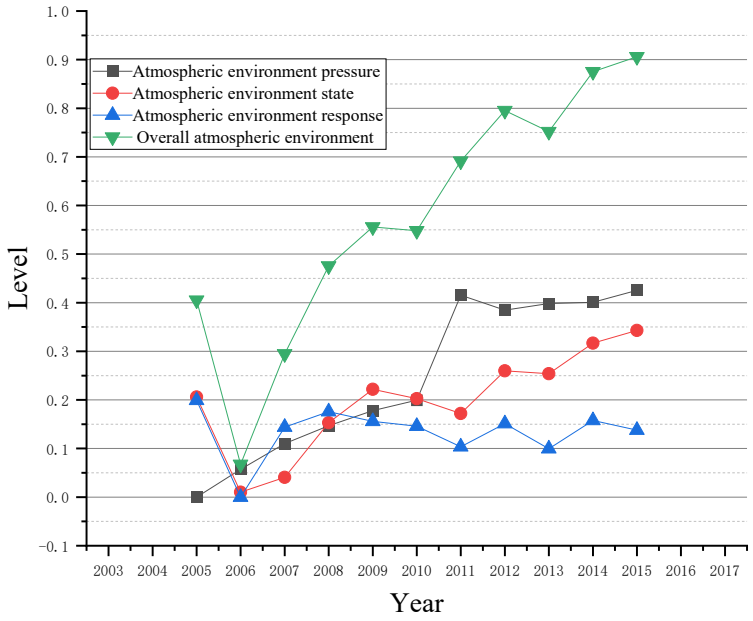


Figure 2. Comprehensive atmospheric environment level

According to the Fig.2, where the trend of atmospheric environment system and the atmospheric environment subsystems are shown, from 2005 to 2015, the atmospheric system level declined dramatically during the period from 2005 to 2006, primarily as a result of the surging population and industrial production demand. From 2006 to 2015, the atmospheric environment level showed a fluctuate growth trend. This is because the fully implement of the "*Decision on Implementing the Scientific Outlook on Development and Strengthening Environmental Protection*" of China General Office of the State Council and completed the compilation of the "*Shenzhen Ecological City Construction Plan*" and fully launched the work on building an ecological city. The atmospheric environment state level and the atmospheric environment response level both declined from 2005 to 2006. The atmospheric environment state level met a fluctuate increase from 2006 to 2015 and the atmospheric environment response level increased from 2006 to 2008 and maintained a stable fluctuation from 2008 to 2015. The atmospheric environment pressure level remained fluctuate increase from 2005 to 2015, such process was derived from the implement of the "*Shenzhen Ecological City Construction Plan*" in 2006 and the "*Shenzhen Environmental Quality Improvement Action Plan*" in 2011.

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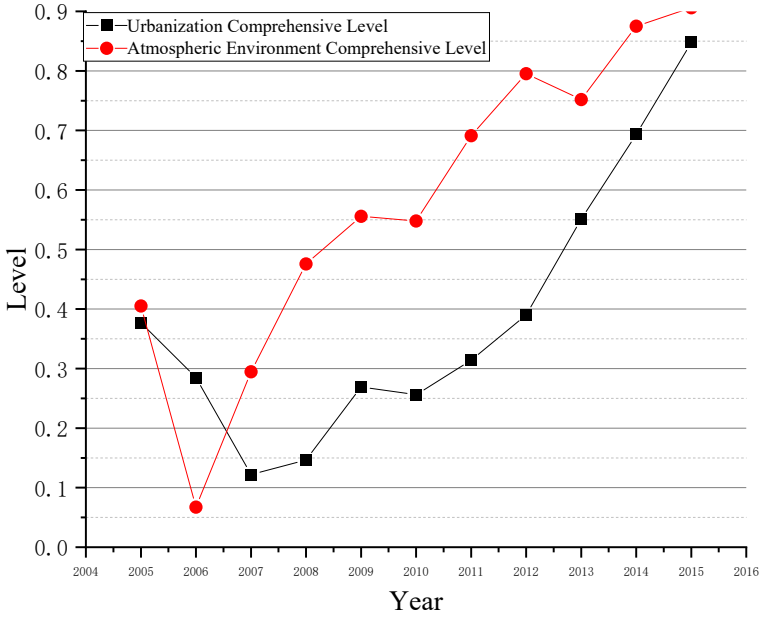


Figure 3. Comprehensive urbanization and atmospheric environment levels

Fig.3 illustrates the correlation between urbanization and atmospheric systems from 2005 to 2015, highlighting how changes in urban development directly impacted air quality.

3.3. The analysis of the CCD

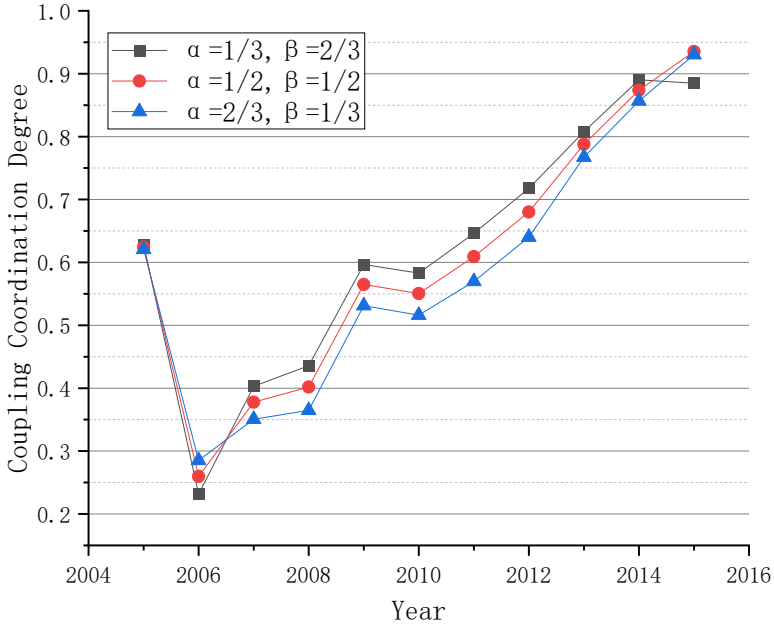


Figure 4. The CCD trend

The CCDM, applied here to assess the coordination between urbanization and atmospheric conditions, shows that while initial phases of urbanization in Shenzhen led to severe environmental stress, subsequent policy interventions improved both coordination and environmental outcomes.

DOI: 10.54254/2753-8818/75/2024.LA19358

The CCD trend of urbanization and atmospheric environment is shown in the Fig.4. The CCD is dimensionless and thus does not involve specific units. Based on the study conducted by the previous researchers [13], the graph reveals three types of contribution degree of urbanization system and atmospheric system. According to the Fig.4, the trends of the three coordination types are similar, indicating minimal differences in the contribution share of the two systems to overall coordination.

Based on Fig.4, together with Fig.3 and Table 3, the evolution of CCD can be divided into four phases. The phases are shown in the Table 4.

Table 4. The evolution trend of coupling coordination degree in three types of contribution

Year	$\alpha = \frac{1}{3}, \beta = \frac{2}{3}$	$\alpha = \frac{1}{2}, \beta = \frac{1}{2}$	$\alpha = \frac{2}{3}, \beta = \frac{1}{3}$
2005	Basically uncoordinated – Balanced development	Basically uncoordinated – Balanced development	Basically uncoordinated – Balanced development
2006	Severely uncoordinated-atmospheric environment hindered	Severely uncoordinated-atmospheric environment hindered	Severely uncoordinated-atmospheric environment hindered
2007	Basically uncoordinated-urbanization hindered	Basically uncoordinated-urbanization hindered	Basically uncoordinated-urbanization hindered
2008			
2009	Basically coordinated - urbanization hindered	Basically coordinated - urbanization hindered	Basically coordinated - urbanization hindered
2010			
2011			
2012			
2013	Highly coordinated - urbanization hindered		
2014		Highly coordinated - urbanization hindered	Highly coordinated - urbanization hindered
2015	Highly coordinated - Balanced development	Highly coordinated - Balanced development	Highly coordinated – Balanced development

From 2005 to 2006, the CCD decreased rapidly, degraded from Basically uncoordinated - Synchronized degradation to Severely uncoordinated-atmospheric environment hindered, indicating that urbanization and atmospheric environment development have entered an unbalanced phase. The comprehensive level of two systems both declined. Compared to the urbanization, the comprehensive atmospheric environment level witnessed a greater degree of declination. This is because of the degradation of urbanization and suggests that in the first stage, population growth and declining urban life quality increased demands on construction and industry, exerting greater pressure on the atmospheric environment.

From 2006 to 2008, the CCD of urbanization and atmospheric environment met an increase trend. The coordination type gradually shifted from 'Severely uncoordinated - atmospheric environment hindered' to 'Basically uncoordinated - urbanization hindered. The comprehensive level in both two systems increased. This indicates that following the implementation of the 'Outline of the Twelfth Five-Year Plan for National Economic and Social Development of China', the development of urban area and environmental protection were emphasized and the coordination of urbanization and atmospheric environment was fostered. However, the comprehensive level urbanization system was largely lower than the comprehensive level in atmospheric environment, which indicates that the improvement on atmospheric environment exerted a pressure on urbanization.

From 2008 to 2013, the CCD hit the peak at 2009 and slight declined from 2009 to 2010. This is because in 2009, the government Implement proactive measures to address the international financial

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crisis, focusing on domestic demand expansion, growth maintenance, economic development stability promotion and structure adjustment. Then, the CCD increased again from 2010 to 2013. The type of the CCD transformed from Basically coordinated -urbanization hindered to Basically coordinated-urbanization hindered. The comprehensive level in two systems both witnessed fluctuate growth. However, the urbanization level is still largely lower than that of atmospheric environment. This indicates that the coercive effect was still existed.

From 2013 to 2015, the CCD increased gradually. Specifically, it transformed from 'Basically uncoordinated - urbanization hindered' (2013-2014) to 'Highly coordinated – Balanced development' (2014-2015). The comprehensive level in urbanization system and atmospheric environment both increased rapidly and gradually narrowed the gap between them. This suggests that following improvements in urbanization policies, enhancements to the air pollution prevention and control framework, the establishment of responsibility assessment mechanisms for pollution targets, and the implementation of the ‘Shenzhen Air Pollution Emergency Plan’, the development of urbanization and the atmospheric environment became more balanced.

4. Discussion

This study applied the CCDM to investigate the relationship between urbanization and the atmospheric environment in Shenzhen from 2005 to 2015. Several key insights emerged.

First, the CCD between urbanization and the atmospheric environment significantly improved, transitioning from 'Basically Uncoordinated' to 'Highly Coordinated Development.' Both urbanization and the atmospheric environment indices experienced significant growth, with urbanization rising from 0.377 to 0.848 and the atmospheric environment increasing from 0.405 to 0.906. The initial gap between these two systems, observed between 2007 and 2014, diminished by 2015.

Second, changes in the contribution values of the urbanization and atmospheric systems had minimal effect on the overall CCD trends, indicating a similar level of influence from both systems.

Third, spatial urbanization exerted the most substantial influence on the comprehensive urbanization index, highlighting Shenzhen's dependence on infrastructure expansion and development. This suggests that future urban policies should continue to prioritize sustainable urban growth, particularly in infrastructure planning.

Fourth, atmospheric pressure was identified as the primary factor influencing the atmospheric environment index, emphasizing the importance of controlling industrial emissions and environmental pressures in improving air quality.

This study offers a new perspective on the urbanization-environment relationship using CCDM, filling gaps in research that has previously focused on broader ecological impacts. The study reveals that while the urbanization-atmosphere interaction is complex, varying system contributions exert minimal influence on the CCD, indicating the robustness of the model. Furthermore, spatial urbanization's dominant role in Shenzhen's urban growth underscores the need for policies centered around sustainable urban expansion.

Future research should explore spatial variations in CCD across different regions and extend the analysis to other environmental factors, such as water quality. Additionally, applying the Triadic Coupling Coordination Degree Model could provide a more holistic understanding of urbanization's interaction with multiple environmental systems. Longer-term analyses incorporating recent policy developments would offer valuable insights into the sustained impacts of urbanization and environmental protection measures.

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