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Research on the Interrelationship Between Carbon Markets

-- Based on the Method of Wavelet Coherence

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Abstract: In recent years, the excessive use of fossil fuels has led to global warming and a series of environmental crises. Carbon emissions trading, as a market-based mechanism to reduce carbon emissions, has received widespread attention and application. This paper investigates the dynamic dependency and causal interrelationships between Chinese pilot city carbon markets and the European Union Emissions Trading System (EU ETS). Using the wavelet analysis method, this paper empirically examines the data of various cities' carbon markets in China and the EU ETS from June 2014 to February 2023. Significant differences are found in the relationships between Chinese city carbon markets and the EU ETS. The study indicates that, with the exception of Shenzhen, the dynamic interactions between Chinese city carbon markets are weak in the short term but gradually strengthen in the long term. Not all city carbon markets in China have strong correlations, but they are closely related to factors such as local policies, economies, and industrial structures. There is no stable lead-lag relationship among the prices of carbon markets in different Chinese cities. After 2022, there is a trend of positive lag relationship of carbon market prices in Chinese cities (such as Guangdong, Shanghai, Chongqing) with those in the EU ETS. This paper summarizes the relationship between Chinese city carbon markets and the EU ETS and puts forward suggestions for the development of Chinese carbon market construction, including improving institutional systems, strengthening market supervision, promoting technological innovation, and implementing policies to stabilize price fluctuations.

Keywords: Carbon emissions trading, Carbon market, EU ETS, Wavelet analysis.

1. Introduction

In recent years, the excessive use of fossil fuels has triggered global warming and a series of environmental crises, posing serious challenges to the sustainable development of humanity [1]. To address this global issue, governments and international organizations have taken various measures to reduce carbon emissions [2]. Since the signing of the Kyoto Protocol, carbon emission trading has gained widespread attention and application as a market-based carbon reduction mechanism [3]. During this process, the European Union Emissions Trading System (EU ETS), as the world's first and largest carbon market, has maintained a leading position globally, significantly reducing carbon emissions, promoting economic restructuring, and demonstrating the complementary relationship between environmental protection and economic development.

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As one of the world's largest carbon emitters, China is also actively promoting carbon reduction efforts. In 2011, the General Office of the National Development and Reform Commission of China issued a notice on launching pilot carbon emission trading schemes [4], initiating carbon trading pilots in Beijing, Guangdong, Shenzhen, Tianjin, Chongqing, and Shanghai. These pilot cities have accumulated rich experience in carbon market construction, laying the foundation for the establishment of Chinese national carbon market. On July 16, 2021, Chinese carbon emission trading market officially commenced trading, marking a new development stage for Chinese carbon market [5]. Despite significant progress, Chinese carbon market, as an emerging market, still lags behind the EU ETS in terms of marketization and maturity. This situation underscores the importance of in-depth research on the internal development and future trends of Chinese carbon market [6]. The relationships between the pilot cities' carbon markets deserve thorough exploration, as their interconnections can provide strong guidance for the construction of Chinese carbon market [7]. The development of carbon markets in Chinese pilot cities is influenced by various factors, including local government policy support [8], industrial structure [9], enterprise participation [10], and technological innovation [11]. By analyzing the performance of these pilot cities' carbon markets, this paper identifies how different factors influence market development and provides policy insights for the construction of Chinese carbon market, such as learning from the successful experiences of the EU ETS, optimizing trading mechanisms, and enacting relevant policies. These measures can help improve the operational efficiency of Chinese carbon market and promote its healthy development.

This paper employs wavelet analysis to study the relationships between the carbon markets of Chinese pilot cities and the EU ETS. Although previous empirical studies have reported evidence of dependency and causal relationships between carbon markets and other markets (such as electricity [12], energy [13], and bond markets [14]) and various external factors (such as policy changes [15] and market mechanism alterations [16]) (as discussed in the literature review), little is known about the dependency and causal relationships between carbon markets at different time scales. To fill this gap, this paper examines how the dependencies between the carbon markets of Chinese pilot cities and the EU ETS evolve over time and differ across various time scales, with a particular focus on the dynamic correlations based on wavelet coherence.

This paper considers the carbon markets of six major pilot cities in China (Beijing, Guangdong, Shenzhen, Tianjin, Chongqing, and Shanghai) and the EU ETS, conducting an empirical analysis of daily carbon emission trading prices from June 2014 to February 2023. Empirical evidence shows significant differences in the interactions between Chinese city carbon markets at different periods. Except for Shenzhen, the dynamic interactions between the carbon markets of the other five pilot cities are weaker in the short term but increase in the long term. Regarding causal relationships, the results indicate that some carbon markets (e.g., Beijing and Tianjin, Guangdong and Chongqing) exhibit causal relationships at different time scales. The strength and direction of these causal relationships vary depending on the time scale, both at higher and lower frequencies. Overall, the carbon markets of Chinese cities do not exhibit strong correlations universally but are closely related to factors such as policies, economy, industrial structure, and mechanisms in each city. Similar cities show higher correlations during specific periods. Specifically, the EU carbon market shows less correlation with the Chinese cities except for Shanghai. However, after the COVID-19 pandemic eased in 2022 and Chinese carbon market was formally established, a certain positive correlation and lagged relationship trend emerged between some Chinese city carbon markets (e.g., Beijing, Guangdong, Chongqing, Shanghai) and the EU ETS. This trend may be due to the improvement of Chinese carbon market mechanisms and strengthened policy support, gradually aligning Chinese city carbon markets with international markets, while the EU ETS, being more mature with larger trading volumes and diverse participants, better reflects global carbon market supply and demand changes. This trend needs further observation over time to determine its stability and durability. Future research

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will continue to focus on the dynamic interactions between these markets, particularly under different time scales and economic environments, to better understand the operational mechanisms and development trends of carbon markets.

The paper is structured as follows: Section 2 reviews carbon market price studies; Section 3 details the wavelet methodology for analyzing relationships between Chinese city carbon markets and the EU ETS and describes data characteristics and analysis; Section 4 presents results on dynamic dependencies and implications; Section 5 summarizes findings and offers policy recommendations.

2. Literature Review

2.1. The Relationships Between Carbon Markets in China

Previous studies have explored the relationships between carbon markets in Chinese cities. For instance, Qian Wang and Cuiyun Gao [17] used the VAR-GARCH-BEKK model and social network analysis to study the structural characteristics and spatial correlations among Chinese carbon markets, finding bidirectional volatility spillover effects among most carbon markets. Xiaowen Xie et al. [18], from the perspective of rolling time windows, further analyzed the transmission mechanisms of mutual influences between the carbon markets of Chinese cities based on economic foundation and market contagion theories. However, their data covered a shorter period and did not capture the price fluctuations in the carbon markets following the COVID-19 pandemic in 2020 and the formal establishment of Chinese carbon market in 2021, limiting the observation of long-term impacts among the carbon markets of Chinese cities. Jiawang Zhang et al. [19] systematically analyzed the spillover effects of returns and volatility among the seven pilot carbon markets in China from an information spillover perspective, discovering an "M"-shaped periodic volatility trend but lacking analysis and reasonable explanation of spillover effects among city carbon markets across different time domains.

2.2. The Relationships Between Chinese and EU's Carbon Markets

Regarding the relationships between Chinese carbon market and the EU ETS, most studies have focused on qualitative analysis. For example, Li M and Weng Y [20] simulated the connections between Chinese national carbon emission trading system and the EU ETS and analyzed the impacts of these connections on emissions, energy, and the economy. Verde S F et al. [21] analyzed the role of complementary policies in the regulation of emission reductions within the EU ETS and related policy interactions, aiming to provide insights for the forthcoming emissions trading system (ETS) in China. Additionally, Zhang Jingjie et al. [22], Shen Qixia, and Zhao Changhong [23] provided suggestions for the construction and improvement of Chinese carbon market based on Chinese national conditions and the experiences and lessons of the EU ETS.

However, there are fewer studies on the quantitative relationships between the prices of Chinese carbon market and the EU ETS. Yang Min et al. [24] combined structural breakpoints and Hurst values to form HIBSB, analyzing the market efficiency of the EU, Hubei, and Shanghai carbon markets from 2014 to 2019, only mentioning the small correlation and the weakly efficient market characteristics. Liu Jianhe and Liang Jiali [25] explored the spillover relationships between Chinese carbon market, Chinese coking coal market, and the EU ETS, noting that the EU ETS had relatively small spillover effects on Chinese carbon market, while Chinese carbon market had almost no spillover effects on the EU ETS.

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2.3. The Relationships Between Carbon Markets and Other Factors

While the aforementioned studies provide valuable insights, a few have further investigated the relationships between carbon markets and economic and social factors. For instance, some studies have shown that carbon markets are not only directly influenced by supply and demand factors but also driven by various economic and social factors. Changes in policies and regulations, corporate environmental investments, and the enhancement of public environmental awareness significantly impact carbon markets. Hu Jun et al. [26] found that the implementation of the carbon emission trading mechanism significantly promotes corporate technological innovation, and the higher the liquidity of the carbon market, the stronger the incentive-based environmental regulation on corporate technological innovation. Wu Yinyin et al. [27], from the perspective of the synergistic effect of market mechanisms and administrative interventions, found that neither carbon prices nor market liquidity measured by market mechanisms had significant carbon reduction effects, while the stronger the government administrative intervention in the carbon market, the stronger the carbon reduction effects. These studies highlight the complex role of carbon markets in the broader economic system and indicate the need for further in-depth analysis of how these factors specifically impact the operation and long-term development trends of carbon markets.

2.4. Conclusion

This paper makes the following innovations and contributions:

This study provides new evidence on the correlations and causal relationships between carbon markets, which can also support the mutual influence of carbon markets with other economic and social factors.

This paper employs discrete and continuous wavelet analysis methods to study the frequency components of carbon market price time series. The advantage of this method is that it retains time-domain information without assuming specific parametric models to explain the commonly observed features in financial time series, such as time-varying volatility, covariance, and structural breaks.

Although wavelet analysis methods have been widely used to study dependencies between energy assets and between energy assets and other financial variables [28-32], no studies have yet explained the correlation and causal relationships between carbon market prices or analyzed the dynamic dependencies of carbon market prices across time scales using cross-wavelet coherence and phase analysis. This approach can more comprehensively capture the complex dynamic relationships between carbon market prices, helping to understand the operational mechanisms of carbon markets and their interactions with other factors.

This study also has important practical value, providing powerful tools for policymakers and market participants to address market volatility and optimize trading strategies.

Overall, this study not only fills gaps in the existing literature but also provides new directions and methods for future research. Through further research and data analysis, we can better understand the complexity of carbon markets and their crucial role in the global financial system. Future studies can further refine these analyses, explore the interactions between different markets, and develop more precise market regulation measures to ensure the healthy development of carbon markets and contribute to the achievement of the global carbon neutrality goals.

3. Methodology and Data

3.1. Methodology

This study employs continuous wavelet and cross-wavelet transforms to reveal how the local variance and covariance of two time series evolve over time. Additionally, wavelet coherence and phase

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analysis are utilized to measure the local co-movement between two time series in the time-frequency domain. Wavelet analysis is a mathematical tool used for analyzing the time-frequency characteristics of signals [33]. Unlike traditional frequency domain analysis methods such as Fourier transform, wavelet analysis can provide local information about the signal, making it more advantageous in capturing non-stationary signals and short-term features. The basic idea is to decompose the signal into wavelet functions of different scales and frequencies, and then perform inner product operations between these wavelet functions and the signal to obtain the local characteristics of the signal at different times and frequencies [34-36].

In this study, the wavelet analysis method, particularly the continuous wavelet transform (CWT), is used to investigate the relationships between carbon markets and the EU carbon market. Scalogram images are generated to show the changes in the signal's energy distribution over time and scale (frequency). This is achieved by applying the continuous wavelet transform to the signal. Although spectrograms are more commonly associated with short-time Fourier transforms (STFT), similar image representations of time-frequency distribution results are also used in wavelet analysis in this study.

Furthermore, this study uses the wavelet power spectrum to display the energy density of the signal at different times and frequencies, typically presented in color images where the color represents the power intensity. To better understand the interrelationships between carbon markets, wavelet coherence (WTC) images are generated to show the coherence between two time series in the time-frequency plane, which is commonly used to analyze the interrelationships between two signals [37].

In data processing, the study applies logarithmic transformation and first-order differencing, as described below:

$$\mathrm{y} = \frac{\ln(x_2 - x_1)}{ln x_1} \tag{1}$$

Where x_1 is the previous set of daily carbon trading prices, and x_2 is the subsequent set of daily carbon trading prices.

Wavelets are functions created from a single wavelet known as the mother wavelet, which is a real-valued square-integrable function [38], given by the following equation:

$$\varphi_{\tau,s}(t) = \frac{1}{\sqrt{s}}\varphi\left(\frac{t-\tau}{s}\right) \tag{2}$$

The above $\frac{1}{\sqrt{s}}$ is a normalization constant ensuring that the wavelet has unit variance. Here, τ and s are position and scale parameters, respectively, determining the exact location and dilation or stretching of the wavelet. Wavelets must satisfy an admissibility condition, meaning they have useful time-frequency localization in both the time and frequency domains.

The continuous wavelet transform$W_x(s)$ can analyze the time evolution of the frequency content of a given time series. It is defined as:

$$W_x(s) = \int_{\infty}^{\infty} x(t)\varphi^*\left(\frac{t-\tau}{s}\right)dt \tag{3}$$

Where φ^* denotes the complex conjugate, and the scale parameter s determines whether the wavelet can detect higher or lower components of the sequence $x(t)$.

The cross-wavelet transform W_{xy} of two time series $x(t)$ and $y(t)$ is defined as:

$$W_{xy}(s) = W_x(s)W_y^*(s) \tag{4}$$

Where $W_y^*(s)$ is the complex conjugate of the wavelet transform of the time series $y(t)$.

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The wavelet coherence $R^2(s)$ is used to measure the dependence between two time series in both time and frequency domains. It is defined as:

$$R^2(s) = \frac{\left|S(s^{-1}W_{XY}(s))\right|^2}{S(s^{-1}|W_x(s)|^2)\cdot S(s^{-1}\left|W_y(s)\right|^2)} \tag{5}$$

Where S denotes the smoothing operator in both time and scale domains. The value of $R^2(s)$ close to 0 indicates weak dependence, while a value close to 1 indicates strong dependence between two time series.

This study also utilizes wavelet coherence phase difference to capture the positive and negative correlations as well as the lead-lag relationships between two time series in the time-frequency space [39]. The coherence phase difference$\phi_{xy}(s)$ is defined as:

$$\phi_{xy}(s) = \tan^{-1}\left(\frac{\mathrm{Im}\left(W_{xy}(s)\right)}{\mathrm{Re}\left(W_{xy}(s)\right)}\right) \tag{6}$$

Where Im and Re denote the imaginary and real parts of the smoothed power spectrum, respectively.

3.2. Data

This study conducted empirical analysis on the dependency and causal relationships among the prices of different carbon markets in various Chinese cities at different time scales, using the daily average trading prices from the European Union carbon market and the carbon markets in the six pilot cities in China. The data sources are as follows: European Union (European Environment Agency, EEA), Beijing (Beijing Carbon Exchange), Guangdong (Guangdong Emissions Exchange), Shenzhen (Shenzhen Emission Rights Exchange), Tianjin (Tianjin Emission Rights Exchange), Chongqing (Chongqing Emission Allowance Trading Market), and Shanghai (Shanghai Environment and Energy Exchange).

The study covered a total of 1643 sets of daily carbon trading prices from June 2014 to February 2023 across these carbon exchanges. In the process of wavelet analysis of carbon trading price data, some preprocessing was applied to the carbon market prices.

Firstly, logarithms were taken of the prices, followed by calculating the first-order difference for each price. Taking logarithms helps reduce differences between prices, making the data smoother and more consistent with the assumption of normal distribution [40]. Calculating the first-order difference eliminates the trend component in price series, capturing the rate of change of relative prices more accurately. This processing method helps to clearly observe the fluctuation characteristics of prices, identify trends, and periodicities in price changes. By processing price series through logarithmic transformation and first-order differencing, wavelet analysis can effectively reveal the fluctuation patterns of prices at different time scales, thereby gaining deeper insights into the dynamics and trends of carbon market prices.

Figure 1 displays the dynamic prices of eight major carbon markets including the European Union and various cities in China. Over the period from June 2014 to February 2023, it is observed that overall prices in each carbon market showed an upward trend with significant price fluctuations, indicating considerable variability in carbon market prices.

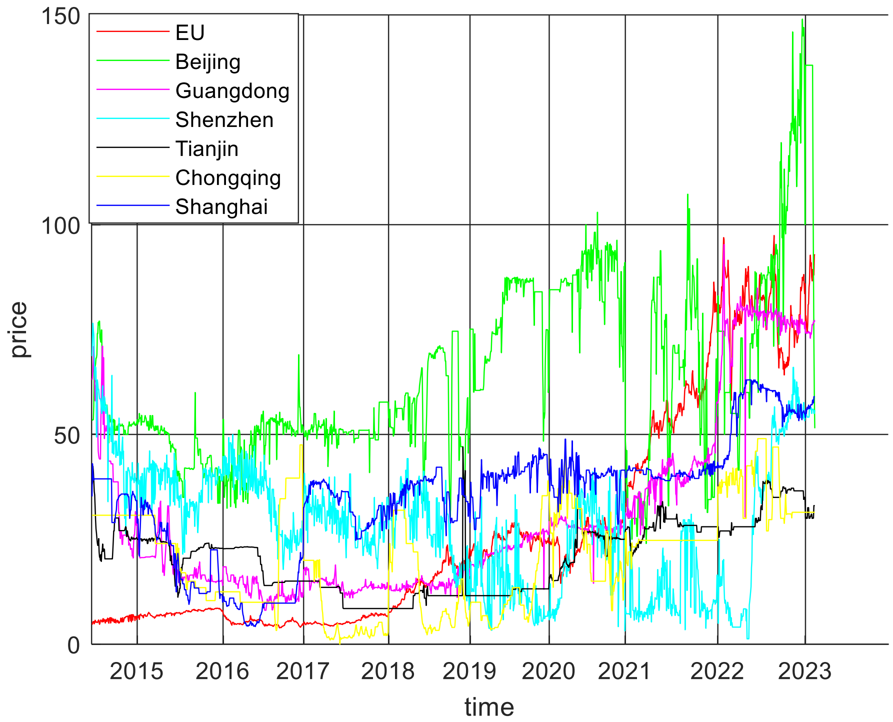

Figure 1: The fluctuation of carbon market prices.

In this study, detailed descriptive statistical analysis was conducted on carbon market price data from Europe, Beijing, Guangdong, Shenzhen, Tianjin, Chongqing, and Shanghai (The price unit of the EU carbon market is Euro, and the price unit of the Chinese carbon market is RMB.). These data were systematically interpreted to reveal the characteristics and differences in carbon market prices across various cities after first-order differencing. Statistical indicators included mean, standard error, median, mode, standard deviation, variance, kurtosis, skewness, range, minimum value, maximum value, sum, and confidence interval.

As shown in Table 1:

Specifically, the average prices of carbon markets in various cities indicate that Shenzhen's average price is significantly higher than that of other cities, suggesting more frequent or larger price fluctuations. Other cities exhibit relatively lower and closer average values, such as Europe, Beijing, Guangdong, Tianjin, Chongqing, and Shanghai, reflecting smaller price fluctuations and relative market stability. Shenzhen shows significantly higher standard errors and standard deviations compared to other cities, indicating greater price volatility and measurement uncertainty. In contrast, cities like Beijing and Tianjin exhibit lower volatility and higher market stability. Median and mode values for all cities are 0, indicating that price changes are concentrated near zero, suggesting minimal price fluctuations. This characteristic is prevalent across all cities, reflecting low volatility and stability in carbon market prices.

Kurtosis and skewness reflect the distribution of prices. Shenzhen and Tianjin have kurtosis values of 782.90 and 476.37 respectively, much higher than other cities, indicating more extreme values or peaked phenomena in price changes. Regarding skewness, Shenzhen and Tianjin exhibit high values, demonstrating a long-tail effect in price distribution with more positive or negative extreme values. This phenomenon is particularly significant in carbon markets, as extreme price fluctuations can have a significant impact on market participants.

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Price range reflects the magnitude of price fluctuations in each city's market [41]. Shenzhen has the largest price range, with minimum and maximum values of -0.881 and 7.78 respectively, further confirming its highest price volatility. Other cities such as Beijing, Guangdong, and Tianjin have relatively smaller price ranges and less volatility. Confidence intervals indicate the accuracy and reliability of price estimates. Shenzhen has the widest confidence interval, indicating greater uncertainty, while cities like Europe, Beijing, and Tianjin have narrower intervals, reflecting higher estimate accuracy.

In summary, the descriptive statistical results of carbon market prices after first-order differencing reveal significant differences between markets. Shenzhen's market exhibits the highest volatility and uncertainty, reflecting greater market activity and price fluctuations. In contrast, cities like Beijing, Tianjin, and Shanghai experience relatively lower price volatility and higher market stability. This provides evidence for the subsequent discussion on the correlation between Shenzhen's carbon market prices and those of other Chinese cities and the EU carbon market, consistent with findings in other literature [42].

Table 1: Descriptive statistics.

	EU	Beijing	Guangdong	Shenzhen	Tianjin	Chongqing	Shanghai
Mean	0.00083	0.0002	0.00037	0.01102	0.00016	0.00392	0.00027
Standard Error	0.00051	0.0005	0.00065	0.00572	0.00049	0.00241	0.00044
Median	0.00035	0	0	0	0	0	0
Mode	0	0	0	0	0	0	0
Standard Deviation	0.02051	0.02011	0.0263	0.23134	0.0199	0.09722	0.01768
Variance	0.00042	0.0004	0.00069	0.05352	0.0004	0.00945	0.00031
Kurtosis	13.94488	12.79053	37.10323	782.90161	476.37498	104.42001	36.57866
Skewness	0.51806	-0.13563	1.37738	23.87285	11.72895	6.50446	1.70297
Range	0.30805	0.34659	0.5061	8.65831	0.91412	2.28459	0.40182
Minimum	-0.14007	-0.16839	-0.22373	-0.87981	-0.34217	-0.59017	-0.1691
Maximum	0.16798	0.17821	0.28237	7.7785	0.57195	1.69442	0.23272
Sum	1.35547	0.3219	0.60733	18.00845	0.26037	6.41184	0.44121
Count	1634	1634	1634	1634	1634	1634	1634
Maximum (1)	0.16798	0.17821	0.28237	7.7785	0.57195	1.69442	0.23272
Minimum (1)	-0.14007	-0.16839	-0.22373	-0.87981	-0.34217	-0.59017	-0.1691
Confidence Level (95.0%)	0.001	0.00098	0.00128	0.01123	0.00097	0.00472	0.00086

4. Empirical Results

4.1. Relationships Between Carbon Markets in China

Figure 2 presents the cross-wavelet transforms between the carbon markets of several representative cities, reflecting the correlations and causal relationships of these indices across different times and frequencies. The figure shows that covariance increases gradually with scale, indicating that the relationships between city carbon markets are more influenced by long-term and sustained changes rather than short-term shocks. When cross-wavelet coherence is particularly high, specific time periods (2017 to 2019) and low frequencies can generally be identified, except for the relationship between Shenzhen and other city carbon markets, which exhibits low cross-wavelet coherence and short durations. We also observe that the degree of influence between city carbon markets diminishes over time, while post-2021, covariance of all time scales and indices increased. Furthermore, the Guangdong carbon market shows a good correlation with other cities (such as Beijing, Tianjin,

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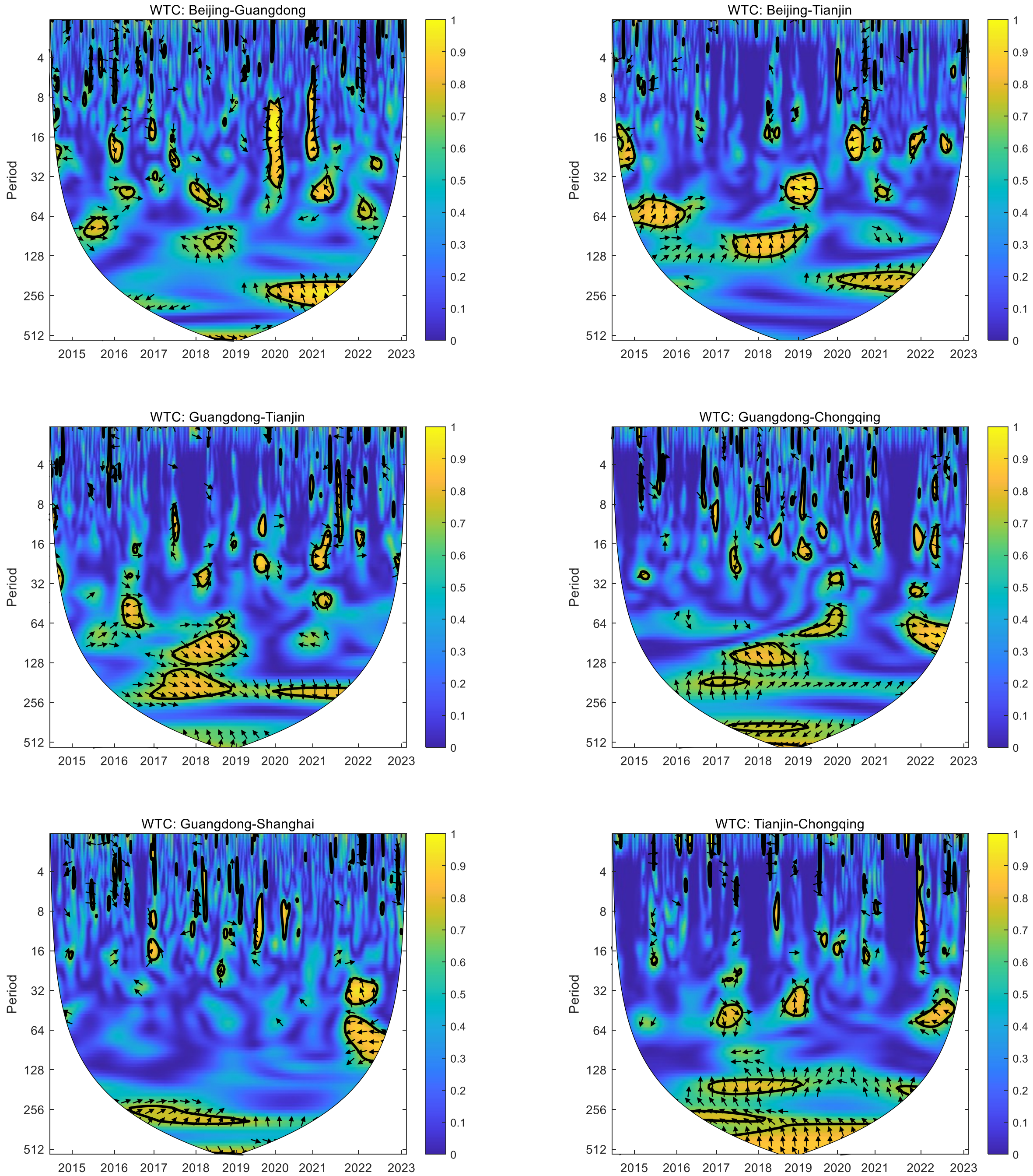
Chongqing, and Shanghai) in both long-term low and high frequencies. Additionally, the phase information (indicated by arrows) reveals that the relationships between city carbon markets are not uniform across scales, as the arrows may point in various directions at different scales.

Specifically, the influences among city carbon markets can be explained by different regional policies, energy structures, and industrial structures. Literature reflects these differences, indicating that Chinese carbon market impacts the competitiveness of each province differently; some provinces face higher emission reduction costs, while others gain economic benefits. These impacts also change with the design of Chinese carbon market mechanisms. The Guangdong carbon market is well-developed, with high trading volumes and relatively comprehensive features, leading to strong correlations with other cities. Guangdong covers six industries, and enterprises with annual emissions of 20,000 tons of CO2 or more, and this specific industrial structure and allocation system in Guangdong may explain its better market development.

However, this does not imply that the Guangdong carbon market always leads when it shows strong correlations with other city carbon markets at a specific time scale. For example, from 2016 to 2019, the Guangdong carbon market showed a lag relationship with the Shanghai carbon market at a frequency of around 260. It also does not imply that the Guangdong carbon market maintains a positive correlation with other city carbon markets at all times. For instance, from 2018 to 2019, the Guangdong carbon market showed a negative correlation with the Chongqing carbon market at a frequency of around 120, but a positive correlation at a frequency of around 150. This indicates that while a well-developed carbon market tends to have strong correlations with other markets, the positive or negative nature of these correlations and their causal relationships cannot be definitively established.

Beijing carbon market also shows certain correlations with other city carbon markets, thanks to its comprehensive institutional support, including a trading price warning mechanism, and covering mostly service industry enterprises and institutions. It can be observed that the Beijing carbon market, despite having strong correlations with several other markets, shows varying causal relationships with different city carbon markets at the same time scale. For instance, from 2020 to 2022, the lag relationships between the Beijing carbon market and the Guangdong and Tianjin carbon markets differ. The causal relationships can also differ with the same city carbon market at different time scales, such as leading from 2017 to 2019 between the Beijing and Tianjin markets but lagging from 2020 to 2022.

In summary, there is no overall strong correlation between city carbon markets in China over a long period. However, prices show some correlations at certain time scales between cities with similar industrial structures, policy formulations, and energy structures. Cities with more complete mechanisms and stronger policy support develop more systematically and have stronger correlations with other city carbon markets. Due to the instability in the development of Chinese city carbon markets, strong correlations do not impact the positive or negative nature of correlations and causal relationships, which remain random and unpredictable when comparing different city carbon markets and different time scales. Additionally, in comparisons between two specific city carbon markets, the positive or negative correlations may differ at different frequencies, while they remain mostly consistent at the same frequency.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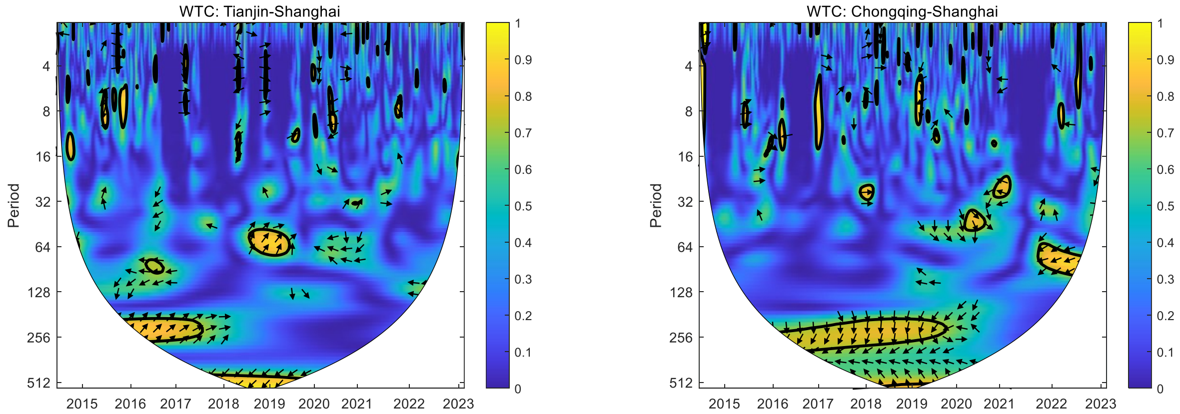

Figure 2: The relationship between carbon markets in various cities in China.

4.2. Relationships Between the EU Carbon Market and Chinese Carbon Markets

Figure 3 shows the cross-wavelet transforms between the EU ETS and the carbon markets of various Chinese cities, illustrating the correlation relationships of their indices across different times and frequencies. Through cross-wavelet transforms, a positive correlation between the EU ETS and the Shanghai carbon market from 2015 to 2018 can be identified. This correlation is manifested as significant energy density concentration areas in the wavelet power spectrum, indicating that the fluctuations in these two markets have similar frequencies and phases during this period, showing significant similar fluctuation patterns at these time scales. On the other hand, although other cities did not show significant correlations with the EU ETS from 2015 to 2018, some correlated trends might be present between these city carbon markets and the EU ETS from 2022 to 2023. These trends can be identified by observing changes in energy density in the cross-wavelet transform graph, where higher energy density and coherence coefficients indicate that these markets are beginning to show signs of common fluctuations at specific time scales.

Specifically, the Shanghai carbon market has a strong correlation with the EU ETS from 2014 to 2019. This could be due to Shanghai's industrial structure being similar to Europe's high-emission industries, its mechanism design drawing from EU experiences, and maintaining high linkage with international markets. During this period, a long-term stable positive correlation existed between the EU carbon market and the Shanghai carbon market, indicating consistent price fluctuations between the two markets. The correlation between the EU ETS and other city carbon markets, except for Guangdong, significantly decreased during 2020-2021 due to the pandemic's impact. This could be because the pandemic had uneven effects on economic activities and emissions in different regions. After 2022, with the pandemic's alleviation and the implementation of Chinese "National Carbon Emission Trading Management Measures (Trial)", the Chinese carbon market was established and further improved. Therefore, the price trends of city carbon markets and the EU ETS might exhibit higher correlations due to the improved market mechanisms that enhance market stability and connectivity.

The study finds a tendency for positive correlations between the EU carbon market and Chinese city carbon markets (such as Beijing, Guangdong, Chongqing, and Shanghai) after 2022, representing the established positive and negative correlations between the two relatively stable carbon markets. Notably, there is a tendency for the EU carbon market to lead in causal relationships with Chinese city carbon markets. This may be because the EU carbon market was established earlier, with more mature market mechanisms, higher trading volumes, and diversified participants. Its prices can reflect supply and demand changes in the market. Additionally, the EU has stricter emission reduction targets and timelines, with frequent and impactful policy changes. Due to its broad industry coverage, large market size, and high liquidity, the EU carbon market is sensitive to changes in information and policies.

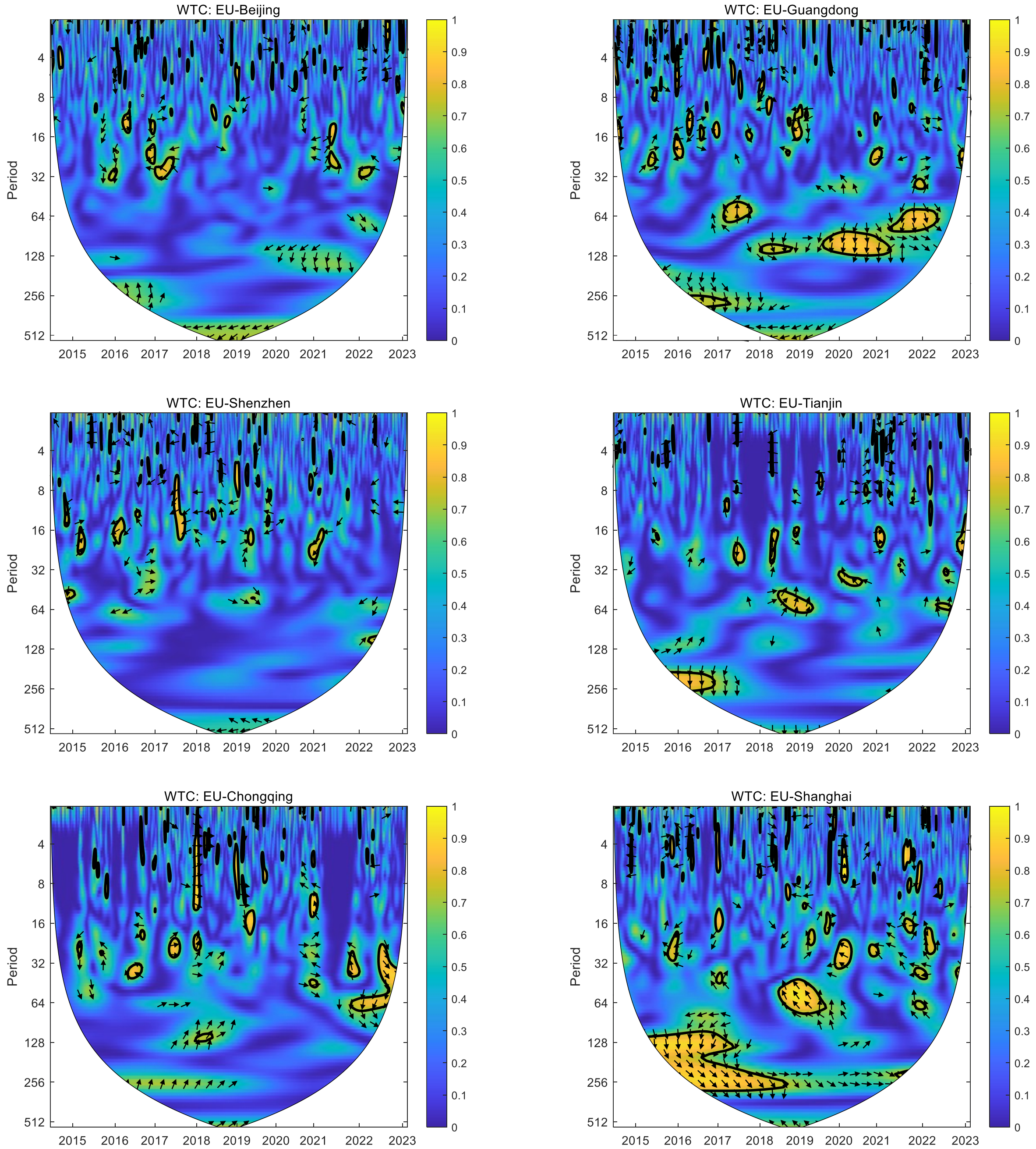

Figure 3: The relationship between EU ETS and carbon markets in various cities in China.

4.3. Summary

Through wavelet image analysis of the price impacts of Chinese city carbon markets and their interactions with the EU carbon market, this study finds that the relationships between Chinese city carbon markets are more influenced by long-term and sustained changes rather than short-term shocks. Cities with more comprehensive mechanisms and policies exhibit stronger correlations with other

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cities. The construction of Chinese carbon market still needs improvement, as the positive and negative correlations between city carbon markets vary at different frequencies. There is no consistent causal relationship among city carbon markets, and after the formal establishment of Chinese carbon market, there is a trend of maintaining a positive correlation with the EU carbon market, with a tendency to lag behind the EU market.

5. Conclusions and Policy Implications

5.1. Conclusions

This paper uses daily transaction prices from 1,643 sets of data from the EU ETS and Chinese city carbon markets from June 2014 to February 2023. Using wavelet analysis, the study examines the correlations and causal relationships between carbon markets. The results indicate that there is no strong overall correlation between all Chinese city carbon markets in the long term, though some individual cities show good correlations. The Guangdong carbon market has the best correlation with other city carbon markets, likely due to its well-developed operational mechanism and specific industry outcomes. The study also finds a high-frequency correlation between the Shanghai carbon market and the EU carbon market over a long period (2014-2019), possibly due to its close alignment with foreign markets and similar industrial structures. During 2020-2021, except for Guangdong, there was essentially no correlation between Chinese city carbon markets and the EU carbon market, likely due to several reasons, including the relatively small impact on Guangdong's economic activities and emissions. After 2022, a potential correlation and causal relationship between Chinese city carbon markets and the EU carbon market emerged, related to the easing of the pandemic and the final establishment of Chinese carbon market, further confirming the increased stability of city carbon markets in China post-establishment.

5.2. Policy Implications

This study has several policy implications:

Firstly, considering the varying conditions, industrial structures, and local investors in different cities, the state should introduce a differentiated quota allocation method based on historical emissions data and emission reduction potential. This ensures fairness and incentivizes enterprises to actively reduce emissions. The state should also promote regional market linkage and cooperation, strengthen the interconnectivity between different regional carbon markets, expand market scale, and ultimately achieve market operational efficiency and stability.

It is worth noting that government policies should consider the impact of price fluctuations among city carbon markets. These policies not only affect the financial prices within the carbon market but also cause chain reactions between different carbon markets, influencing overall market forecasts and analyses. The government should also be aware of the potential leading relationship between the EU carbon market and the Chinese carbon market. Timely policy adjustments should be made in response to price fluctuations in the EU carbon market to maintain the stability of the Chinese carbon market.

Secondly, the development of the carbon market should focus on internal optimization and enhancement. Local governments should emphasize technological progress to gradually reduce the cost of emission reductions for enterprises, improve emission reduction efficiency, and encourage more enterprises to participate in carbon market trading. Market transparency and regulatory enforcement still need to be enhanced. The government should establish a unified information disclosure platform and introduce independent third-party institutions to supervise and evaluate market operations, preventing market manipulation and unfair competition. The government should also introduce more financial instruments, diversify market trading varieties, meet the needs of different investors, and enhance market attractiveness and liquidity.

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Finally, this study finds that after the establishment of the Chinese carbon market, it is gradually moving towards healthy development and showing a trend of aligning with the EU carbon market model. Strengthening cooperation and exchanges with international carbon markets, such as the EU, to learn from their advanced experiences and technologies is essential. Through international cooperation, advanced emission reduction technologies and management experiences can be introduced and promoted, enhancing overall emission reduction capabilities and market operational efficiency. In the future, the Chinese carbon market is expected to play a more important role in the global carbon trading system. The state should promote the healthy and sustainable development of the carbon market through comprehensive enhancement and optimization of policies, technologies, and market mechanisms, achieve carbon neutrality goals, and make greater contributions to global climate change governance.

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