Volatility and Linkage of China's Carbon Pilot Markets Based on Wavelet Analysis

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Abstract. Against the backdrop of accelerating global climate governance and the full advancement of China's "Dual Carbon" goals, the carbon emissions trading market has become a core market-based policy tool for promoting greenhouse gas emission reduction and achieving green and low-carbon economic transformation. However, China's carbon market is still in the early stage of development and faces practical problems such as unbalanced development among regional pilots. Clarifying the price volatility characteristics, inter-market linkages, and price transmission paths of regional carbon markets is critical to improving the construction of a unified national carbon market. This paper takes China's eight carbon trading pilots as research samples, selects the daily closing prices of carbon emission allowances for each pilot as core indicators, and constructs a time-frequency dual analysis framework using continuous wavelet transform and wavelet coherence analysis. It systematically explores the heterogeneous characteristics of price volatility and regional linkage effects in carbon pilot markets. The study finds that the price volatility of carbon allowances in China's carbon market shows significant time-frequency heterogeneity, and policy shocks and market maturity are the core factors determining volatility patterns. The linkage effects among pilot markets present remarkable cycle heterogeneity. The Shenzhen pilot has outstanding price discovery and leading roles in the national pilot system, and it forms stable long-term linkages with pilots that are geographically adjacent and institutionally coordinated. This paper remedies the deficiencies of existing studies in sample coverage and analytical methods, and provides empirical evidence and decision references for policy expectation management, carbon price stabilization mechanism construction, deepening regional market coordination, and improving the unified national carbon market in China.

Keywords: carbon market, wavelet analysis, price volatility, market linkage.

1. Introduction

Against the backdrop of accelerating global climate governance and the full advancement of China's "Dual Carbon" goals, the carbon emissions trading market is in the process of becoming a central market-based policy tool for promoting greenhouse gas emission reduction and making the realization of green and low-carbon economic transformation. After more than ten years of development, the institutional framework of China's carbon market has been continuously improved and has played a key role in promoting green production. However, the market is still in the initial stage of development and suffers from unbalanced development among regional pilots, insufficient price linkage, and low market integration. Clarifying the price volatility characteristics, inter-market linkages, and price transmission paths of regional carbon markets is a key theoretical and practical issue for improving the unified national carbon market and enhancing market efficiency.

Existing academic research on China's carbon market has yielded abundant results and laid a solid theoretical foundation for the present paper. Early studies in the main focused on the policy effectiveness of the carbon market. making use of provincial panel data and methods including such items as the difference-in-differences model, studies have systematically confirmed that the carbon trading pilot policy can to a comparatively clear degree make the total amount and intensity of carbon emissions in pilot areas lower. They have identified three central emission reduction pathways: optimizing energy structure, promoting green technological innovation, and advancing low-carbon industrial transformation, verifying the emission reduction advantages of market-based carbon products.

The present paper takes China's eight carbon trading pilots as research samples and selects the daily closing prices of carbon emission allowances for each pilot as central indicators, covering the complete trading cycle of each pilot. Relying on ongoing wavelet transform and wavelet coherence analysis, it makes a construction of a time-frequency research framework to systematically explore the price volatility characteristics and regional linkage effects of carbon pilot markets.

The innovations of the present paper focus on two dimensions: method and content. In terms of method, it breaks by means of the limitations of traditional time-domain analysis, depicts the time-varying characteristics of carbon prices, makes an identification of non-linear linkages and price transmission paths across cycles, and compensates for the inability of traditional methods to capture cycle heterogeneity. It gives a more suitable analytical tool for carbon market linkage research. In terms of content, first, it carries out a full-sample analysis of all carbon trading pilots, gives clarification of the heterogeneity of volatility cycles and their causes, and makes up for the insufficient sample coverage in existing studies. Second, from the dual perspectives of geographical proximity and institutional similarity, it confirms the leading role of the Shenzhen carbon market in price discovery and enriches research on price transmission in regional carbon markets. Third, it tests the heterogeneity and driving factors of market linkages across cycles, providing empirical evidence and policy references for trading decisions and the integration of the national carbon market.

2. Literature Review

2.1. Review of Research Content

The policy effects of carbon trading and the operational characteristics of regional markets are central premises for studying carbon price volatility and linkages. Zhang et al. [2] and Xu et al. [9] both verified the comparatively clear emission reduction effects of the carbon trading pilot policy making use of the difference-in-differences model. The former found obvious regional divergence in the operational efficiency of China's pilot carbon markets. The latter identified optimizing energy structure and promoting green technological innovation as the central emission reduction pathways, and noted that policy effects are more pronounced in less developed provinces with a higher share of high-carbon industries, explaining the unbalanced development of regional carbon markets.

Lu et al. [8] reviewed the experience of mature international carbon markets and the development of China's carbon market. They pointed out that Even though China's national carbon market ranks first in the world in scale, it still faces central problems including such items as unbalanced regional pilot development, insufficient liquidity, and weak price discovery function, which anchors the practical starting point of the present study. Chen et al. [4] confirmed that the country-specific carbon emission factor for coal combustion in China is to a comparatively clear degree lower than the IPCC default value. Regional differences in accounting parameters are the underlying cause of the divergence in allowance supply-demand and price characteristics across pilot markets. Ding et al. [5] clarified the impact mechanism of allowance policies on emission reduction decisions of market participants making use of a two-layer game model. Wang et al. [6] proved that the policy effects of dual constraints on energy and carbon emissions show comparatively clear industry heterogeneity, with stronger impacts on high-carbon industrial enterprises. This is an important micro-foundation for the divergence in price sensitivity and volatility characteristics across regional pilot carbon markets.

Price linkage effects and price discovery function are central manifestations of carbon market efficiency and the focus of the present paper. Cao et al. [1] took five regional carbon markets in China as samples and confirmed that the linkage between climate uncertainty and carbon market returns has comparatively clear time-frequency heterogeneity making use of wavelet coherence analysis. This verified the unique advantage of wavelet analysis in capturing non-linear linkages in carbon markets. Long et al. [3] used wavelet analysis and found that the linkage between China's carbon prices and international crude oil prices shows comparatively clear time-frequency heterogeneity, with stronger medium- and long-term correlations. The linkage has increased to a comparatively clear degree after the launch of the national carbon market. Cevik et al. [7] pointed out that the weak linkage and insufficient price discovery between China's national carbon market and stock market in the main result from inadequate market liquidity, highlighting the practical need to make the price discovery mechanism better. Xu et al. [10] suggested strictly controlling excessive intervention in carbon prices and prioritizing the optimization of quantitative tools across markets to make the carbon market system better.

In terms of research methodology evolution, early carbon market studies mostly used models including such items as difference-in-differences and fixed effects to evaluate policy effects, and ARCH-type models and Granger causality tests to analyze carbon price volatility and linkages. These methods only support time-domain analysis and cannot capture time-varying characteristics or non-linear linkages across cycles (Zhang et al. [2]; Xu et al. [9]). In the recent period, wavelet analysis has been in a gradual way applied to carbon market research due to its dual time-frequency advantages. Studies by Cao et al. [1] and Long et al. [3] confirmed that this method can in an effective way identify cycle heterogeneity, non-linear linkages, and lead-lag directions in carbon price series. It is well suited to the non-stationary and policy-sensitive nature of carbon prices and gives a suitable analytical tool for The present study.

2.2. Review of Research Methods

Analytical methods for carbon market research have evolved from traditional linear time-domain models to non-linear time-frequency analysis. Early policy evaluation relied on traditional econometric methods including such items as difference-in-differences and fixed-effects models, which in an effective way identified the average treatment effects of carbon policies but struggled to characterize time-varying volatility in carbon price series. To address non-linear volatility and linkages, scholars often used ARCH-type models and Granger causality tests. However, these methods only support time-domain analysis and cannot capture differences in variable linkages across cycles. In the recent period, wavelet analysis has been increasingly used in carbon market research for its dual time-frequency strengths, as it can in an effective way identify cycle heterogeneity and non-linear linkages in series.

Existing studies have systematically verified the emission reduction effects of China's carbon trading policy, clarified the central laws of carbon price linkage, and confirmed the applicability of wavelet analysis in carbon market research, laying a solid foundation for the present paper. However, obvious deficiencies remain. First, sample coverage is incomplete, as no full-sample analysis includes all carbon trading pilots. Second, research perspectives are traditional. Existing wavelet analysis mostly focuses on external has an influence on on carbon prices, and few systematically explore price transmission and lead-lag relationships among regional pilots. Third, cycle dimension analysis is insufficient, as no study systematically distinguishes short-, medium-, and long-term cycles to test the heterogeneity and driving factors of market linkages.

Against this background, the present paper takes China's eight carbon trading pilots as samples and makes use of ongoing wavelet transform and wavelet coherence analysis to build a time-frequency framework. It systematically makes an exploration of the price volatility heterogeneity and regional linkage effects of pilot markets to remedy the gaps in existing research and provide empirical support for building a unified national carbon market.

3. Research Model and Sample

3.1. Research Model

Traditional time-domain econometric models (ARCH-type models, Granger causality tests) only characterize linear volatility and average linkage effects of carbon price series. They cannot capture time-varying price volatility, non-linear inter-market linkages, or price transmission paths across cycles. To overcome these shortcomings, The present paper adopts ongoing wavelet transform (CWT) and wavelet transform coherence (WTC) to construct a dual time-frequency analysis framework.

ongoing wavelet transform makes an identification of the volatility characteristics and heterogeneity of carbon price series in the eight pilot markets across time and cycles. Wavelet coherence analysis characterizes the time-frequency local linkages between the Shenzhen carbon market and other pilots and gives clarification of price fluctuation directions across cycles.

3.1.1. Continuous Wavelet Transform and Wavelet Power Spectrum

ongoing wavelet transform decomposes a one-dimensional time series into a two-dimensional time-frequency space by shifting and scaling a mother wavelet. It accurately captures both short-term fluctuations and long-term trends and fits well with the policy-sensitive, non-linear, and non-stationary features of carbon price series. The present paper makes use of the Morlet mother wavelet, which is widely applied in financial time series analysis. It has complex-valued properties and a Gaussian envelope, extracts both amplitude and phase information, and achieves an optimal balance between time and frequency resolution. Its basic expression is:

where is the central frequency of the wavelet. Following mainstream literature, ensure direct conversion between scale and cycle for daily carbon price analysis.

For any carbon price time series $x(t) \in L2(R)$, the ongoing wavelet transform is:

where is the scale factor. A smaller means higher time resolution and lower frequency, capturing short-cycle fluctuations. A larger means higher frequency and lower time resolution, capturing long-term trends. is the translation factor that controls the wavelet's position on the time axis to capture series features at different time points. is the complex conjugate of the mother wavelet.

To quantify the volatility intensity of carbon price series in the time-frequency domain, The present paper makes use of the wavelet power spectrum (WPS) to measure the local volatility of a single market:

A larger wavelet power spectrum indicates stronger carbon price volatility in the corresponding time-frequency interval, consistent with the color scale in the ongoing wavelet figures. To ensure statistical significance, The present paper makes use of Monte Carlo simulations to generate surrogate series and calculates the of central importance value of the wavelet power spectrum at the 95% confidence level to identify comparatively clear volatility intervals.

On the basis of ongoing wavelet transform and wavelet power spectrum, The present paper accurately makes an identification of time-varying volatility characteristics of the eight pilot carbon markets across short, medium, and long cycles. It gives clarification of the differential impacts of policy shocks, compliance cycles, and institutional adjustments on carbon price volatility across cycles.

3.1.2. Cross Wavelet Transform and Wavelet Coherence Analysis

To characterize the time-frequency linkages and price transmission paths between two carbon price series, The present paper first makes use of cross wavelet transform to capture co-fluctuations. It then quantifies linkage strength making use of wavelet coherence coefficients and makes an identification of lead-lag relationships via phase differences.

(1) Cross wavelet transform. For two carbon price time series and, the cross wavelet transform is:

where and are the ongoing wavelet transforms of and, and $Wy(a,\tau)$ is the complex conjugate of $y(t)$. The cross wavelet power spectrum is $|Wxy(a,\tau)|$. A larger value indicates a more comparatively clear common high-power region, meaning stronger co-fluctuation driven by common factors.

(2) Wavelet coherence coefficient. Cross wavelet transform only captures high-power co-fluctuations and cannot identify local correlations in low-power intervals. Thus, the present paper makes use of wavelet coherence coefficients to quantify full time-frequency linkage strength:

where is a smoothing operator in time and scale, and. A value closer to 1 means stronger linkage; a value closer to 0 means no comparatively clear linkage, consistent with the color scale in wavelet coherence figures.

Phase difference and lead-lag relationship. To clarify price transmission direction and lead-lag relationships, The present paper makes use of wavelet phase difference to characterize linkage direction and timing:

where Im· and Re· denote the imaginary and real parts of the cross wavelet transform. The economic meaning is:

① When $\phi_{xy} \in (-\pi/2, \pi/2)$, the two carbon price series are positively correlated; when $\phi_{xy} \in (\pi/2, 3\pi/2)$, they are negatively correlated.

② When $\phi_{xy} \in (0, \pi/2)$, arrows point to the upper right, meaning the Shenzhen carbon market lags behind the counterpart market.

③ When $\phi_{xy} \in (-\pi/2, 0)$, arrows point to the lower right, meaning the Shenzhen carbon market leads the counterpart market.

On the basis of the above models, the present paper systematically tests the linkage strength, duration, and price transmission paths between the Shenzhen carbon market and the other seven pilots across time and cycles. It confirms the price discovery and leading roles of the Shenzhen market in the pilot system, providing empirical support for regional coordination and national carbon market development.

3.2. Research Sample

The present paper obtains panel data of carbon emission allowance trading volumes for China's eight carbon pilot markets from 2013 to 2024, with 14,040 valid observations. Data are sourced from the Wind database. Overall, the distribution of selected variables is consistent with theoretical expectations and findings of similar studies. Data preprocessing is standardized, with no serious outliers or sample selection bias. (See Table 1 and Table 2)

Table 1. Descriptive Analysis and Robustness Test Results (1)

Indicator	Shenzhen ETS	Shanghai ETS	Hubei ETS	Tianjin ETS
Number of Observations	4911	1386	2043	826
Maximum	2.246646275	2.479477627	2.479477627	2.479477627
Minimum	0.481442629	-2.321045718	-4.126650397	-4.126650397
Mean	1.395066372	-0.000115812	-0.002117338	-0.005093315
Sample Variance	0.109458758	0.130029649	0.122404449	0.133174977
Sample Standard Deviation	0.330845519	0.360596241	0.349863472	0.364931469
ADF Test p-value	0.001	0.001	0.001	0.001
ADF Test Statistic	-17.46580637	-48.18047191	-46.85784591	-27.76348454
JB Test p-value	0.001	0.001	0.001	0.001
JB Test Statistic	429.6922296	19003.66729	58532.3188	40446.83752

Table 2. Descriptive Analysis and Robustness Test Results (2)

Indicator	Beijing ETS	Chongqing ETS	Fujian ETS	Guangdong ETS
Number of observations	1324	728	922	1900
Maximum	2.459830709	2.479477627	2.291309642	2.479477627
Minimum	-4.171305603	-4.126650397	-4.126650397	-4.126650397
Mean	-0.003309688	-0.005880823	-0.003856436	-0.002258137
Sample variance	0.148443735	0.248006766	0.141034925	0.132203784
Sample standard deviation	0.385283966	0.498002778	0.375546168	0.363598383
p-value of ADF test	0.001	0.001	0.001	0.001
ADF test statistic	-39.77728734	-28.04984574	-28.52003648	-45.63338919
p-value of JB test	0.001	0.001	0.001	0.001
JB test statistic	31837.77203	5828.658936	27153.49005	45466.7627

3.2.1. Descriptive Statistics

The eight carbon pilots show comparatively clear regional divergence in operational characteristics. In terms of trading continuity, the Shenzhen carbon market has 4,911 valid observations, the highest in the sample, indicating leading trading activity and continuity. Pilots including such items as Chongqing, Tianjin, and Fujian have fewer valid observations, directly reflecting unbalanced development. In terms of price performance, only the Shenzhen carbon market has a positive mean price; others have negative means close to zero. This confirms that the Shenzhen market has stable long-term price support and mature market-based pricing, and at the same time other pilots show a slight long-term downward trend. In terms of extremes, the Shenzhen market has no negative price extreme, with a floor of 0.4814 and strong downside resistance. Other pilots have negative extremes around -4, indicating higher extreme price risk. In terms of volatility, volatility is negatively correlated with market maturity. The Shenzhen market has the lowest sample variance and standard deviation, with the smallest price fluctuations and most stable operation. The Chongqing market has the highest variance and standard deviation, with the most violent fluctuations and worst stability. Pilots with higher maturity including such items as Hubei, Guangdong, and Shanghai show moderate volatility, further verifying that market development stabilizes carbon prices.

3.2.2. Robustness Tests

To ensure the validity and reliability of empirical analysis, The present paper carries out stationarity and normality tests on sample series to verify the rationality of research design and method selection. For stationarity, the ADF unit root test gives the result that all eight pilot price series have a p-value of 0.001, strongly rejecting the null hypothesis of non-stationarity at the 1% significance level. The absolute values of test statistics are much higher than the 1% of central importance value, confirming that all central series are stationary. This fully meets the data stationarity requirement for wavelet analysis, avoids spurious regression, and ensures robust empirical results. For normality, the Jarque–Bera test shows all series have a p-value of 0.001, strongly rejecting normality at the 1% level. This confirms that China's carbon pilot prices feature comparatively clear non-linearity and leptokurtosis. This result directly gives support to the method choice of The present paper: traditional linear time-domain models only apply to normal linear series and cannot capture non-linear carbon price volatility, and at the same time wavelet analysis fits non-stationary and non-linear price series and further ensures credible central conclusions.

4. Empirical Results Analysis

4.1. Continuous Wavelet Analysis

Figure 1 presents the results of ongoing wavelet analysis, which decomposes time series into the time-frequency domain and gives a description of the temporal and spatial characteristics of volatility. The horizontal axis represents time, and the vertical axis represents cycles. Warm colors indicate stronger market volatility. Figure 1 clearly shows volatility differences across China's carbon markets at different stages.

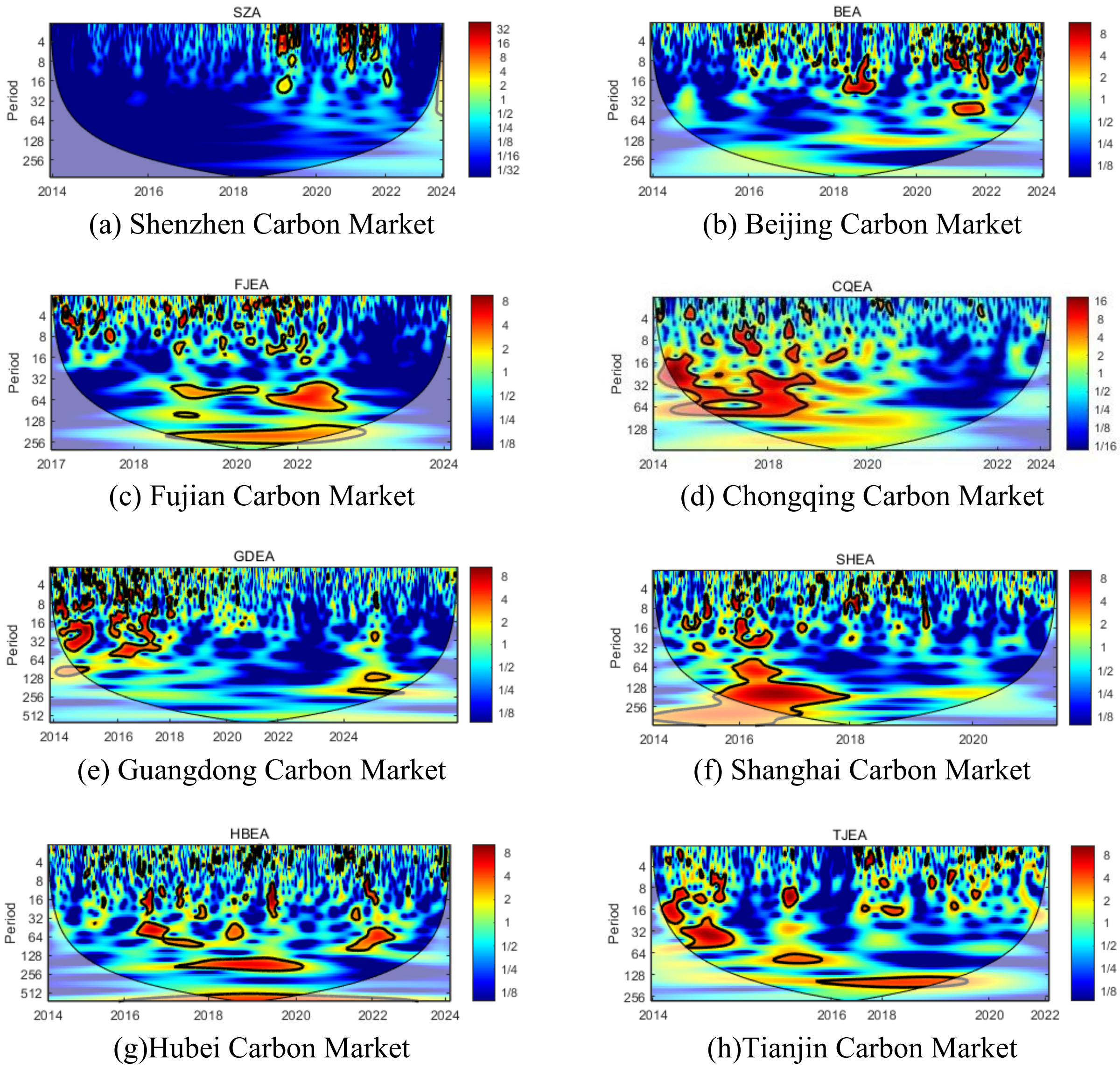
Panels (a) and (b) show volatility in the Shenzhen and Beijing carbon markets. Both experienced relatively strong medium-cycle volatility from 2019 to 2022 and low long-cycle volatility overall. Since 2019, Shenzhen has continuously tightened allowance allocation and optimized compliance rules. As early pilots, Shenzhen and Beijing have mature operational mechanisms and stable long-term market expectations, resulting in low long-term volatility.

Panel (c) shows volatility in the Fujian carbon market, launched in 2017, later than early national pilots. It saw exceptionally strong medium- and long-cycle volatility from 2020 to 2022, with large periodic medium-cycle fluctuations. The Dual Carbon goal and the national carbon market boosted linkage and trading activity, driving strong medium- and long-cycle volatility. Panel (d) gives the result that the Chongqing carbon market had strong volatility throughout the sample period. Long-term volatility dropped sharply after 2020, with only occasional medium-cycle fluctuations. After the Dual Carbon goal in 2020, market rules and long-term policy expectations stabilized, reducing long-term volatility.

Panel (f) shows volatility in the Shanghai carbon market. It had comparatively clear long-cycle volatility and synchronized short- and medium-cycle fluctuations from 2014 to 2018. Volatility fell rapidly after 2018, and the 2020 Dual Carbon goal and national carbon market only caused small medium-cycle fluctuations. Frequent early rule changes and the national carbon trading center launch drove high volatility. After 2018, stable market positioning and expectations reduced volatility.

Panels (e) and (g) show volatility in the Guangdong and Hubei carbon markets, both early pilots with high maturity, large allowances, and active trading. They had strong medium-cycle volatility from 2014 to 2016 and to a comparatively clear degree increased medium- and long-cycle volatility from 2020 to 2022, with stable volatility in other periods. After 2022, fewer major policy adjustments and stable expectations reduced volatility.

Panel (h) shows volatility in the Tianjin carbon market. It had strong short- and medium-cycle volatility from 2014 to 2016, peaked medium- and long-cycle volatility from 2016 to 2020, and sharply reduced full-cycle volatility after 2020 with only occasional short-term fluctuations. Frequent early allowance and compliance rule changes drove short- and medium-cycle volatility, and medium-term policy adjustments drove long-cycle volatility. After 2020, clear Dual Carbon and national carbon market policies stabilized expectations and reduced volatility.



(a) Shenzhen Carbon Market (b) Beijing Carbon Market

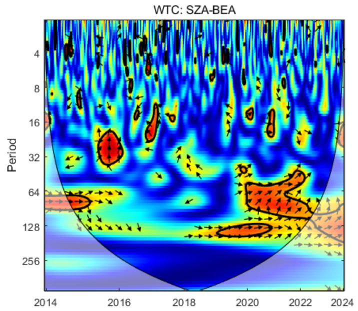
(c) Fujian Carbon Market (d) Chongqing Carbon Market

(e) Guangdong Carbon Market (f) Shanghai Carbon Market

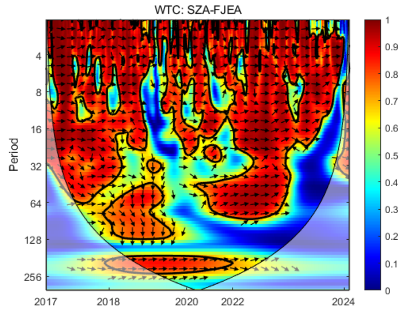
(g)Hubei Carbon Market (h)Tianjin Carbon Market

Figure 1. Continuous Wavelet Results

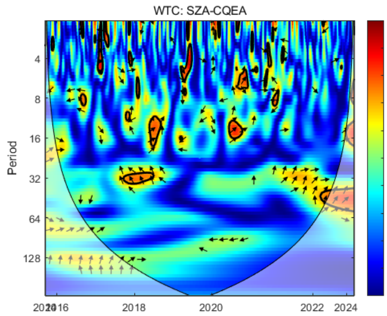
4.2. Wavelet Coherence Analysis



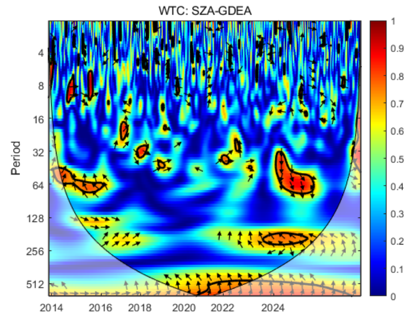
(a) Shenzhen Carbon Market – Beijing Carbon Market



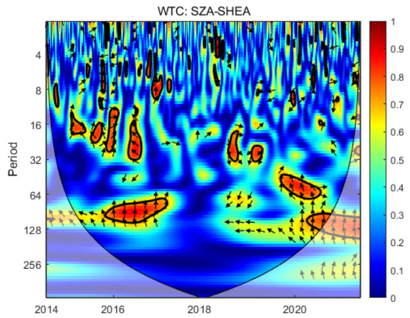
(b) Shenzhen Carbon Market – Fujian Carbon Market



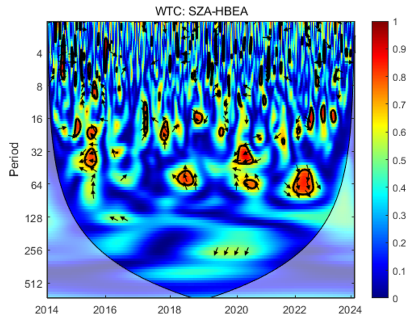
(c) Shenzhen Carbon Market – Chongqing Carbon Market



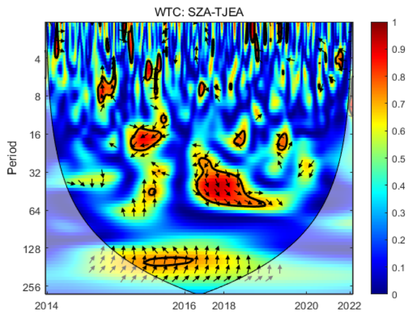
(d) Shenzhen Carbon Market – Guangdong Carbon Market



(e) Shenzhen Carbon Market – Shanghai Carbon Market



(f) Shenzhen Carbon Market – Hubei Carbon Market



(g) Shenzhen Carbon Market – Tianjin Carbon Market

Figure 2. Wavelet Coherence Results

Figure 2 shows wavelet transform coherence (WTC) results between each pilot and the Shenzhen carbon market. WTC is on the basis of ongoing wavelet transform and characterizes local time-frequency correlation and phase linkage between two time series. The horizontal axis is time, the vertical axis is cycles, and the color scale represents coherence coefficients from 0 to 1. Redder colors mean stronger correlation. The thick black line marks the 95% confidence comparatively clear coherence region. Arrows indicate phase difference: right for positive correlation, left for negative correlation; upper right for Shenzhen lagging, lower right for Shenzhen leading.

Panel (a) shows WTC between Shenzhen and Beijing. In the comparatively clear 32–128-day medium- and long-cycle region from 2019 to 2022, arrows point mostly upper right, indicating positive correlation and Beijing leading. In the comparatively clear over-256-day ultra-long cycle region from 2020 to 2022, arrows point mostly lower right, indicating Shenzhen leading. Beijing piloted national carbon market policies from 2019 to 2021. After the 2021 national carbon market launch, Shenzhen's market mechanism and liquidity advantages emerged, leading in the long cycle.

Panel (b) shows WTC between Shenzhen and Fujian, with high comparatively clear coherence across all cycles from 2017 to 2022. In the comparatively clear medium- and long-cycle region from 2017 to 2019, arrows point upper right, indicating positive correlation and Fujian leading. In the comparatively clear long-cycle region from 2020 to 2022, arrows point lower right, indicating Shenzhen leading. Short-cycle arrows point mostly right, indicating synchronized positive correlation. Shenzhen and Fujian have similar allowance management and trading rules. After the 2020 Dual Carbon goal, Shenzhen's mature mechanism became the price benchmark, and both fluctuate synchronously due to common policies.

Panel (c) shows WTC between Shenzhen and Chongqing, with only periodic short- and medium-cycle positive correlation from 2015 to 2017 and 2019 to 2021, with Chongqing leading and no stable long-cycle linkage. Chongqing has low liquidity and maturity, differing greatly from Shenzhen in long-term development. They only fluctuate synchronously under short-term shocks including such items as national policies and compliance windows.

Panel (d) shows WTC between Shenzhen and Guangdong, with comparatively clear 32–128-day medium-cycle positive correlation from 2014 to 2016 and 2020 to 2022, with Shenzhen leading. Weak over-256-day ultra-long-cycle coherence exists only from 2018 to 2022 with no clear lead-lag. Both are in the Guangdong-Hong Kong-Macao Greater Bay Area with strong policy linkage. Shenzhen launched earlier and has a more mature mechanism, leading in medium cycles. They fluctuate synchronously in the long cycle due to unified policies.

Panel (e) shows WTC between Shenzhen and Shanghai, with comparatively clear 32–64-day medium-cycle positive correlation from 2015 to 2018, with Shanghai leading. From 2019 to 2020, Shenzhen took the lead in the 16–32-day short cycle, with no stable long-cycle comparatively clear coherence. Shanghai had strong financial innovation and institutional participation from 2015 to 2018, leading price changes. After 2019, Shenzhen's more flexible mechanism responded faster to short-term policy shocks and took the lead. Different long-term market structures led to no stable long-cycle linkage.

Panel (f) shows WTC between Shenzhen and Hubei, with only periodic short-cycle positive correlation from 2015 to 2017 and 2021 to 2023, with Hubei leading and no comparatively clear medium- and long-cycle linkage. Hubei has high liquidity and trading volume and hosts the national carbon market registration system, responding fastest to national policy signals and leading short-term price changes. Different regional policies and market structures led to no stable medium- and long-cycle linkage.

Panel (g) shows WTC between Shenzhen and Tianjin, with comparatively clear 32–64-day medium-cycle positive correlation from 2015 to 2018, with Tianjin leading. From 2018 to 2020, Shenzhen took the lead in the 16–32-day short cycle, with no comparatively clear coherence after 2020. Frequent allowance and compliance rule changes in Tianjin from 2015 to 2018 drove early price changes. After 2018, Tianjin's liquidity and pricing power weakened, and at the same time Shenzhen's mechanism improved and took the lead. Diverging development paths eliminated comparatively clear linkage after 2020.

Overall, China's pilot carbon markets had strong volatility in the early stage. From 2016 to 2020, volatility declined and operation stabilized as the market system matured. After the Dual Carbon goal, trading activity rose, and carbon prices showed periodic heterogeneous volatility driven by local policies. Market and financial maturity determine volatility persistence. Guangdong and Shanghai, with the highest maturity and carbon financial innovation, have much longer full-cycle volatility persistence. Late and small pilots including such items as Tianjin and Fujian only have volatility during policy shocks, with no long-term sustained fluctuations.

At the individual level, most pilots are positively correlated with Shenzhen in the short cycle. In medium and long cycles, Shenzhen maintains stable positive correlation with geographically adjacent and institutionally coordinated pilots including such items as Fujian and Guangdong, and at the same time showing periodic heterogeneous long-cycle coherence with others. In most comparatively clear coherence regions, Shenzhen leads other pilots in price changes, with strong price discovery and market leadership. It occupies a central dominant position in the pilot system, and its operation in an effective way gives a reflection of common patterns of the national carbon market with strong national representativeness.

5. Conclusions and Policy Implications

On the basis of the results, the present paper draws two main conclusions. First, the price volatility of carbon allowances in China's pilot carbon markets shows comparatively clear time-frequency heterogeneity, and policy shocks and market maturity are central determinants of volatility patterns. Second, the linkage effects among China's pilot carbon markets feature comparatively clear cycle heterogeneity, and the Shenzhen pilot has outstanding price discovery and leading roles in the national pilot system. After more than ten years of development since the launch of local pilots, China's carbon market has continuously improved its institutional framework and trading mechanism, with in a gradual way stable overall operation. comparatively clear price linkage and information transmission have formed among regional pilots, and cross-market interdependence has expanded over time.

Wavelet analysis gives the result that China's carbon market prices are to a high degree sensitive to policy shocks. Prices adjust sharply in the short term in response to external policy shocks, including allowance allocation rule changes, compliance mechanism optimization, the Dual Carbon goal, and national carbon market development. This gives a reflection of slow adjustment of market expectations. Most participants lack stable long-term expectations, mature pricing capabilities, and risk preparedness for supply-demand changes caused by policies, leading to somewhat blind trading behavior. On the one hand, this allows the market to adjust emission management and trading strategies in a gradual way according to policy guidance. On the other hand, short-term market imbalance after policy implementation can cause large carbon price swings. As the pricing basis for carbon financial products, short-term carbon price volatility directly increases risks in green credit and may disrupt the normal function of the green financial system, failing to in an effective way guide capital to green industries or manage risks. Excessively high short-term prices also make enterprises' emission reduction incentives lower. In the long run, this harms the long-term low-carbon transition plan and high-quality green economic development of China.

To ensure the long-term effectiveness of China's carbon market and guide the green development of enterprises, The present paper puts forward targeted policy suggestions On the basis of the above conclusions. First, strengthen policy expectation management. Establish an advance announcement and regular interpretation mechanism for central carbon market rule adjustments. Clarify the revision cycle and adjustment logic of policies including such items as allowance allocation and compliance management to make sudden policy shocks lower, guide stable long-term expectations of market participants, and mitigate sharp short-term carbon price fluctuations. Second, make the carbon price stabilization mechanism better. Set up a dynamic allowance reserve and a reasonable price range, use market-based operations to stabilize extreme price movements, maintain the price discovery function of carbon prices, and prevent financial investment risks caused by abnormal carbon price fluctuations. Third, deepen regional market coordination. Rely on the price leadership of mature pilots including such items as Shenzhen, unify basic trading rules across regional markets, open cross-market information transmission channels, and make overall market stability better. Fourth, enrich carbon financial risk-hedging instruments. Guide enterprises to make carbon asset management systems better, make blind trading lower, and ensure the carbon market steadily serves the Dual Carbon strategic goals.

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