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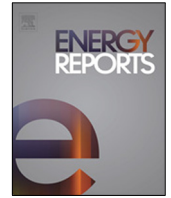
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Research paper

Does the carbon price in Chinese seven carbon markets converge or not? – Based on the Fourier quantile unit root test

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ABSTRACT

While previous studies focus on linear unit root test to study the convergence of carbon price in some developed countries and the results might be biased due to the lower power of these linear unit root tests. China provides an interesting arena to investigate its carbon price convergence due to its fast economic development since its inception of open door policy in the late 1970s. In this paper that we use the non-linear quantile unit root test (in terms of Fourier function) to study the convergence of the carbon price in China's seven carbon markets over the period of April 6, 2014 to February 17, 2017. Empirical results from our study demonstrate that the carbon prices in Beijing, Shanghai, Shenzhen, Guangzhou and Hubei carbon market do converge on all quantiles. However, the prices of Chongqing and Tianjin carbon emission markets though converge but only converge under certain quantiles. Apparently, that our empirical have important policy implications for Chinese government conducting carbon dioxide emission reduction policy during its economic development process.

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1. Introduction

Carbon dioxide and other greenhouse gases lead to global warming has attracted worldwide attention. Every country is looking for ways to reduce carbon emissions. Under the guidance of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, the carbon emission rights trading market (hereinafter referred to as the carbon market) has boomed. EU emission trading system (EU-ETS) has been operating since 2005 and is the oldest and largest carbon trading system around the world. Since then, the US Chicago Climate Exchange, the Australian Carbon Exchange, and the Japanese carbon exchange have also been set up. Western countries, represented by Europe and the United States, try to use carbon emission rights and carbon taxes combined approach to reduce carbon dioxide emissions. China, a big country of carbon dioxide emissions, bears a significant responsibility in reducing carbon dioxide emissions. In order to better implement the reduction of carbon emissions, China has learned from the successful experience of Europe and the United States via giving carbon emission rights quotas to enterprises whose carbon emission exceeds a certain limit, and establishing a carbon emission rights trading pilot.

During September 2010, China set up its first carbon emission quota trading pilot: Shenzhen carbon emission trading. Since then, China has set up six additional carbon emission trading pilots, forming the current pilot pattern of “two provinces and five cities”.

In 2016, China officially joined the “Paris Climate Agreement”. The Chinese government has made clear that it would bear some of the international responsibility for reducing carbon dioxide emission, and will further promote the construction of China's carbon markets. However, seven carbon markets of China are still independent of each other. The price difference between different carbon markets will likely cause the plant to migrate in order to reduce the cost of carbon emission. Enterprises will move from areas with high carbon taxes to areas with low carbon taxes, and creating additional pollution in these places. This is clearly contrary to China's intention to establish carbon markets, having an adverse effect on China's development of corresponding emission reduction plans. In terms of the carbon price difference, we raise the following questions: Does the carbon price in China's seven carbon markets converge or not? Is the convergence of carbon price the same or not? In order to answer these questions, this paper uses the panel data of the transaction prices in China's seven carbon markets with the use of the non-linear unit root test method to empirically study the carbon price convergence.

In this paper, we study the convergence of carbon price in different carbon markets by using the method of Fourier quantile

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unit root test. The purpose is to find the convergence range of carbon price, so that it provides as a reliable basis for China to regulate carbon price after establishing a unified carbon market.

The structure of this paper is as follows: Section 2 describes the previous research. Section 3 analyzes the convergence test and tests the data using the quantile unit root of the Fourier function proposed by Bahmani-Oskooee et al. (2015). Section 4 interprets the data used in this article. Section 5 first describes the simple unit root test results, and then explains the Fourier quantile unit root test results. Finally, Section 6 summarizes the paper and puts forward policy recommendations.

2. Literature review

It has been widely recognized around the world that carbon emission trading mechanism plays an important role in the promotion of low-cost emission reduction. In order to discuss the mechanism of Chinese carbon market, some Chinese scholars have carried out relevant research. He (2011) found that in the early days of the establishment of the carbon market, China should distribute a certain amount of free carbon emission rights, which would help the formation of Chinese carbon market and let market supply and demand determine the carbon price. He (2013) studied the EU's carbon trading mechanism, which was the EU-ETS trading mechanism. She found that Chinese national conditions were similar to that of the EU. As a result, China could establish its carbon market and carbon trading mechanism by referring to the EU model. Wu et al. (2014) found that the total control of carbon emission rights was more suitable for present stage actual situation of Chinese carbon reduction when studying the marginal cost of carbon reduction for each province in China.

In terms of the issue of the carbon price, existing literature mainly consist two aspects. One is to explore the factors that affect the carbon price. Wang et al. (2013) proposed a more rational and scientific pricing model for carbon emission rights by studying the highest and lowest price of carbon in China. Huang and Zhang (2014) found that demand, supply, policy and technology were main factors affecting carbon price. Another is to study the impact of carbon price on the economic system. Murphy et al. (2013) found that fluctuation in EU carbon price had a huge impact on airline stock price. Whether carbon price fluctuated significantly or less, it both affected the airline share price. Ellerman and Buchner (2008) studied the EU-ETS trading mechanism and found that carbon price stability would contribute to the efficient functioning of the carbon market. Maarten and Venmans (2016) studied the different levels of uncertainty in carbon price and the different levels of impact on firms and investors. The study pointed out that high and low uncertainty would increase the risk of investors, and medium uncertainty may increase the value of carbon option.

Existing literature does not discuss the convergence of carbon price, instead most articles focus on commodity price convergence. Leo and Simon (2004) used the concept of σ convergence and β convergence to study the income convergence assumptions in the Asia-Pacific region and their income differences between East Asia and ASEAN during the 1960–1999 study. The study found that in 17 APEC countries and 10 Eastern European countries, There is evidence of the convergence of conditional β , but the convergence rate is very slow. In view of the special situation of market segmentation in Chinese regional market, En (2007) used the unit root test method of panel data to study the convergence of the price gap between 28 provinces in China and found that the price gap in different periods existed from divergence to convergence. However, this paper finds that with the use of simple unit root test only a small number of carbon market have convergence with the carbon price. Yavuz and Yilanci (2013) used

the recently proposed TAR panel nonlinear unit root test to test the convergence of per capita carbon emission in the G7 countries during 1960–2005 period and found that the emissions were non-linear, suggesting that whether the convergence hypothesis is non-linear should be considered first before determining whether there is convergence or not. Li et al. (2018) revisit whether CO2 emissions converge in G18 countries over the 1950–2013 using a more powerful quantile unit root test for per capita CO2 emissions. Empirical results indicate that conventional unit root tests fail to reject convergence in CO2 emissions for those G18 countries, quantile unit root test results demonstrate CO2 emissions converged in 5 of these G18 countries (i.e., Australia, Brazil, Canada, Germany and India). Ozcan and Gultekin (2016) apply both two-break LM test and three-step RALS-LM unit root test for relative per capita carbon dioxide emissions in OECD countries and found out that relative per capita carbon emissions are not converge, however relative per capita carbon emissions are converged when structural breaks are taking into account. These results indicate that energy usage or environmental protection policies of OECD countries have not long-run impacts on the relative per capita emissions series of the sample countries. Moreover, Bahmani-Oskooee et al. (2015) pointed out that long-term time series data may be structurally fractured, while the quantile unit root test cannot take into account structural fracture in the test, which may lead to failure of null hypothesis of unit roots. Thus Bahmani-Oskooee et al. (2018) improved the quantile unit root test when studying the situation of purchasing power parity theory in 23 OECD countries, using the Fourier quantile unit root method. The test results of 23 countries indicated that there was more evidence to support the theory of purchasing power. On the other hand, Cai et al. (2018) also apply quantile unit root test with Fourier function for per capita CO2 emissions in 21 OECD countries and their findings show that per capita CO2 emissions shown mean-reverting or convergence in certain quantile for some OECD countries.

Based on the theory of price convergence, this paper tests the convergence of the carbon price of seven carbon markets in China by using the latest and most efficient method of Fourier quantile unit root test (or quantile unit root test with Fourier function). We hope that our paper can bridge the gap of the current literature.

3. Research methods

3.1. Convergence test

The approach of this paper is derived from the study of Evans (1998), which uses the concept of a common trend, meaning that the long-term carbon price gap between the two markets must be fixed. In order to verify this setting, it is assumed that the logarithm of the carbon price y_{it} in each carbon market is non-stationary at time $t = 1$ and there is a unit root. Then, any difference between any y_{jt} and y_{it} is stable (where $i \neq j$), which means that y_{jt} and y_{it} are cointegrated. In simple terms, the difference between each value of a single time series and their mean at each time point is stable, that is, the pairwise convergence is satisfied.

Based on this assumption, we use the following regression to test:

$$\tilde{y}_{it} = \alpha_i - \mu_i t + \beta_i \tilde{y}_{it-1} + e_{it}$$

where $\tilde{y}_{it} = y_{it} - \frac{1}{N} \sum_{j=1}^N y_{jt}$ is the relative carbon price. α_i is the intercept term. μ_i is the trend term and e_{it} is the random perturbation term associated with both i and t . The key parameter of this model is β_i which tests the degree of convergence of the model variables. If $\beta_i = 1$, it means that the sequence i is a sequence with unit roots, and the sequence is not convergent; if $\beta_i < 1$, then the sequence i does not contain unit roots, and the sequence is convergent.

Assumption. $H_0: \beta_i = 1$ for all sequences i

$H_1: \beta_i < 1$ for part of sequences i

Thus, if there is at least one market carbon price containing convergence in the seven carbon markets, the original hypothesis is rejected. If the carbon prices of the seven carbon markets do not converge, the original hypothesis is true.

3.2. Fourier quantile unit root test

According to the study by Bahmani-Oskoei et al. (2018), it can be assumed that the time series follows the following data generation process (DGP)

$$\tilde{y}_{it} = Z_i \lambda + \sum_{k=1}^n \gamma_{1,k} \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n \gamma_{2,k} \cos\left(\frac{2\pi kt}{T}\right) + \xi_t \quad (1)$$

In order to make the data smooth and make the unknowns obtain approximate global deterministic components, we use the method proposed by Gallant (1981), the Fourier approximations $\sum_{k=1}^n \gamma_{2,k} \cos\left(\frac{2\pi kt}{T}\right)$ and $\sum_{k=1}^n \gamma_{1,k} \sin\left(\frac{2\pi kt}{T}\right)$, and put them into the model. In the model, we choose to use the cosine function $\cos\left(\frac{2\pi kt}{T}\right)$ and sine function $\sin\left(\frac{2\pi kt}{T}\right)$, mainly because the Fourier function is absolutely integrable, and the expectation of the Fourier function can be accurate to any precision. In the model, k, T and t are the size, the frequency value of the trend term and the time respectively. Z is a selectable exogenous variable and we assume that it is a constant. n denotes the frequency of the approximation function, and satisfies $n \leq \frac{1}{2}$. ξ_t is a random error term, and $\pi = 3.1416$.

The estimated value of Eq. (1) is related to the choice of two parameter values, that is the selection of n and k . According to Becker et al. (2004) we set $n = 1$ so that we can find the frequency of $\gamma_{1,k} = \gamma_{2,k} = 0$, which can effectively reduce the degree of freedom and prevent over-fitting. Based on above consideration, we redefine the formula (1) as follows:

$$\tilde{y}_{it} = Z_i \lambda + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \xi_t \quad (2)$$

Where $\gamma = [\gamma_1, \gamma_2]'$ is the amplitude to measure the frequency component. In special cases, when $\gamma_1 = \gamma_2 = 0$, Eq. (2) is the standard linear equation.

When determining the optimal value of k , we set the maximum value of k as 5. For any $K = k$, we use the least squares (OLS) method to estimate Eq. (2) and preserve the sum of square residual (SSR). The optimum frequency k^* is set at the frequency when the SSR is minimum. On the basis of above assumption and consideration about deterministic components, this paper examines the following null hypothesis:

$$H_0 : \xi_t = v_t, \quad v_t = v_{t-1} + \mu_t \quad (3)$$

Assumptions. Assume μ_t has a zero mean. In order to test the null hypothesis, this paper uses the method proposed by Christophoulos and León-Ledesma (2010) to test the statistics with the following three steps.

Step 1: Set the maximum value of k as 5, and then find the optimal frequency k^* by the following method. Calculate OLS residual

$$e_t = \tilde{y}_{it} - \hat{\alpha}(t) \quad (4)$$

$$\hat{\alpha}(t) = Z_i \hat{\lambda} + \hat{\gamma}_1 \sin\left(\frac{2\pi k^* t}{T}\right) + \hat{\gamma}_2 \cos\left(\frac{2\pi k^* t}{T}\right) \quad (5)$$

Step 2: Test the unit roots of the OLS residual given by Eq. (4) via using the quantile regression introduced by Koehler and

Xiao (2004). This test begins with the enhanced version of the Dickey–Fuller (ADF) test, which allows adjustments to long-term equilibria for different quantiles. The ADF test results are more accurate than DF tests when external shocks are heavy tail.

$$e_t = \rho_1 e_{t-1} + \sum_{k=1}^{K=5} \rho_{1+k} \Delta e_{t-k} + \varepsilon_t \quad (6)$$

The random variable is the estimated residual value from Eq. (4). In (6) ρ_1 is the AR coefficient, reflecting the persistence, where $|\rho_1| < 1$. Koehler and Xiao (2004) define the conditions as follows:

$$Q_{e_t}(\tau | \xi_{t-1}) = \alpha_0(\tau) + \rho_1(\tau) e_{t-1} + \sum_{k=1}^{K=5} \rho_{1+k}(\tau) \Delta e_{t-k} + \theta_t \quad (7)$$

$Q_{e_t}(\tau | \xi_{t-1})$ is the τ th quantile under the condition of e_t information set. $\xi_{t-1} \alpha_0(\tau)$ is the τ th conditional quantile of θ_t . $\rho_1(\tau)$ measures the average regression speed of e_t of each quantile. The optimal delay is selected by the AIC information criterion.

The coefficients of $\alpha_0(\tau)$, $\rho_1(\tau)$ and $\rho_2(\tau), \dots, \rho_{k+1}(\tau)$ are estimated by minimizing the sum of the asymmetric weighted absolute deviations:

$$\min \sum_{t=1}^n (\tau - I(e_t < \alpha_0(\tau) + \rho_1(\tau) e_{t-1} + \sum_{k=1}^{K=5} \rho_{k+1}(\tau) \Delta e_{t-k})) \times \left| e_t - \alpha_0(\tau) + \rho_1(\tau) e_{t-1} + \sum_{k=1}^{K=5} \rho_{k+1}(\tau) \Delta e_{t-k} \right| \quad (8)$$

$I = 1$, if $e_t < \alpha_0(\tau) + \rho_1(\tau) e_{t-1} + \sum_{k=1}^{K=5} \rho_{k+1}(\tau) \Delta e_{t-k}$, otherwise $I = 0$. According to the unit root solution proposed by Koehler and Xiao (2004), after solving Eq. (8), the following t-ratio statistics can be used to test the randomness of θ_t within τ th quantile:

$$t_n(\tau_i) = \frac{\hat{f}(F^{-1}(\tau_i))}{\sqrt{\tau_i(1-\tau_i)}} (E'_{-1} P_X E_{-1})^{\frac{1}{2}} (\hat{\rho}_1(\tau) - 1) \quad (9)$$

In Eq. (8), E_{-1} is the vector of the lagged variable (e_{t-1}), and P_X is the projection matrix on the space orthogonal to $X = (1, \Delta e_{t-1}, \dots, \Delta e_{t-k})$. $\hat{f}(F^{-1}(\tau_i))$ is a consistent estimate of $f(F^{-1}(\tau_i))$. Koehler and Xiao (2004) indicate that it can be expressed as:

$$\hat{f}(F^{-1}(\tau_i)) = \frac{(\tau_i - \tau_{i-1})}{X'(\varphi(\tau_i) - \varphi(\tau_{i-1}))} \quad (10)$$

Among them, $\varphi(\tau_i) = (\alpha_0(\tau_i), \rho_1(\tau_i), \rho_2(\tau_i), \dots, \rho_{1+R}(\tau_i))$ and $\tau_i \in [\underline{\lambda}, \bar{\lambda}]$. In this article, set $\underline{\lambda} = 0.1$ and $\bar{\lambda} = 0.9$. We can test the unit root assumption of each quantile through using $t_n(\tau_i)$ statistics. However, ADF and the other conventional unit root test only test the unit root on the conditional set trend and cannot satisfy our demand for non-linear unit root test.

To evaluate the unit root behavior of this series of quantiles, Koehler and Xiao (2004) recommend the use of the Quantile Kolmogorov–Smirnov (QKS) test to describe unit root condition:

$$QKS = \sup \tau_i \in [\underline{\lambda}, \bar{\lambda}] |t_n(\tau_i)| \quad (11)$$

In this paper, we construct QKS statistics by choosing the largest $|t_n(\tau)|$ statistic in $\tau_i \in [0.1, 0.9]$. As described by Koehler and Xiao (2004), the limit distributions of $t_n(\tau_i)$ and QKS statistical tests are nonstandard and depend on the perturbation parameters. In order to derive the critical value of above detection, this paper uses the re-sampling procedure proposed by Koehler and Xiao (2004). In this paper, the empirical distribution function is used to construct the 95% confidence interval for both $\alpha_0(\tau)$ and $\rho_1(\tau)$.

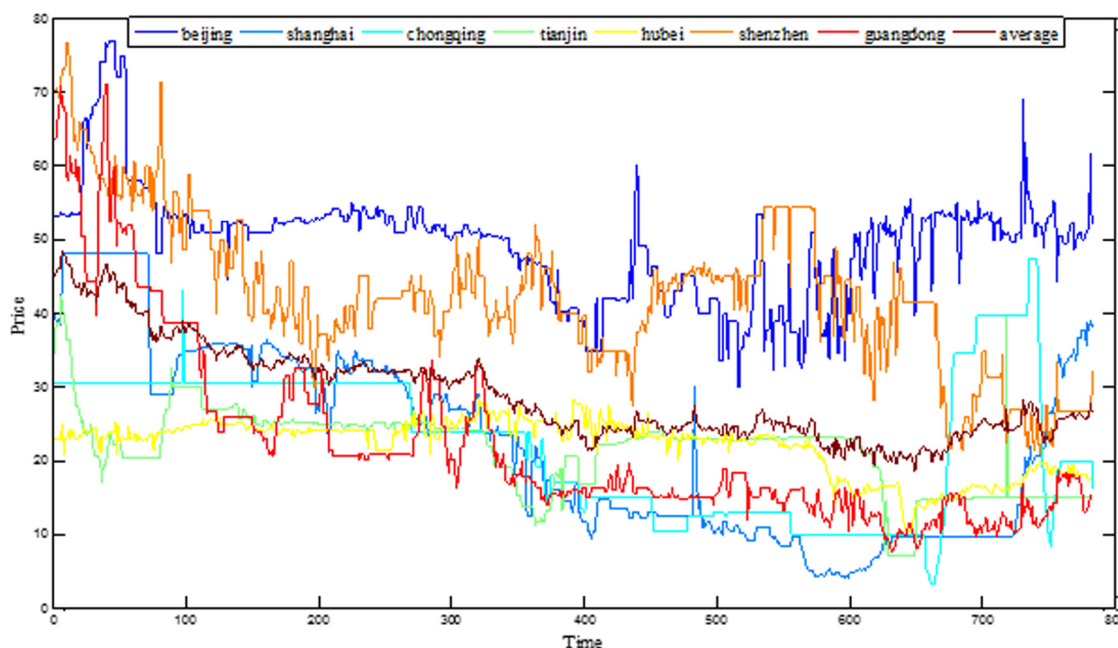


Fig. 1. China's seven major carbon market price volatility map.

Table 1

China's seven carbon trading market carbon price summary statistics.

	Mean	Max	Min	Std.Dev.	Skew	Kurt	J-B
Beijing	49.57	77	30	7.54	0.51	5.13	182.33
Shanghai	22.51	48	4.2	12.90	0.40	1.996	54.12
Chongqing	22.63	47.52	3.28	9.75	0.06	1.88	41.08
Tianjin	21.49	42.41	7	5.45	-0.16	4.08	41.91
Hubei	22.05	28.69	10.07	3.70	-0.95	2.94	118.01
Shenzhen	42.60	76.79	20.87	10.35	0.35	3.35	20.63
Guangdong	22.35	71.09	7.57	12.65	1.75	5.75	650.77

Note: 1. ***, ** and * represent the significance levels of 0.01, 0.05 and 0.1, respectively.

2. Data is the daily trading data for the period from 6 April 2014 to 17 February 2017.

4. Description of sample data

This paper utilized daily trading data of Chinese seven major carbon markets from April 6, 2014 to February 17, 2017. The data are derived from Chinese seven major carbon markets. In order to make the data consistent, this article does not simply use the daily transaction carbon price y_{it} of each exchange, but pretreats the data. In order to better anticipate the trend of future carbon price and make the data comparison benchmark consistent, we selected the average daily transaction price \bar{y}_t of each of the seven carbon markets as the base price, assuming that the average carbon price is the expected carbon price for the subsequent national market.

Fig. 1 shows the time series of daily carbon prices in Beijing, Shanghai, Chongqing, Tianjin, Hubei, Shenzhen and Guangdong carbon markets. Table 1 shows the numerical characteristics of Beijing, Shanghai, Chongqing, Tianjin, Hubei, Shenzhen and Guangdong carbon prices.

It can be seen from Fig. 1 and Table 1 that the carbon prices in Beijing and Shenzhen are significantly higher than the other seven carbon markets, while the carbon prices in Tianjin, Hubei and Chongqing are significantly lower. Moreover, prices in these carbon markets have obvious fluctuations, and do not have a noticeable convergence trend at a certain price level. Then, we carried out empirical tests through specific econometric analysis.

5. Empirical results

5.1. The empirical results of univariate unit root test

In order to compare with the Fourier quantile unit root test, this paper uses several conventional univariate unit root tests to examine the unit root null hypothesis of the seven carbon markets studied in this paper (using the deviation carbon price of each market \tilde{y}_{it}). Table 2 (no trend) and Table 3 (with trend) show the results of three univariate unit root tests – the ADF test, the PP test and the KPSS test. The results in Tables 2 and 3 clearly show that ADF and PP tests cannot reject the unit root null hypothesis for most of the carbon markets. KPSS also rejects fixed zero assumption for most carbon markets. From the results in Tables 2 and 3, the three univariate unit root tests cannot reflect the zero point of the non-stationary carbon price of most carbon markets.

Three univariate unit root tests' results also show that during the sample period, with the absence of trend, only the carbon prices in Beijing and Shenzhen converge (both with a 1% confidence level). The remaining five carbon markets do not have convergence. In the case of a trend, the carbon prices in Shanghai (at 1% confidence level) and Guangdong (at 10% confidence level) converge with evidence, while Tianjin, Hubei and Chongqing still do not have convergence. This paper suggests that the reason for this situation may be that when the carbon prices are highly continuous, the three univariate unit root tests are less efficient and cannot find more evidence of convergence.

5.2. Empirical results of quantile unit root tests

It is well known that univariate unit root test may be inefficient when applied to finite sample. If only the average convergence of carbon price itself is taken into account ignoring the effect of various external shocks, the result is that the conventional unit root test fails to test the unit root null hypothesis. As a result, the quantile unit root test is a good tool to improve the accuracy of estimation and verification. Table 4 shows the results of the quantile unit root test, where QKS statistics show that carbon prices are still not converging in Chongqing, Tianjin

Table 2
Univariate unit root test (With intercept only).

	Level			1st difference		
	ADF	PP	KPSS	ADF	PP	KPSS
Beijing	-3.77(2)***	-4.49(2)***	1.06 (21)***	-23.54 (1)***	-31.16(22)***	0.05(26)
Shanghai	-2.26(1)	-2.13(16)	2.72(22)***	-32.33(0)***	-34.64(20)***	0.07 (24)
Chongqing	-2.38(1)	-2.68(8)	3.33(22)**	-30.68(0)***	-30.54(9)***	0.32(7)
Tianjing	-2.24(2)	-2.74(7)*	1.17(22)***	-26.32(1)***	-39.59(4)***	0.07(8)
Hubei	-0.08(2)	-0.18(30)	1.68(22)***	-25.46(1)***	-46.12(24)***	0.62(45)**
Shenzhen	-3.62(2)***	-4.21(27)**	0.31(22)	-15.17(5)***	-39.65(70)***	0.18(81)
Guangdong	-2.11(0)	-1.83(9)	1.63(22)***	-18.71(2)***	-27.59(7)***	0.08(6)

Note: ***, ** and * represent the significance levels of 0.01, 0.05 and 0.1, respectively. The numbers in parentheses indicate the lag order based on recursive t statistic selection by Perron (1989) or the Bartlett kernel truncation proposed by the Newey–West test (1987).

Table 3
Univariate unit root test (With Intercept and Trend).

	Level			1st difference		
	ADF	PP	KPSS	ADF	PP	KPSS
Beijing	-5.75(0)***	-5.17(3)***	0.31(21)***	-23.53(1)***	-36.11(22)***	0.04(26)
Shanghai	-4.74(1)***	-5.01(4)***	0.25(21)**	-32.31(0)***	-34.62(20)***	0.06(24)
Chongqing	-2.90(0)	-3.00(7)	0.32(22)***	-30.72(0)***	-30.59(9)***	0.21(6)**
Tianjin	-2.80(2)	-3.52(9)**	0.34(22)***	-26.30(1)***	-39.57(4)***	0.05(8)
Hubei	-1.44(2)	-1.64(26)	0.71(22)***	-25.57(1)***	-51.37(27)***	0.06 (51)
Shenzhen	-3.62(2)**	-4.20(27)***	0.29(22)***	-15.17(5)***	-39.84(70)***	0.17(87)**
Guangdong	-3.30(0)*	-3.15(11)*	0.40(21)***	-18.72(2)**	-27.60(6)***	0.03(6)

Note: ***, ** and * represent the significance levels of 0.01, 0.05 and 0.1, respectively. The numbers in parentheses indicate the lag order based on recursive t statistic selection by Perron (1989) or the Bartlett kernel truncation proposed by the Newey–West test (1987).

Table 4
Empirical results of quantile estimates and unit root tests for quantiles (regardless of Smooth Breakpoints).

	τ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Beijing	$\rho_1(\tau)$	0.909**	0.944***	0.965***	0.977***	0.981***	0.988*	0.986	0.990	0.950
	QKS for quantiles Of	10%~90%: 3.798***								
Shanghai	$\rho_1(\tau)$	0.986	0.983**	0.983***	0.988***	0.993*	0.990**	0.986**	0.985**	0.982
	QKS for quantiles Of	10%~90%: 3.190**								
Chongqing	$\rho_1(\tau)$	1.000	1.000	1.000	0.996	0.996	0.996	0.995	0.990	0.987
	QKS for quantiles Of	10%~90%: 1.677								
Tianjin	$\rho_1(\tau)$	1.004	1.007	0.998	1.000	0.995	0.990*	0.985**	0.979***	0.958**
	QKS for quantiles Of	10%~90%: 2642								
Hubei	$\rho_1(\tau)$	0.999	0.997	0.994	0.997	0.991	0.998	1.008	1.009	1.013
	QKS for quantiles Of	10%~90%: 1.401								
Shenzhen	$\rho_1(\tau)$	0.926***	0.974	0.985	0.988*	0.995	0.994	0.993	0.968	0.966
	QKS for quantiles Of	10%~90%: 3.140**								
Guangdong	$\rho_1(\tau)$	0.927***	0.960***	0.972***	0.978***	0.990*	0.996	1.002	1.018	1.060
	QKS for quantiles Of	10%~90%: 4.340***								

Note: ***, ** and * indicate the significance of 1%, 5% and 10%, respectively. The lag length p is calculated based on the Schwartz information criterion and the maximum hysteresis is set to 12. For $\alpha_1(\tau)$ unit root value with $t_{\tau}(\tau)$ statistic test.

and Hubei. However, if we take into account the data structure fragmentation as pointed out by Perron (1989) and Bahmani-Oskooee et al. (2015), we found that there is a drawback of the quantile unit root test which is that the structure disruption in the test is likely to reject the null hypothesis. In order to reduce the effect of this drawback on our empirical test and to further enhance and ensure the accuracy of the unit root estimation and inspection, we applied the Fourier quantile unit root test newly developed by Bahmani-oskooee et al. (2017).

Because the form of data interruption is unknown and there is no prior knowledge, this research first performs a grid search to find the best frequency. Based on the recommendations of Enders and Lee (2012), we estimated the value of each integer $k = 1 \dots 5$ in Eq. (7). Single frequency is able to capture various interruptions. The single frequency represented by the smallest residual squared sum (RSS) ($k = 0.1, 1.0, 1.5, 0.5, 0.1, 1.5$ and 0.1) has

the most effective influence on the seven carbon markets. Table 5 shows the results of our Fourier quantile unit root test. It clearly shows that when using the Fourier quantile unit root test, the carbon prices of the other five carbon markets are significantly converged except that the carbon prices in the Chongqing and Tianjin do not converge. By observing the coefficient ($\rho_1(\tau)$ measure of persistence), it is found that carbon prices converge under different quantiles. Beijing in the 0.1–0.9 quantile, Shanghai in the 0.3–0.9 quantile, Hubei in the 0.1–0.9 quantile, Shenzhen in the 0.1–0.9 quantile and Guangdong in 0.1–0.4 quantile are convergent. In addition, the convergence coefficients of Beijing, Shanghai and Shenzhen are mostly above 0.95. The carbon prices of the above three carbon markets are closer to the unified market price. These results show that the impact of external changes on carbon price is non-linear and asymmetric. For Chongqing and Tianjin carbon markets, we find that the coefficient ($\rho_{-1}(\tau)$) is

Table 5

Empirical results of Fourier quantile estimates and unit root tests for Fourier quantiles (consider smooth breakpoints).

	τ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	
Beijing	$\rho_1(\tau)$	0.939	0.964**	0.968***	0.975***	0.978***	0.984**	0.976**	0.967*	0.875**	
	QKS for quantiles Of	10%~90%:	3.207**								
	Optimal frequency 0.1	F-Statistics for $\gamma_1 = \gamma_2 = 0$ 160.20***									
Shanghai	$\rho_1(\tau)$	0.951**	0.964***	0.975**	0.981**	0.986**	0.982**	0.975**	0.962***	0.940***	
	QKS for quantiles Of	10%~90%:	3.405**								
	Optimal frequency 1.0	F-Statistics for $\gamma_1 = \gamma_2 = 0$ 764.08***									
Chongqing	$\rho_1(\tau)$	0.964*	0.996	1.002	0.995	0.995	0.998	0.996	0.986	0.977	
	QKS for quantiles Of	10%~90%:	2.128								
	Optimal frequency 1.5	F-Statistics for $\gamma_1 = \gamma_2 = 0$ 306.47 ***									
Tianjin	$\rho_1(\tau)$	0.997	0.997	0.993	0.992	0.992	0.987	0.980**	0.982	0.966	
	QKS for quantiles Of	10%~90%:	2.333								
	Optimal frequency 0.5	F-Statistics for $\gamma_1 = \gamma_2 = 0$ 374.58***									
Hubei	$\rho_1(\tau)$	0.933	0.924**	0.934***	0.934***	0.940***	0.929***	0.936***	0.928**	0.906**	
	QKS for quantiles Of	10%~90%:	4.068***								
	Optimal frequency 0.1	F-Statistics for $\gamma_1 = \gamma_2 = 0$ 2297.10***									
Shenzhen	$\rho_1(\tau)$	0.912*	0.925*	0.962	0.971***	0.979**	0.963***	0.953**	0.927**	0.912	
	QKS for quantiles Of	10%~90%:	2.941*								
	Optimal frequency 1.5	F-Statistics for $\gamma_1 = \gamma_2 = 0$ 504.55***									
Guangdong	$\rho_1(\tau)$	0.800***	0.928***	0.954***	0.980*	0.989	0.999	1.001	1.001	1.021	
	QKS for quantiles Of	10%~90%:	4.570***								
	Optimal frequency 0.1	F-Statistics for $\gamma_1 = \gamma_2 = 0$ 499.08***									

Note: ***, ** and * indicate the significance of 1%, 5% and 10%, respectively. The lag length p is calculated based on the Schwartz information criterion and the maximum hysteresis is set to 12. For $\alpha_1(\tau)$ unit root value with $t_1(\tau)$ statistic test.

also Convergent in certain quantiles. These results clearly show that there is more evidence to support the fact that the carbon price do converge when using the Fourier function in the model.

Our empirical results also show that data structure disruption may lead to more unit null hypothesis being rejected, which highlights the importance of considering the structure disruption of carbon price when establishing appropriate models. On the other hand, our empirical results have important policy implications for the Chinese government to direct efficient and effective energy policies to reduce the CO₂ emissions in China.

6. Conclusion

In this paper, we use Fourier quantile unit root test to study whether Chinese current carbon prices in seven carbon markets converge. Traditional unit root test results show that carbon prices only converge in Beijing, Shanghai, Shenzhen and Guangdong. The carbon prices in the other three carbon markets do not converge. However, this paper finds more convergence evidence by using the more efficient Fourier quantile unit root test. The carbon prices in the Beijing, Shanghai, Hubei and Shenzhen will show convergence in most of the quantiles. The carbon prices in these four carbon markets are consistent with movements of assumed national unified carbon price. These four carbon markets are relatively mature. Carbon price in Guangdong converges and is consistent with the unified market price in low quantile. The carbon market in Guangdong is relatively immature. Carbon price in Chongqing only converges at 0.1 quantile, which means that carbon price may converge when price is low. Carbon price in Tianjin only converges at 0.7 quantile which means that carbon price may converge when price is high. The carbon prices of Chongqing and Tianjin are basically inconsistent with the unified market price. There are obvious market shortcomings in these two markets, which cannot provide effective market functions for carbon trading.

This paper finds that there are obvious price differences in different carbon markets. Carbon prices in economically developed regions are significantly higher than those in economically depressed areas. This situation may lead to the transfer of factories. Then, companies choose to purchase carbon emission rights to solve the problem of carbon dioxide emission, rather than trying

to improve the emission reduction technology. This is clearly contrary to Chinese strategic plan of implementing energy-saving emission reduction.

At present, Chinese seven carbon markets are still pilot markets independent from each other. There are trade barriers between the seven carbon markets. The divergence of prices in Chongqing and Tianjin indicates that market operation mechanism is not yet sound. One possible reason is that two local governments give out excessive carbon emission rights for the purpose of protecting local enterprises, which affects the normal operation of the carbon market. China plans to build a unified national carbon market by 2020 and ultimately achieve convergence with the global carbon market. However, the current immature Chongqing and Tianjin carbon markets will likely hinder the formation of a unified carbon price in Chinese carbon market, further affect the carbon market's effective control of carbon supply and demand and the efficiency of reducing carbon dioxide emission.

For the establishment of Chinese unified carbon market, we put forward the following two suggestions: (1) After research, we found that the carbon prices in Chongqing and Tianjin market only converge in extreme quantile. This indicates that these two markets are not yet mature. In order to establish a sound unified carbon market, we need to strengthen the control of these two markets and improve two markets' mechanism as laying a solid foundation. (2) Establish a unified carbon market as soon as possible, call on each local government to formulate a reasonable allocation policy of carbon emission quota and prevent local government from excessively allocating carbon emission quota in order to protect local enterprises. Thus, effectively encourage enterprises to implement energy-saving emission reduction technology. As a result, achieve Chinese strategic objective of reducing carbon dioxide emission as soon as possible.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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