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The Convergence of Sulphur Dioxide (SO_2) Emissions Per Capita in China

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Abstract: As the third-largest SO_2 emitter in the world, China is facing mounting domestic and external pressure to tackle the increasingly serious SO_2 pollution. Figuring out the convergence and persistence of sulfur dioxide (SO_2) emissions matters much for environmental policymakers in China. This study mainly utilizes the Fourier quantile unit root test to survey the convergence of the SO_2 emissions per capita in 74 cities of China during the period of December 2014 to June 2019, by conducting five traditional unit root tests and a quantile root unit test as a comparative analysis. The empirical results indicate that the SO_2 emissions per capita in 72 out of 74 cities in China are convergent in the sample period. The results also suggest that the unit root behavior of the SO_2 emissions per capita in these cities is asymmetrically persistent at different quantiles. For the cities with the convergent SO_2 emissions, the government should consider the asymmetric mean-reverting pattern of SO_2 emissions when implementing environmental protection policies at different stages. For Hefei and Nanjing, the local governments need to enact stricter environmental protection policies to control the emission of sulfur dioxide.

Keywords: SO_2 emissions per capita; quantile unit root test; Fourier quantile unit root test; mean-reverting property

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1. Introduction

China has, all at once, achieved tremendous economic growth but has also witnessed severe environmental pollution under the heavy industrialization mode characterized by high consumption of resources and energy, which has attracted a great deal of focus at home and abroad. For the recent decade, however, China has adopted a series of creative environmental protection measures to control the environmental pollution caused by the heavy industrialization mode, such as the "Action plan for prevention and control of air pollution" released in 2013 and the "Three-year plan on defending the blue sky" announced in 2018. Meanwhile, China has stepped into a new energy-saving and material-saving recycling industrial system, which not only improves the utilization efficiency of resources but also reduces the waste emissions in the way of economic output. Benefiting from the effective energy policy measures and the active transformation of the industrial system, China's environmental pollution has been controlled to some degree. According to the "China Air Quality Improvement Report (2013–2018)" released in 2019, the atmospheric pollutant concentrations were significantly reduced in 2018, which brings an improvement of the overall environmental air quality. As for the 74 cities which implemented the first batch of "Environmental Air Quality Standards", the average concentration of the sulfur dioxide (SO_2) emissions decreased by 68%, and the average concentration of PM2.5 decreased by 42% between 2013 and 2018. In addition, the total emissions of nitrogen oxides and SO_2 have fallen by 28% and 26% since 2013, respectively.

Despite the initial achievement, SO_2 emissions in China still surpass the sum of the members of the Organization for Economic Cooperation and Development (OECD) and the U.S. [1]. According to the statistics in China Statistical Yearbook (2019), by the year 2018, in China's total energy consumption, the share of fossil energy (including coal, crude oil, and natural gas) has remained above 85%, while the share of renewable energy (including hydropower, nuclear power, and wind power) has been below 15%. More specifically, in the year 2018, the consumption of coal represents 59% of the total level of energy consumption in China, which leads to the fact that the SO_2 emissions per capita have continuously increased. As the third-largest SO_2 emitter in the world, China is facing mounting domestic and external pressure to tackle the increasingly serious SO_2 pollution.

High SO_2 emission is a tremendous threat to the environment change. It is one of the most important on-going anxieties for both emerging countries and developed countries. As a typical traditional contaminant, SO_2 brings many adverse effects to the human body, such as breathing difficulty, pulmonary edema, eye irritation, asthma attacks, cardiopulmonary diseases [2–4]. Meanwhile, SO_2 has considerable negative impacts on the ecological environment. For example, a high concentration of SO_2 will change the potential of hydrogen (pH) value of plants, which will lead to agricultural production reduction and forest death. Wei et al. [5] found that in 899 Chinese counties, the estimated cost of agricultural losses induced by SO_2 air pollution reached USD 1.43 billion. According to the data from the Ministry of Ecology and Environment of China, in 2018, the proportion of acid rain (average precipitation pH less than 5.6) was 18.9%, 0.1 percentage point higher than the previous year; the proportion of cities with heavier acid rain (average precipitation pH below 5.0) was 4.9%, 1.8 percentage points lower than the previous year. Moreover, the type of acid rain was generally the sulfuric acid type, which means that SO_2 is still the main cause of acid rain.

Finding effective ways to control SO_2 emissions levels has become one of the most invoking issues for environmental policymakers. China's effective regulation of SO_2 emissions not only improves its own environmental conditions but also contributes to the sustainable development of the entire world. In order to achieve this purpose and shape the effective energy policy to reduce SO_2 emissions, policymakers should have a clear knowledge of whether the SO_2 emission series is convergent or not. That is because convergence implies that the impact from the SO_2 emissions per capita reduction policy is temporary and the SO_2 emissions series would revert to a trend path in the long run. In view of this, the aim of the present paper is to investigate the time series property of the SO_2 emissions per capita in 74 cities of China.

Numerous studies have been conducted to examine whether harmful gas is characterized as a random walk or mean-reverting process. The first study on pollutant emissions in the field of environmental economics is List [6], who ascertained the convergence of SO_2 and nitrogen oxides emissions of ten Environmental Protection Agency regions of the U.S. over the period of 1929–1994. After that, the convergence of pollutant emissions between countries has been investigated, essentially for CO_2 and SO_2 emissions. Briefly speaking, the extant studies can be divided into two strands by surveying the convergence through various unit root tests and modeling the distribution for air pollutant emissions.

The first strand of the literature which focuses on mean reversion of air pollutants mostly implements the traditional unit root tests, such as the ADF test [7], the DF–GLS test [8], the PP test [9], the KPSS test [10], and the MZa test [11]. For example, Strazicich and List [12] utilize panel unit root tests and cross-section regressions to draw a conclusion that CO_2 emissions converge for 21 OECD nations between 1960 and 1997. Aldy [13] utilized the univariate unit root ADF test to survey the CO_2 emissions in 88 selected countries. The results showed that the unit root null hypothesis of divergence in relative emissions can only be rejected in 13 countries, of which three are OECD countries. Using over a century of data across 28 developed and developing countries, Westerlund and Basher [14] obtained support in favor of CO_2 emission convergence at the international level through the panel unit root test. Lee and Chang [15] presented that the CO_2 emissions in 14 out of 21 OECD countries exhibited divergence using the DF test. Recent work also relies on some nonlinear unit root tests to examine the time series property of hazardous gas emissions. For instance, Payne et al. [16] explored the stochastic convergence of SO_2 emissions per capita among U.S. states by conducting the residual augmented least squares–Lagrange multiplier (RALS–LM) unit root test with structural breaks. Yavuz et al. [17] tested the CO_2 per capita emissions using the TAR panel unit root test and found that the United Kingdom is the transition country whose CO_2 per capita emissions determines the switch from one regime to the other. Li et al. [18] utilized the panel KSS unit root test with a Fourier function, and the results indicated that CO_2 emissions only converge in 12 out of the 50 U.S. states in our analysis.

The other strand of the literature contributes to model the distribution of the data series to investigate the convergence. Wu et al. [19] employed a continuous dynamic distribution approach and panel data of 286 cities at the prefecture and above-prefecture level; the results showed that per capita CO_2 emissions tend to converge during the sample period of 2002 to 2011. Herrerias [20] utilized the distribution dynamics approach to analyze the convergence of CO_2 emissions per capita among the EU-25 countries between 1920 and 2007 and found that the convergence patterns differ strongly before and after World War II. Burnett [21] utilized the two-stage procedure to examine the convergence of the states in the U.S. and obtained the conclusion that 26 states converged to a unique steady-state equilibrium. Yang et al. [22] examined the SO_2 geographical distributions in 113 main cities of China and found that the cities located in the north of the country are heavily polluted, while cities with low pollution levels mainly agglomerate in the south. Zhou et al. [23] studied the nexus of SO_2 emissions and economic development by employing the spatial panel model and suggested an inversely N-shaped environmental Kuznets curve. Yu et al. [24] investigated the carbon emissions intensity convergence of 24 industrial sectors in China between 1995 and 2015, and based on an environmental performance index method and the convergence model, the results indicated that find the carbon intensities of all sectors converged to different steady levels. Ulucak and Apergis [25] employed the club clustering approach to test for the convergence of ecological footprint by employing the annual data for the case of the European Union countries; the empirical results documented the presence of certain convergence clubs.

There is an increasing consensus that the conventional unit root tests do not consider the existence and the number of structural breaks in the data series, such as the ADF test and the traditional quantile unit root test proposed by Koenker and Xiao [26]. The neglect of structural breaks may cause the efficiency of detecting the mean reversion of the data, and thus the ensuing results may not be convincing. In other words, ignoring the structural breaks sway the analysis toward accepting the null hypothesis of a unit root [27]. The structural break tests were first introduced to the literature by Perron [27] and tested by several authors [28–30]. Lee and Chang [31] further found that the CO_2 emissions per capita of 21 OECD countries were stationary using the panel unit root test with multiple breaks. Nonetheless, it is an enormous obstacle to accurately detect the locations of the estimated structural breaks and the number of breaks in the series. Taking the number and the specific dates for structural breaks into consideration, Becker et al. [32] proposed a stationary test with a Fourier function. Christopoulos and Leon-Ledesma [33] developed tests for unit roots that account jointly for structural breaks and nonlinear adjustment. Lee et al. [34] and Meng and Lee [35] developed a two-step LM and a three-step RALS-LM Fourier unit root test, respectively; they both utilize the Fourier function to control for a small number of smooth breaks of an unknown functional form and nonlinearity. Considering the merits and demerits, Bahmani-Oskooee et al. [36] proposed a newly Fourier quantile unit root test to examine the integrational properties. This approach can solve the inaccurate inference generated by structural breaks and is able to test the unit root hypothesis in each quantile of data distribution and capture the type of asymmetric dynamics by allowing different speeds of adjustment at various quantiles of data distribution.

As a preliminary practice, we first utilize five conventional univariate unit root tests and the quantile unit test to investigate the stationarity of the SO_2 emissions per capita of 74 cities in China. Then we utilize the newly Fourier quantile unit test proposed by Bahmani-Oskooee et al. [36] to re-investigate the convergence of the SO_2 emissions per capita from the perspective of both particular quantiles and overall conditions. It is able to capture the asymmetric dynamics by allowing different speeds of adjustment at various quantiles of the SO_2 emissions per capita distribution, regardless of whether the SO_2 emissions per capita of a city are above or below its steady-state. Therefore the economic implications would be suggested not only relying on whole quantiles, but also at each quantile. In addition, different from the quantile unit root test, the Fourier quantile unit root test could estimate the optimal frequency, which makes it able to deal with smooth breaks in time series without identifying beforehand the breaking numbers, breaking dates, or breaking forms.

The main contribution of this paper lies in two aspects. First, we conduct both the conventional and the newly proposed Fourier unit root tests to examine the SO_2 emissions per capita convergence for 74 Chinese cities. As such, a robust conclusion regarding the convergence of SO_2 emissions of different cities can be obtained through the comparison between the results of different unit root tests. Moreover, the 74 cities will be divided into two groups according to the time-series properties of the SO_2 emissions. In doing so, differentiated policy measures could be proposed for different groups to combat the SO_2 pollution. Second, we concentrate on the mean-reverting properties of SO_2 emissions both at selected quantiles and at overall conditions. As such, shedding new light on previous literature that treats the data-generating process of the SO_2 emissions as being linear, the potential asymmetric behavior of the SO_2 emissions can be clearly detected and the possible smooth breaks in the data series can be fully accounted for. Empirical results indicate that the SO_2 emissions per capita converge in 72 out of the 74 Chinese cities in our analysis during the period of December 2014 to June 2019.

2. Data and Method

2.1. Data Source

The analysis uses the monthly data of SO_2 emissions per capita for 74 cities of China, which implements the first batch of “Environmental Air Quality Standards” from December 2014 to June 2019. According to the "Environmental Air Quality Standards", we further divided the 74 cities into 6 categories: Beijing–Tianjin–Hebei Urban Agglomeration, Yangtze River Delta, Pearl River Delta, municipalities, provincial capital cities, and under separate state planning. All of the data used are retrieved from the Chinese Environmental Monitoring Station.

Table 1 reports summary statistics of the SO_2 emissions per capita in concerned 74 cities. As we can see, the maximum for the SO_2 emissions per capita belongs to Yinchuan, where coal is the main energy resource. The minimum of the SO_2 emissions per capita belongs to Beijing, Hainan, Suzhou, Yancheng, Jiaxing, Zhuhai, Zhongshan, and Changchun. We can also observe that most of the cities experience wide volatility of SO_2 emissions. For instance, the maximum per capita SO_2 emissions of Shenyang is 200, but the minimum is 10. In the penultimate column, we report the Jarque–Bera test statistic [37] and its significance. Clearly, all cities except Zhenjiang, Zhoushan, Shenzhen, Zhaoqing, Lhasa, Kunming, and Xiamen exhibit a clear sign of non-normal distribution, and it is strong evidence that favors the use of the Fourier quantile regression unit root test of Bahmani-Oskooee et al. [36].

Table 1. Descriptive statistics of the SO_2 emissions per capita.

City	Mean	Max	Min	Skewness	Kurtosis	Jarque-Bera
Beijing–Tianjin–Hebei Urban Agglomeration						
Beijing	9.073	35	3	1.786	5.802	47.222 ***
Tianjin	19.364	77	5	2.283	8.301	112.182 ***
Zhangjiakou	19.673	62	7	1.670	5.180	36.445 ***
Chengde	17.109	50	6	1.660	6.011	46.019 ***
Qinhuangdao	27.382	80	9	1.563	5.258	34.094 ***
Langfang	16.127	54	4	1.666	5.053	35.113 ***
Cangzhou	31.691	93	13	1.664	5.872	44.300 ***
Tangshan	40.127	85	16	1.218	4.749	20.596 ***
Handan	35.455	131	9	1.656	5.519	39.687 ***
Hengshui	24.382	79	7	1.716	5.327	39.394 ***
Xingtai	42.127	146	13	1.667	5.401	38.667 ***
Shijiazhuang	34.618	127	10	1.757	6.008	49.030 ***
Baoding	35.673	166	10	2.343	8.539	120.657 ***

Table 1. *Cont.*

City	Mean	Max	Min	Skewness	Kurtosis	Jarque-Bera
Yangtze River Delta						
Shanghai	12.727	35	5	1.612	6.401	50.343 ***
Nanjing	15.382	33	8	0.940	3.962	10.223 ***
Wuxi	16.527	47	6	1.434	5.121	29.168 ***
Nantong	22.000	51	7	1.042	4.749	16.955 ***
Lianyungang	20.364	53	5	1.138	3.973	14.050 ***
Suzhou	14.327	42	3	1.224	5.338	26.266 ***
Huaian	15.255	41	6	1.240	5.008	23.336 ***
Changzhou	20.073	48	8	1.153	3.799	13.640 ***
Tàizhou	15.964	45	5	1.140	4.359	16.144 ***
Yancheng	13.564	42	3	1.544	6.607	51.684 ***
Suqian	16.000	46	4	1.215	4.557	19.095 ***
Zhenjiang	17.582	39	6	0.349	2.323	2.169
Yangzhou	18.673	44	8	1.033	3.848	11.429 ***
Xuzhou	26.400	69	7	1.067	4.042	12.926 ***
Zhoushan	7.673	14	4	0.418	2.745	1.749
Lishui	8.818	26	5	3.065	14.176	372.366 ***
Ningbo	11.545	33	5	2.037	9.038	121.567 ***
Wenzhou	11.691	29	6	1.507	5.520	35.366 ***
Quzhou	13.745	44	4	1.860	8.600	103.589 ***
Jiaxing	13.109	51	3	2.357	9.794	156.709 ***
Jinhua	14.218	52	5	2.581	11.418	223.446 ***
Huzhou	14.873	37	5	1.302	5.232	26.959 ***
Hangzhou	11.855	34	4	1.945	8.803	111.852 ***
Shaoxing	15.545	60	5	2.124	8.696	115.719 ***
Táizhou	15.964	45	5	1.140	4.359	16.144 ***
Pearl River Delta						
Guangzhou	10.891	21	5	0.505	4.260	5.978 **
Shenzhen	7.618	12	4	−0.194	3.813	1.860
Zhuhai	7.600	17	3	0.827	3.313	6.491 **
Foshan	13.164	35	6	1.733	8.146	88.208 ***
Jiangmen	11.782	37	5	2.055	8.730	113.957 ***
Dongguan	11.418	22	7	1.085	4.311	14.725 ***
Zhongshan	9.964	24	3	0.990	5.019	18.330 ***
Huizhou	8.655	16	6	1.374	6.060	38.768 ***
Zhaoqing	14.873	26	7	0.413	2.359	2.5066
Municipality						
Chongqing	12.127	27	6	1.238	4.571	19.710 ***
Provincial capital cities						
Lhasa	7.782	13	4	0.079	2.958	0.061
Haikou	5.582	9	4	0.857	3.820	8.266 **
Kunming	15.218	22	8	−0.063	2.830	0.103
Fuzhou	6.345	10	4	0.740	3.370	5.334 *
Chengdu	11.473	23	5	0.686	3.774	5.682 *
Xi′an	18.273	56	5	1.380	4.475	22.437 ***
Guiyang	13.364	44	5	1.526	4.827	29.006 ***
Urumqi	13.236	44	6	2.139	6.988	78.370 ***
Nanning	11.364	25	6	1.312	5.532	30.476 ***
Xining	25.236	62	11	1.338	4.948	25.096 ***
Shenyang	42.691	200	10	2.028	6.560	66.742 ***
Changchun	25.200	104	3	1.444	4.300	22.972 ***
Harbin	28.764	157	6	2.369	9.199	139.483 ***
Wuhan	11.800	35	4	1.695	6.570	55.546 ***
Yinchuan	45.636	201	9	1.616	5.016	33.245 ***
Lanzhou	20.218	53	7	0.943	2.789	8.254 **
Nanchang	14.545	34	4	0.998	4.995	18.256 ***
Hefei	12.000	29	4	0.961	3.380	8.797 **
Taiyuan	52.218	185	8	1.388	4.005	19.979 ***
Jinan	30.836	101	8	1.595	5.157	33.976 ***
Hohhot	26.309	96	8	1.503	4.897	28.964 ***
Changsha	13.545	34	5	1.518	6.649	51.647 ***
Zhengzhou	23.509	77	4	1.469	5.230	31.181 ***

Table 1. *Cont.*

City	Mean	Max	Min	Skewness	Kurtosis	Jarque-Bera
Cities under separate state planning						
Xiamen	9.527	15	4	−0.043	2.700	0.223
Dalian	20.655	68	6	1.523	4.079	23.918 ***
Qingdao	17.873	60	4	1.550	5.117	32.299 ***

J–B denotes the Jarque–Bera Test for Normality. ***, * *, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

2.2. Methodology

Koenker and Xiao [26] first propose the unit root test based on quantile regression. However, this method does not fully consider the impacts of structural breaks. Given that, Bahmani-Oskooee et al. [36] develop a quantile based unit root test with smooth breaks, which could approximate the unknown breaks in the series.

Firstly, assume y_t, a data series of the SO_2 emissions level which could be determined by a time-varying deterministic component $d(t)$ and a stationary error term with variance δ^2 and zero mean, as follows:

$$y_t = d(t) + \varepsilon_t \tag{1}$$

In order to obtain a global approximation from the smooth transition and equip deterministic components with unknown breaks, the term $d(t)$ could be expressed, as follows:

$$d(t) = c + at + \alpha_k \sin(\frac{2\pi kt}{T}) + \beta_k \cos(\frac{2\pi kt}{T}) \tag{2}$$

The reason to conduct the Equation (2) in the model is based on the fact that a Fourier expression is capable of approximating absolutely integrable functions to any desired degree of accuracy. k represents the frequency of the Fourier function,α_k and β_k measures the amplitude and displacement of the frequency component, respectively, and π = 3.1416.

Then, the Equation (1) can be written as follows:

$$y_t = c + at + \alpha_k \sin(\frac{2\pi kt}{T}) + \beta_k \cos(\frac{2\pi kt}{T}) + \varepsilon_t \tag{3}$$

A desired feature of Equation (2) is that the standard linear specification emerges as a special case by setting $\alpha_k = \beta_k = 0$. It also follows that at least one frequency component must be present if there is a structural break. Here, to reject the null hypothesis $\alpha_k = \beta_k = 0$, the series must have a nonlinear component. Becker et al. [32] created a more powerful test to detect structural breaks under an unknown form. We set the maximum of $K = 5$ when we determine an optimal k. For any $K = k$, we estimate Equation (3) by employing the ordinary least squares (OLS) method and save the sum of squared residuals (SSR). Frequency is setting as the optimum frequency at the minimum of SSR. With the above assumption and respect to the deterministic components, we can test the following null hypothesis:

$$H_0:\ \xi_{\mathrm{t}} = v_t, v_t = v_{t-1} + u_t \tag{4}$$

To test the null hypothesis, Bahmani-Oskooee et al. [36] compute the OLS residuals as

$$e_t = y_t - \hat{c} - \hat{a}t - \hat{\alpha}_k \sin(\frac{2\pi kt}{T}) - \hat{\beta}_k \cos(\frac{2\pi kt}{T}) \tag{5}$$

Next, Bahmani-Oskooee et al. [36] used the quantile unit root test proposed by Koenker and Xiao [26] to investigate the stationarity of e_t. The test is an extension of the ADF unit root test and has much more power than a standard ADF test when a given shock exhibits heavy-tailed behavior. Another advantage of the test is that it allows for different adjustment mechanism towards the long-run equilibrium at different quantiles. The ADF regression model on e_t can be presented as follows:

$$e_t = \alpha_0 e_{t-1} + \sum_{i=1}^{p} \alpha_i \Delta e_{t-i} + \varepsilon_t \tag{6}$$

where P is the lag order. α_0 is used to reflect the persistence degree. As usual, $\alpha_0 = 1$ means that e_t contains a unit root with persistency, and $|\alpha_0| < 1$, e_t is required for the mean-reverting properties of SO_2 emissions per capita and for ruling out explosive behavior. Equation (6) could be rewritten based on quantile regression, as follows:

$$Q_{e_t}(\tau|e_{t-1},\ldots,e_{t-p}) = Q_\varepsilon(\tau) + \theta(\tau)e_{t-1} + \sum_{i=1}^{p} \varphi_i \Delta e_{t-i} \tag{7}$$

where $Q_\varepsilon(\tau)$ is τ th conditional quantile of v_t and its estimated value captures the magnitude of the shock in each quantile, $\theta(\tau)$ measures the speed of mean reversion within each quantile; here, the quantiles are set to be $\tau_i \in (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9)'$. Optimum lags are selected by the AIC information criteria. To obtain the coefficient $\theta(\tau)$ and $\sum\limits_{i=1}^{p} \varphi_i$, we minimize the following equation:

$$\min\sum_{t=1}^{n}\left(\tau - I_t\left(e_t < Q_\varepsilon(\tau) + \theta(\tau)e_{t-1} + \sum_{i=1}^{p} \varphi i \Delta e_{t-i}\right)\right)\left|e_t - Q_\varepsilon(\tau) - \theta(\tau)e_{t-1} - \sum_{i=1}^{p} \varphi_i \Delta e_{t-i}\right| \tag{8}$$

where, $I_t(\cdot) = 1$ if $e_t < Q_\varepsilon(\tau) + \theta(\tau)e_{t-1} + \sum\limits_{i=1}^{p} \varphi_i \Delta e_{t-i}$, otherwise $I_t(\cdot) = 0$. Koenker and Xiao [26] further proposed a t-ratio statistic with the null non-stationary hypothesis $\alpha(\tau) = 1$ against different alternative hypotheses, $\alpha(\tau) < 1$, $\alpha(\tau) > 1$ and $\alpha(\tau) \neq 1$, to check the unit root hypothesis at specific quantiles, which can be expressed as

$$t_n(\tau_i) = \frac{f\left(\hat{F}^{-1}(\tau_i)\right)}{\sqrt{\tau_i(1-\tau_i)}}\left(Y'_{-1}P_{(1,\Delta e_{t-1},\ldots,\Delta e_{t-p})}Y_{-1}\right)^{\frac{1}{2}}\left(\hat{\theta}(\tau) - 1\right) \tag{9}$$

where $f(\cdot)$ is probability functions of e_t, and $F(\cdot)$ is the cumulative density function of series e_t, Y_{-1} is the vector of lagged dependent variables (e_{t-1}), and P_X is the projection matrix onto the space orthogonal to $X = (1, \Delta e_{t-1}, \ldots, \Delta e_{t-p})$. $f(\hat{F}^{-1}(\tau_i))$ is a consistent estimator of $f(F^{-1}(\tau_i))$ indicated by Koenker and Xiao [26], which can be expressed as

$$f(F^{-1}(\tau_i)) = \frac{(\tau_i - \tau_{i-1})}{G'(\omega(\tau_i) - \omega(\tau_{i-1}))} \tag{10}$$

where $\omega(\tau_i) = (c(\tau_i), \theta(\tau_i), \varphi_1(\tau_i), \ldots, \varphi_{\mathrm{P}}(\tau_i))$ and $\tau_i \in \left[\underline{\lambda}, \overline{\lambda}\right]$. In this paper, we set $\underline{\lambda} = 0.1$ and $\overline{\lambda} = 0.9$ with interval 0.1. Obviously, we test the unit root hypothesis at different quantiles in comparison with the traditional ADF test, which only emphasizes on the conditional central tendency. To assess the unit root behavior over a range of quantiles, Koenker and Xiao [26] recommend the following Kolmogorov–Smirnov (QKS) test which could be presented as

$$QKS = sup_{\tau_i \in [\underline{\lambda}, \overline{\lambda}]}\left|t_n(\tau_i)\right| \tag{11}$$

We select the maximum of $t_n(\tau_i)$ to build the QKS–Fourier statistics over the quantiles $\tau_i \in (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9)'$. Though the limiting distributions of both $t_n(\tau_i)$ and the QKS tests are nonstandard, Koenker and Xiao [26] suggest using the re-sampling procedure to generate the critical values. Hence, to derive critical values for the above-mentioned test, we implement the re-sampling procedures of Koenker and Xiao [26] as follows:

We run following k-order autoregression by ordinary least square:

$$\Delta e_t = \theta(\tau)\Delta e_{t-1} + \in_t \tag{12}$$

We save fitted values $\Delta\hat{e}_t = \theta(\tau)\Delta\hat{e}_{t-1}$ and residuals $\hat{\in}_t$, and then create bootstrap residuals ($\in_t^b$) with replacement from the centered residuals $\hat{\in}_t = \hat{\in}_t - \frac{1}{n-1}\sum\limits_{t=1+1}^{n}\hat{\in}_t$.

We calculate the bootstrap sample of observations as follows:

$$e_t^b = {e_{t-1}}^b + \Delta e_t^b \tag{13}$$

$$\text{with}\begin{cases} \Delta e_t^b = \sum\limits_{k=1}^{l}\theta(\tau)\Delta e_{t-k}^b + \in_t^b; \\ \Delta e_t^b = \Delta e_j \text{ for } j = 1, 2, \ldots, l; \\ \Delta e_t^b = e_1 \end{cases} \tag{14}$$

In this paper, 5000 bootstrap iterations were used to accurately calculate the critical values, and the bootstrap variance estimator is inferior to more classical estimators. In order to carry out the empirical analysis, we need critical values for our tests. These are not available and must be constructed via the Monet Carlo simulation.

3. Results and Discussion

For comparative purposes, we firstly implemented standard unit root tests, including the ADF test, the DF–GLS test, the PP test, the KPSS test, and the MZa test to assess the convergence of SO_2 emissions per capita of 74 cities in China. Table 2 reports the corresponding results. As shown in this table, the DF–GLS and the MZa tests indicate that the SO_2 emissions per capita in 2 out of 74 cities are convergent at a 10% significant level. The KPSS test shows that the SO_2 emissions in 3 out of 74 cities are convergent. The ADF test supports that the SO_2 emissions per capita in 24 out of 74 cities are convergent at the usual significant level. These cities are Tianjin, Langfang, Cangzhou, Hengshui, Xingtai, Shijiazhuang, Baoding, Lianyungang, Zhenjiang, Quzhou, Jiaxing, Hangzhou, Shaoxing, Guangzhou, Chongqing, Xi’an, Shenyang, Changchun, Harbin, Yinchuan, Ji’nan, Zhengzhou, Dalian, and Qingdao. On the contrary, the PP test indicates that only the SO_2 emissions per capita in Zhenjiang are not converging, and all of the other cities are converging. Overall, the empirical results from the five conventional unit root tests are somewhat contradictory. The possible reason may lie in that these tests tend to fail to refuse the null hypothesis of the unit root when the data series exhibit structural breaks and/or non-normal distribution. Moreover, the traditional unit root tests can only provide the convergence over the whole sample; thus the mean-reverting properties cannot be revealed at particular quantiles of the series.

It is well known that univariate unit root tests may be inefficient when applied to finite samples. Next, this paper utilizes the quantile unit root test [26] to revisit the convergence of SO_2 emissions per capita in concerned cities. This approach has the following two advantages. On the one hand, the quantile unit root test is more suitable to test the unit root hypothesis for the non-Gaussian series. On the other hand, the quantile unit root test provides unit root behavior both over the whole quantiles and at each selected quantile. As such, the asymmetric persistency could be uncovered through the quantiles.

Table 2. Results for univariate unit root test.

City	ADF Test	DF–GLS Test	PP Test	KPSS Test	MZ_a Test
Beijing–Tianjin–Hebei Urban Agglomeration					
Beijing	−5.107 ***	1.156	−3.124 **	0.603 **	0.776
Tianjin	−2.225	1.395	−3.921 ***	0.603 **	0.803
Zhangjiakou	−2.684 *	2.938	−3.193 **	0.702 **	0.960
Chengde	−5.307 ***	−1.329	−2.992 **	0.479 **	−3.306
Qinhuangdao	−2.656 *	2.008	−3.355 **	0.550 **	1.038
Langfang	−1.334	1.660	−3.407 **	0.611 **	0.961
Cangzhou	−0.377	2.544	−3.782 ***	0.578 **	1.016
Tangshan	−3.033 **	−0.757	−3.069 **	0.742 ***	−1.293
Handan	−4.272 ***	−1.123	−4.278 ***	0.606 **	−2.217
Hengshui	−1.433	2.245	−3.339 **	0.715 **	0.965
Xingtai	−0.259	2.394	−2.780 *	0.671 **	0.956
Shijiazhuang	−0.662	2.339	−3.493 **	0.575 **	0.575
Baoding	−1.946	2.853	−4.921 ***	0.642 **	0.777
Yangtze River Delta					
Shanghai	−4.217 ***	−0.537	−4.037 ***	0.811 ***	−0.355
Nanjing	−3.330 **	−0.899	−3.330 **	0.861 ***	−1.587
Wuxi	−3.860 ***	−0.630	−3.771 ***	0.851 ***	−0.576
Nantong	−3.340 **	−0.392	−4.020 ***	0.969 ***	−0.568
Lianyungang	−0.621	1.510	−3.363 **	0.617 **	1.239
Suzhou	−3.863 ***	−0.491	−3.789 ***	0.921 ***	−0.303
Huaian	−3.869 ***	−0.690	−3.829 ***	0.907 ***	−0.797
Changzhou	−2.818 *	−0.470	−3.340 **	0.898 ***	−0.790
Tàizhou	−3.554 **	−0.312	−3.554 **	0.928 ***	−0.319
Yancheng	−4.402 ***	−0.455	−4.197 ***	0.897 ***	−0.171
Suqian	−3.633 ***	−0.630	−3.621 ***	0.732 **	−0.674
Zhenjiang	−1.870	−0.158	−2.553	0.984 ***	−0.169
Yangzhou	−3.454 **	−0.950	−3.454 **	0.896 ***	−1.721
Xuzhou	−3.002 **	−0.469	−3.012 **	0.903 ***	−0.319
Zhoushan	−2.853 *	−0.910	−3.617 ***	0.503 **	−2.643
Lishui	−5.909 ***	−1.027	−6.457 ***	0.718 **	−1.724
Ningbo	−5.171 ***	−0.667	−4.949 ***	0.845 ***	−0.637
Wenzhou	−4.612 ***	−1.466	−4.592 ***	0.924 ***	−3.925
Quzhou	−2.044	0.434	−5.206 ***	0.947 ***	0.388
Jiaxing	−2.271	−0.667	−5.064 ***	0.777 ***	−0.592
Jinhua	−5.414 ***	0.576	−5.566 ***	0.804 ***	0.575
Huzhou	−4.495 ***	−1.236	−4.538 ***	0.629 **	−3.018
Hangzhou	−2.092	−0.594	−4.918 ***	0.802 ***	−0.490
Shaoxing	−1.363	−0.703	−5.091 ***	0.890 ***	−0.655
Táizhou	−4.250 ***	−0.736	−4.300 ***	0.759 ***	−1.764
Pearl River Delta					
Guangzhou	−1.660	0.044	−3.651 ***	0.675 **	−0.024
Shenzhen	−2.921 **	−1.142	−2.835 *	0.708 **	−3.214
Zhuhai	−4.040 ***	−1.259	−3.752 ***	0.438 *	−3.024
Foshan	−5.303 ***	−1.021	−5.272 ***	0.965 ***	−1.805
Jiangmen	−5.066 ***	−0.773	−5.066 ***	0.771 ***	−0.912
Dongguan	−3.901 ***	−1.459	−3.934 ***	0.472 **	−4.051
Zhongshan	−4.146 ***	−0.986	−4.162 ***	0.631 **	−1.912
Huizhou	−4.687 ***	−1.136	−4.692 ***	0.446 *	−2.418
Zhaoqing	−3.201 **	−0.558	−2.963 **	0.902 ***	−1.499
Municipality					
Chongqing	−0.766	3.774	−2.928 **	0.836 ***	1.415

Table 2. *Cont.*

City	ADF Test	DF–GLS Test	PP Test	KPSS Test	MZ_a Test
Provincial capital cities					
Lhasa	−3.949 ***	−1.792 *	−3.940 ***	0.725 ***	−5.274 *
Haikou	−5.305 ***	−1.426	−5.254 ***	0.179	−4.341
Kunming	−3.728 ***	−0.326	−3.728 ***	0.875 ***	−0.391
Fuzhou	−3.865 ***	−1.807 *	−3.811 ***	0.168	−6.351 *
Chengdu	−3.504 **	2.012	−3.528 **	0.914 ***	1.726
Xi'an	−0.164	3.034	−3.439 **	0.486 **	1.073
Guiyang	−5.014 ***	0.711	−3.673 ***	0.354 *	0.706
Urumqi	−5.174 ***	−0.955	−4.317 ***	0.444 **	−2.516
Nanning	−4.653 ***	−1.193	−4.682 ***	0.560 **	−2.728
Xining	−4.331 ***	−1.361	−4.221 ***	0.732 **	−3.370
Shenyang	−1.507	3.305	−3.336 **	0.489 **	0.800
Changchun	0.268	4.082	−2.960 **	0.412 *	0.916
Harbin	−2.340	1.988	−4.129 ***	0.360 *	0.716
Wuhan	−3.620 ***	−0.799	−3.558 ***	0.681 **	−1.040
Yinchuan	0.575	2.847	−3.341 **	0.489 **	0.837
Lanzhou	−5.535 ***	0.364	−3.257 **	0.079	0.905
Nanchang	−4.351 ***	0.748	−4.343 ***	0.971 ***	0.743
Hefei	−2.733 *	−0.629	−2.790 *	0.833 ***	−0.775
Taiyuan	−4.617 ***	−1.414	−3.260 **	0.489 **	−3.783
Jinan	−1.386	2.821	−3.372 **	0.749 ***	0.982
Hohhot	−7.009 ***	1.535	−3.001 **	0.357 *	0.900
Changsha	−3.731 ***	−0.641	−3.799 ***	0.913 ***	−0.670
Zhengzhou	−1.964	1.076	−3.293 **	0.687 **	1.007
Cities under separate state planning					
Xiamen	−3.365 **	0.146	−3.358 **	0.468 **	0.661
Dalian	−0.598	1.113	−2.997 **	0.563 ***	0.787
Qingdao	−1.202	1.456	−3.538 **	0.810 ***	0.984

***, **, and * indicate significance at the 1%, 5%, and 10% levels.

To conduct the quantile unit root test beforehand, some parameters should be declared. Specifically, as mentioned earlier, the quantiles are determined by the range of $\tau_i \in (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9)'$, aiming to reveal the unit root behavior at different quantiles. In doing so, we can investigate whether the unit root behaviors of SO_2 emissions per capita are asymmetric at different quantiles. In addition, the QKS statistics are employed to check the stochastic convergence over the whole quantiles. However, given that no standard distribution of $tn(\tau i)$ and QKS statistics are available, we get help from bootstrap techniques with 5000 replications to generate critical values.

Tables 3 and 4 report the results from the quantile unit root tests. Table 3 reports the results of the unit root hypothesis at particular quantiles. It is clear that from quantile 0.1 to 0.9, $t_n(\tau_i)$ is not rejected for the cities of Pearl River Delta; however, from the national level, the Pearl River Delta is undoubtedly far ahead in tackling SO_2 emissions and environmental governance. It is worth noting that the SO_2 emissions per capita are stationary at all quantiles for only one city, Lanzhou. On the contrary, the SO_2 emissions are divergent at all quantiles for 14 cities, that is, Shanghai, Lianyungang, Suzhou, Yancheng, Suqian, Zhenjiang, Guangzhou, Shenzhen, Zhaoqing, Kunming, Chengdu, Hefei, Changsha, and Xiamen. Second, as indicated by the QKS statistics from Table 4, nine cities of the Pearl River Delta are all diverging. Nevertheless, although the quantile unit root test has significant superiority over the traditional unit root tests, it may have low efficiency of detecting the mean reversion of the data when structural breaks exist. In other words, if structural breaks exist in our concerned series, then the above results may not be persuasive.

Table 3. Results for quantile unit root at particular quantiles.

Quantiles	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Beijing–Tianjin–Hebei Urban Agglomeration									
Beijing	−10.52 ***	−5.475 ***	−4.639 ***	−4.235 ***	−2.24 **	−1.776	−1.194	0.15	0.953
Tianjin	−6.84 ***	−6.192 ***	−5.882 ***	−5.245 ***	−4.496 ***	−2.855 ***	−2.29 **	−0.287	0.597
Zhangjiakou	−3.112 *	−2.451 *	−3.526 ***	−3.357 ***	−2.345 **	−2.129	−1.322	−0.465	−0.577
Chengde	−3.479 *	−3.411 ***	−4.269 ***	−4.635 ***	−3.589 ***	−3.526 ***	−2.32	−1.957	−1.405
Qinhuangdao	−5.57 **	−6.345 ***	−5.41 ***	−3.182 ***	−2.798 ***	−2.083*	−1.266	−0.657	−0.526
Langfang	−10.609 ***	−6.047 ***	−4.684 ***	−5.247 ***	−4.13 ***	−3.373 ***	−2.565 **	−1.147	−0.046
Cangzhou	−4.782 **	−3.376 ***	−2.964 **	−1.651	−1.884	−1.736	−1.807	−1.427	−1.03
Tangshan	−2.519	−2.443 *	−3.034 **	−2.439 *	−2.576 **	−2.802 **	−2.27 *	−2.604 **	−0.134
Handan	−7.307 ***	−6.266 ***	−5.361 ***	−4.84 ***	−3.744 ***	−3.139 **	−1.423	−0.154	0
Hengshui	−10.509 ***	−6.028 ***	−3.332 ***	−3.445 ***	−3.714 ***	−3.03 ***	−1.908 *	−1.486	−0.103
Xingtai	−5.389 ***	−2.55 *	−1.904	−3.142 ***	−3.86 ***	−3.69 ***	−3.834 ***	−1.635 *	−1.265
Shijiazhuang	−5.175 **	−3.774 ***	−2.43 **	−2.528 *	−2.147 *	−0.822	−0.135	−0.1	−1.345
Baoding	−8.481 ***	−3.831 ***	−3.355 ***	−4.714 ***	−3.869 ***	−2.718 **	−1.711	−0.729	−0.95
Yangtze River Delta									
Shanghai	−2.274	−1.158	−1.232	−1.503	−1.753	−1.656	−1.862	−1.289	−1.173
Nanjing	−1.466	−1.991	−2.325 **	−2.071	−1.896	−0.902	−0.722	−0.813	−1.592
Wuxi	−5.215 *	−4.998 ***	−4.127 ***	−2.116	−3.057 ***	−2.123 *	0.04	0.076	1.14
Nantong	0.017	−1.423	−1.779	−2.361 *	−2.431 *	−1.382	−0.432	−0.063	0.981
Lianyungang	−3.703	−2.057	−1.664	−1.163	−1.588	−1.241	−1.074	−0.536	0.352
Suzhou	−2.019	−1.341	−0.95	−1.14	−1.606	−0.795	−0.407	−0.536	−0.578
Huaian	−1.367	−2.524 **	−2.641 ***	−2.64 **	−2.498 **	−2.145 *	−1.314	−0.572	0.696
Changzhou	−5.183 *	−3.006 **	−2.646 **	−2.271 *	−0.962	−1.093	−0.515	0.824	2.896
Tàizhou	−4.208 ***	−1.799	−1.139	−0.794	−0.854	−0.687	−0.724	−0.961	0
Yancheng	−1.499	−1.008	−0.941	−0.939	−1.059	−0.672	−0.746	0.733	2.43
Suqian	−2.221	−0.589	−0.761	−1.128	0.027	−0.344	−0.836	−0.677	−0.272
Zhenjiang	−1.092	−1.101	−0.685	−0.393	−1.042	−0.862	−0.793	−0.306	0
Yangzhou	−3.867 *	−3.353 *	−4.563 ***	−1.508	−0.999	−0.186	1.037	2.022	1.525
Xuzhou	−6.415 **	−1.922	−1.139	−1.111	0.449	−0.115	1.024	2.227	3.719
Zhoushan	−4.635 **	−2.731 **	−2.826 ***	−1.979	−0.669	−0.602	0.192	0.281	−0.677
Lishui	−3.547 **	−3.252 ***	−2.666 **	−2.163 *	−1.486	−1.57	−1.878	−1.347	−1.305
Ningbo	−1.251	−1.925	−1.475	−2.115	−3.368 ***	−2.573 **	−2.098	−0.726	0.526
Wenzhou	−2.931 *	−3.05 **	−2.586 **	−3.953 ***	−3.554 ***	−2.203 *	−1.563	−0.295	−1.094
Quzhou	−3.528	−2.49 **	−1.103	−0.219	0.259	−0.388	−0.745	−0.804	−0.776
Jiaxing	−2.592	−3.14 **	−2.291 **	−2.549 **	−2.163 *	−0.606	−0.236	−0.507	0.171
Jinhua	−7.144 ***	−4.733 ***	−4.079 ***	−2.023	−1.422	−1.511	−0.067	−0.611	0.11
Huzhou	−1.795	−2.894 ***	−2.117 *	−2.335 *	−2.611 *	−2.12 *	−2.205 *	−1.573	−1.832
Hangzhou	−2.474	−2.182	−2.085	−0.969	−0.476	−0.188	−0.926	−0.616	0.289
Shaoxing	−7.672 ***	−6.291 ***	−3.063 ***	−2.786 **	−2.405 **	−1.83	−1.115	−1.199	0.515
Táizhou	−2.889 *	−2.786 *	−2.63*	−3.461 ***	−2.719 **	−1.347	−1.536	−1.272	0.729
Pearl River Delta									
Guangzhou	−2.015	−1.565	−1.388	−0.892	0.081	−0.081	0.123	0.82	−0.42
Shenzhen	−0.948	−0.217	0.539	0.025	−0.164	−0.111	0.927	1.055	0.483
Zhuhai	−1.551	−1.919	−1.732	−2.636 **	−2.239 *	−2.161 *	−2.006	−2.67 *	−2.801
Foshan	−3.191 *	−2.11 **	−1.811	−1.757	−2.121 **	−2.294 *	−0.936	−0.214	0.405
Jiangmen	−5.17 *	−2.563	−1.581	−1.233	−0.753	−0.775	−0.085	0.69	2.02
Dongguan	−3.915 *	−1.811	−0.1	−1.048	−0.98	−2.054 *	−1.713	−1.299	−0.572
Zhongshan	−2.926 *	−1.149	−1.879	−1.794	−1.149	−0.878	−1.148	−0.811	−3.235 **
Huizhou	−1.53	−1.444	−1.321	−1.892	−2.561 *	−2.294 *	−1.705	−1.651	−2.497
Zhaoqing	−1.981	−1.256	−0.995	−0.653	−0.955	0.081	−0.53	−1.062	−0.87
Municipality									
Chongqing	−3.672	−3.549 ***	−1.732	−0.67	−0.402	−0.41	−0.096	−0.286	1.339
Provincial capital cities									
Lhasa	−0.933	0	0	−1.68	−1.608	−1.947	−2.236	−2.885 ***	−3.531 **
Haikou	−2.962 *	−2.255 *	−2.58 **	−3.314 **	−3.409 ***	−2.713 ***	−1.4	−1.538	−1.545
Kunming	1.898	1.071	−0.375	−0.331	−0.364	−1.093	−0.418	−0.438	0.572
Fuzhou	−2.071	−1.3	−1.802	−1.3	−1.355	−1.322	−1.313	−1.496	−4.72 *
Chengdu	−2.245	−1.164	−0.582	−0.929	−0.257	−0.262	0.789	1.418	0.216
Xi′an	−9.242 ***	−4.219 ***	−4.575 ***	−3.717 ***	−2.762 **	−2.635 **	−3.056 **	−1.323	−2.221
Guiyang	−8.762 ***	−4.739 ***	−4.5 ***	−3.671 ***	−2.782 **	−1.778	−1.973	−0.548	−1.056
Urumqi	−14.573 ***	−12.138 ***	−9.883 ***	−7.421 ***	−5.396 ***	−3.289 ***	−1.162	−1.096	1.076
Nanning	−5.557 **	−3.668 ***	−4.065 ***	−3.968 ***	−3.905 ***	−3.021 ***	−1.248	−1.406	−0.7
Xining	−3.17 **	−3.879 ***	−4.413 ***	−4.489 ***	−4.1 ***	−3.192 ***	−1.89	−1.84	−1.692
Shenyang	−9.234 ***	−6.22 ***	−4.56 ***	−4.521 ***	−4.247 ***	−2.642 **	−1.99 *	−0.902	−1.059
Changchun	−4.409 **	−4.076 **	−4.351 ***	−3.019 ***	−3.241 ***	−3.017 ***	−1.07	−0.895	−1.757

Table 3. *Cont.*

Quantiles	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Harbin	−11.648 ***	−4.805 ***	−4.886 ***	−4.012 ***	−4.083 ***	−2.644 **	−2.369 **	−1.667	−0.542
Wuhan	−3.652 **	−2.796 ***	−2.901 ***	−1.69	−1.665	−1.467	−1.166	−1.674	−2.894 **
Yinchuan	−8.893 **	−8.574 ***	−6.84 ***	−4.584 ***	−2.668 **	−1.168	−0.977	−0.001	−2.456
Lanzhou	−10.972 ***	−6.794 ***	−4.568 ***	−3.926 ***	−2.56 **	−2.344 **	−1.885 *	−2.517 **	−6.588 **
Nanchang	−1.075	−1.695	−2.842 **	−2.508 **	−1.633	−0.926	−0.726	−0.992	2.525
Hefei	−0.86	−0.832	−0.51	−0.058	−0.032	0.335	−0.611	−0.695	−1.148
Taiyuan	−9.072 ***	−7.119 ***	−5.191 ***	−5.652 ***	−4.674 ***	−2.959 ***	−2.214 **	−0.86	−0.525
Jinan	−10.373 ***	−6.973 ***	−4.522 ***	−2.879 **	−1.829 *	−0.457	0.066	0.997	2.837
Hohhot	−17.668 ***	−7.861 ***	−6.927 ***	−3.603 ***	−2.949 **	−2.473 **	−3.135 ***	−4.034 **	−1.13
Changsha	−3.025	−2.052	−1.610	−1.647	−0.346	−0.323	−0.489	−0.522	−1.301
Zhengzhou	−4.585 *	−1.908	−2.177	−2.096 *	−2.188 *	−0.691	−0.755	−0.493	−0.021
Cities under separate state planning									
Xiamen	−1.832	−1.051	−0.775	−0.565	−0.427	−0.241	0.236	0	0.288
Dalian	−5.167 **	−5.263 ***	−6.797 ***	−4.222 ***	−3.998 ***	−2.330 *	−1.835 *	−1.044	−0.457
Qingdao	−5.175 ***	−3.374 ***	−3.967 ***	−3.024 **	−3.776 ***	−3.241 ***	−1.132	−0.984	−0.051

***, **, and * indicate significance at the 1%, 5%, and 10% significant levels. The critical value for QKS statistics generated by bootstrap techniques with 5000 iterations.

Table 4. Results for overall quantile unit root test.

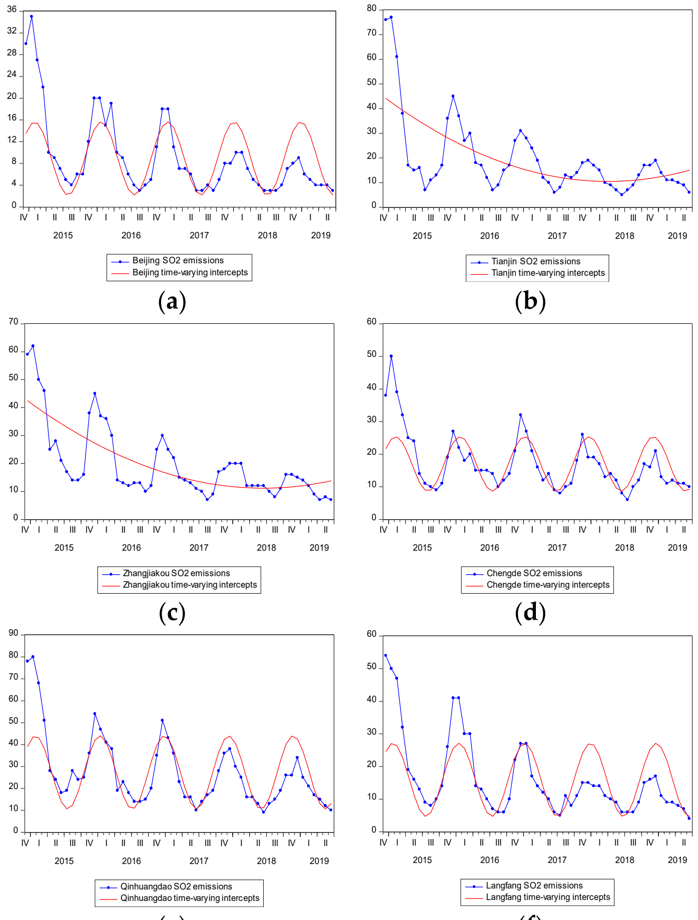
City	QKS statistic	CV 10%	CV 5%	CV 1%
Beijing–Tianjin–Hebei Urban Agglomeration				
Beijing	10.520 ***	4.467	5.382	8.125
Tianjin	6.840 **	5.021	6.385	10.958
Zhangjiakou	3.526	4.917	6.065	10.408
Chengde	4.635	4.953	6.098	9.079
Qinhuangdao	6.345 ***	4.802	5.859	8.781
Langfang	10.609 ***	3.299	3.821	5.359
Cangzhou	6.415 *	5.626	6.860	11.124
Tangshan	3.034	3.875	4.529	6.218
Handan	7.307 ***	3.172	3.670	4.841
Hengshui	10.509 ***	3.325	3.848	5.046
Xingtai	5.389 ***	3.410	3.891	5.310
Shijiazhuang	5.175	5.515	6.715	10.049
Baoding	8.481 ***	3.838	4.461	6.227
Yangtze River Delta				
Shanghai	2.274	4.522	5.607	9.027
Nanjing	2.325	3.342	3.871	5.236
Wuxi	5.215	5.542	7.054	11.447
Nantong	2.431	3.522	3.947	5.254
Lianyungang	3.703	5.423	6.649	10.699
Suzhou	2.019	5.325	6.527	10.989
Huaian	2.641	3.403	3.889	5.177
Changzhou	5.183 *	5.172	6.477	10.237
Tàizhou	4.208 **	3.486	3.965	5.240
Yancheng	2.430	5.585	6.869	10.477
Suqian	2.221	5.942	7.335	11.768
Zhenjiang	1.101	3.472	3.961	5.371
Yangzhou	4.563	5.398	6.817	10.275
Xuzhou	6.415 *	5.626	6.860	11.124
Zhoushan	4.635 **	3.751	4.340	6.433
Lishui	3.547	3.471	3.931	5.079
Ningbo	3.368	3.499	4.020	5.740
Wenzhou	3.953 *	3.937	4.746	6.786
Quzhou	3.528	5.450	6.764	10.200
Jiaxing	3.140	5.013	6.337	9.946

Table 4. *Cont.*

City	QKS statistic	CV 10%	CV 5%	CV 1%
Jinhua	7.144 ***	3.483	3.915	5.459
Huzhou	2.894	4.209	4.985	6.907
Hangzhou	2.474	5.268	6.537	9.889
Shaoxing	7.672 **	4.575	5.587	8.526
Táizhou	3.461	4.236	5.111	7.533
Pearl River Delta				
Guangzhou	2.015	3.847	4.474	6.300
Shenzhen	1.055	5.475	6.848	10.967
Zhuhai	2.801	4.246	5.057	7.525
Foshan	3.191	3.438	3.945	5.179
Jiangmen	5.170	5.813	7.342	12.113
Dongguan	3.915	5.269	6.622	10.757
Zhongshan	3.235	3.529	4.107	5.526
Huizhou	2.561	5.402	6.731	10.846
Zhaoqing	1.981	4.448	5.422	7.924
Municipality				
Chongqing	3.672	5.168	6.523	10.111
Provincial capital cities				
Lhasa	3.531	3.788	4.417	6.187
Haikou	3.409	3.793	4.438	6.207
Kunming	1.898	5.592	7.016	10.946
Fuzhou	4.720	4.778	5.904	9.215
Chengdu	2.245	5.906	7.340	11.347
Xi'an	9.242 ***	4.610	5.776	8.667
Guiyang	8.762 **	4.370	5.410	9.004
Urumqi	14.573 ***	3.495	4.185	6.248
Nanning	5.557 **	4.165	4.942	7.466
Xining	4.489 **	3.259	3.625	4.569
Shenyang	9.234 ***	4.116	5.010	8.102
Changchun	4.409	4.622	5.635	8.748
Harbin	11.648 ***	4.343	5.231	8.410
Wuhan	3.652 *	3.485	3.990	5.448
Yinchuan	8.893 **	4.793	6.072	9.976
Lanzhou	10.972 ***	4.833	6.269	10.536
Nanchang	2.842	3.784	4.412	6.042
Hefei	1.148	5.063	6.398	9.815
Taiyuan	9.072 ***	3.368	3.920	5.471
Jinan	10.373 ***	4.878	6.172	9.586
Hohhot	17.668 ***	4.485	5.424	8.622
Changsha	3.025	4.942	6.016	8.984
Zhengzhou	4.585	5.435	6.888	10.591
Cities under separate state planning				
Xiamen	1.832	3.494	4.020	5.257
Dalian	6.797 **	4.252	5.341	8.122
Qingdao	5.175 **	3.425	3.968	5.524

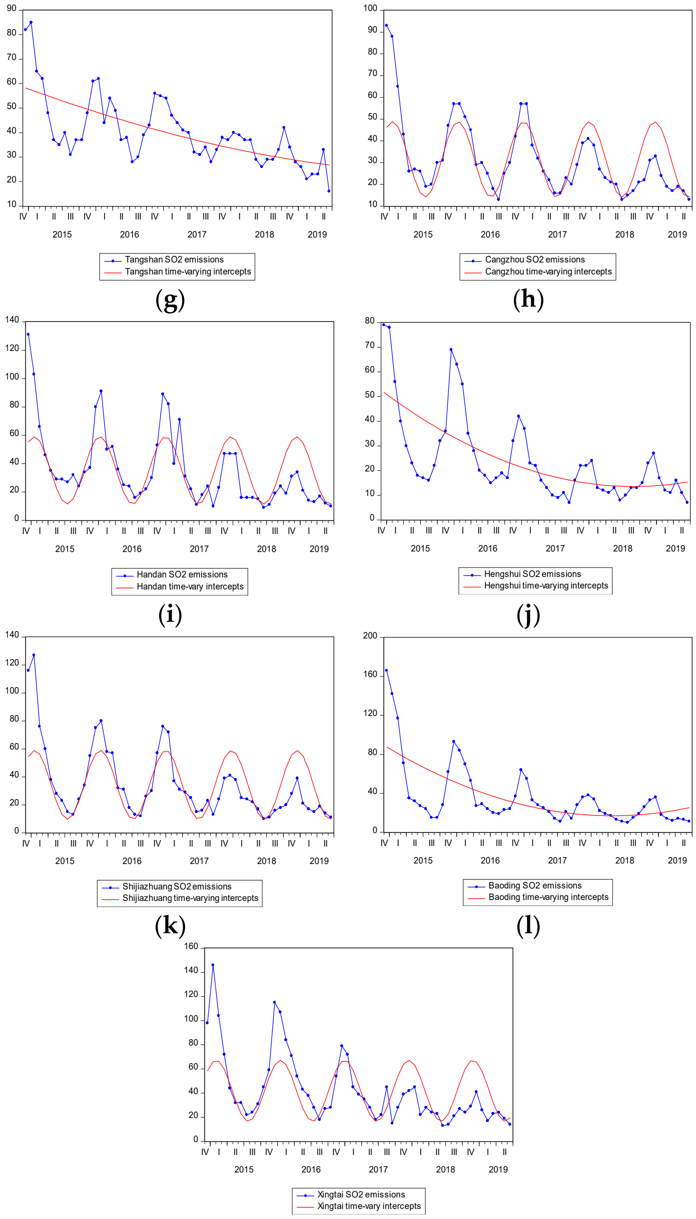
***, **, and * indicate significance at the 1%, 5%, and 10% significant levels. The critical value for QKS statistics generated by bootstrap techniques with 5000 iterations.

To gain more insight, we also display the actual time paths of SO_2 emissions per capita and the fitted time paths by using the Fourier function in Figures 1–6. It is worth noting that the actual nature of break(s) is generally unknown, and there is no specific guide as to where and how many breaks to use in the process of producing fitted SO_2 emissions per capita series. Despite this, we still clearly observe that the fitted series closely followed the actual series for a vast majority of the cities we considered. This implies that the quantile unit root test with a Fourier function has high power in detecting the potential structural breaks and assessing the mean-reverting properties and asymmetric behavior of the SO_2 emissions per capita series. Moreover, the distributions of the SO_2 emissions per capita in concerned 74 cities differ significantly from the normal distribution and the presence of smooth breaks. As a consequence, this paper shifts to test the stochastic properties of the SO_2 emissions per capita using the Fourier quantile unit root test. Similarly, the critical values are generated through the bootstrap technique with 5000 replications.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 1. *Cont.*



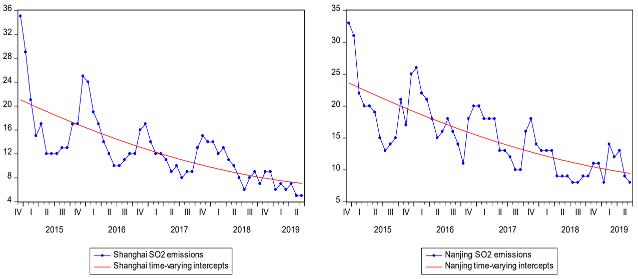
(**g**) (**h**)

(**i**) (**j**)

(**k**) (**l**)

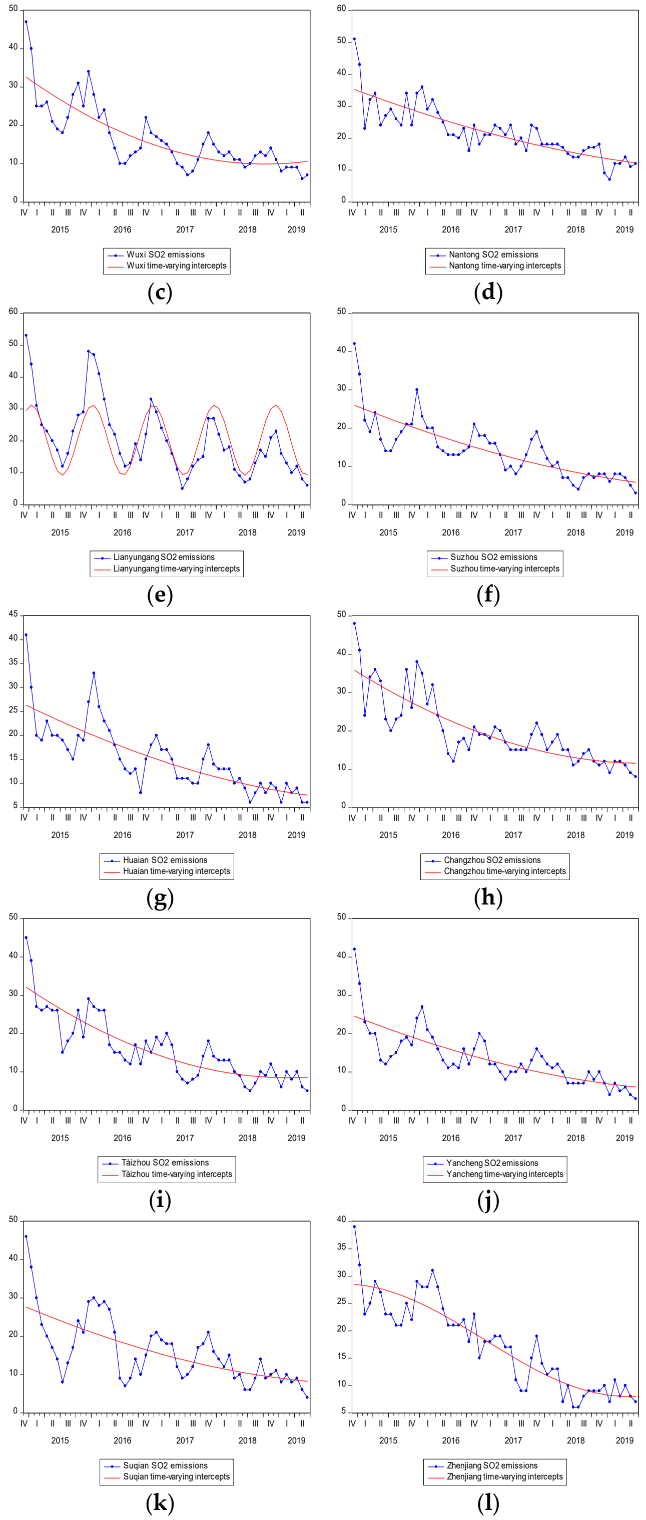
(**m**)

Figure 1. The Plots of the SO_2 emissions per capita and fitted nonlinearities of Beijing-Tianjin-Hebei Urban Agglomeration. (**a**–**m**) respectively represent the plots of the SO2 emissions per capita and fitted nonlinearities of Beijing, Tianjin, Zhangjiakou, Chengde, Qinhuangdao, Langfang, Tangshan, Cangzhou, Handan, Hengshui, Shijiazhuang, Baoding, and Xingtai.



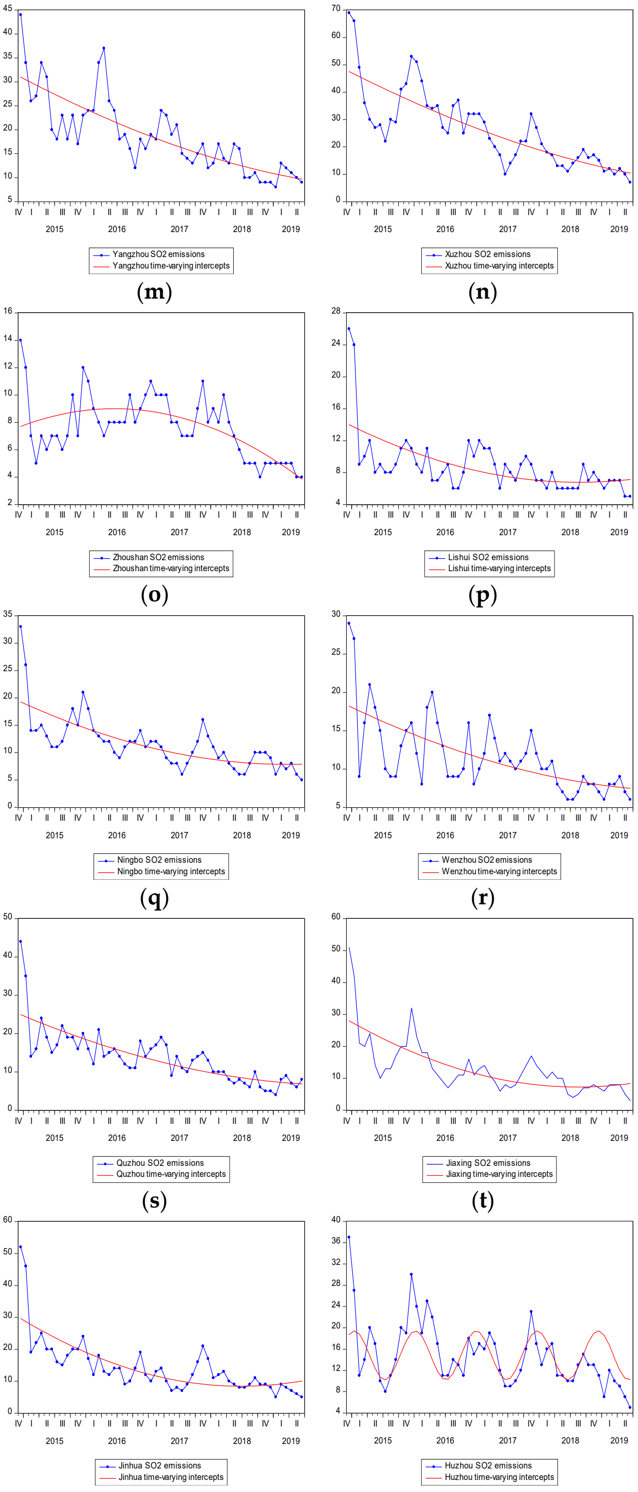
(**a**) (**b**)

Figure 2. *Cont.*



(**c**) (**d**) (**e**) (**f**) (**g**) (**h**) (**i**) (**j**) (**k**) (**l**)

Figure 2. *Cont.*



(m) **(n)**

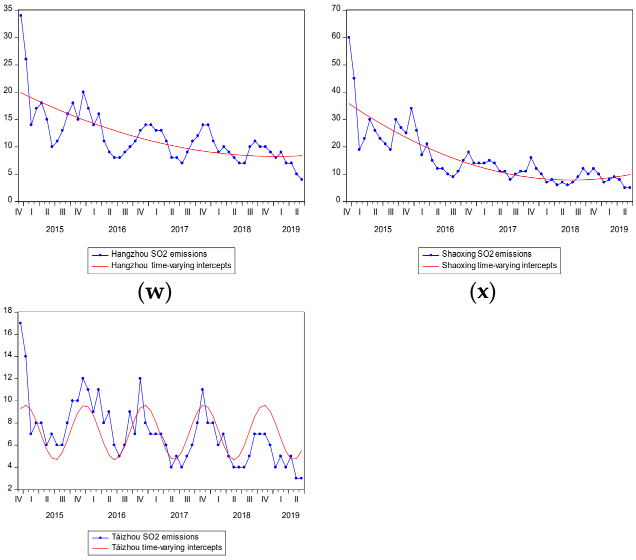
(o) **(p)**

(q) **(r)**

(s) **(t)**

(u) **(v)**

Figure 2. *Cont.*



(**w**) (**x**)

(**y**)

Figure 2. The plots of the SO_2 emissions per capita and fitted nonlinearities of Yangtze River Delta. (**a**–**y**) respectively represent the plots of the SO2 emissions per capita and fitted nonlinearities of Shanghai, Nanjing, Wuxi, Nantong, Lianyungang, Suzhou, Huaian, Changzhou, Tàizhou, Yancheng, Suqian, Zhenjiang, Yangzhou, Xuzhou, Zhoushan, Lishui, Ningbo, Wenzhou, Quzhou, Jiaxing, Jinhua, Huzhou, Hangzhou, Shaoxing, and Táizhou.

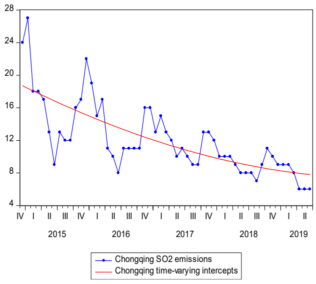
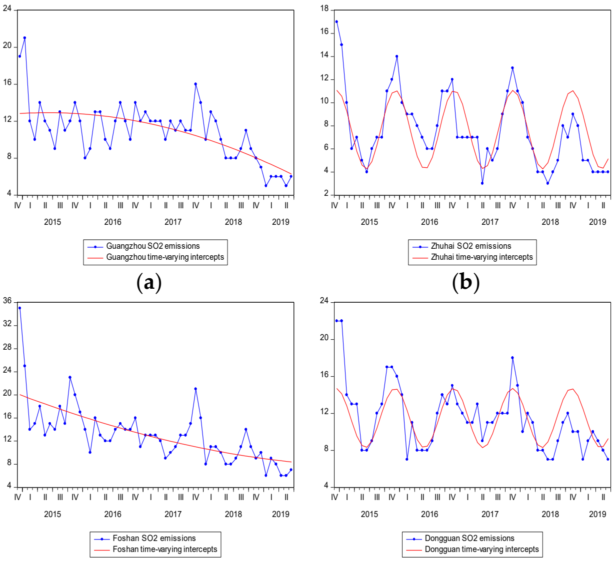


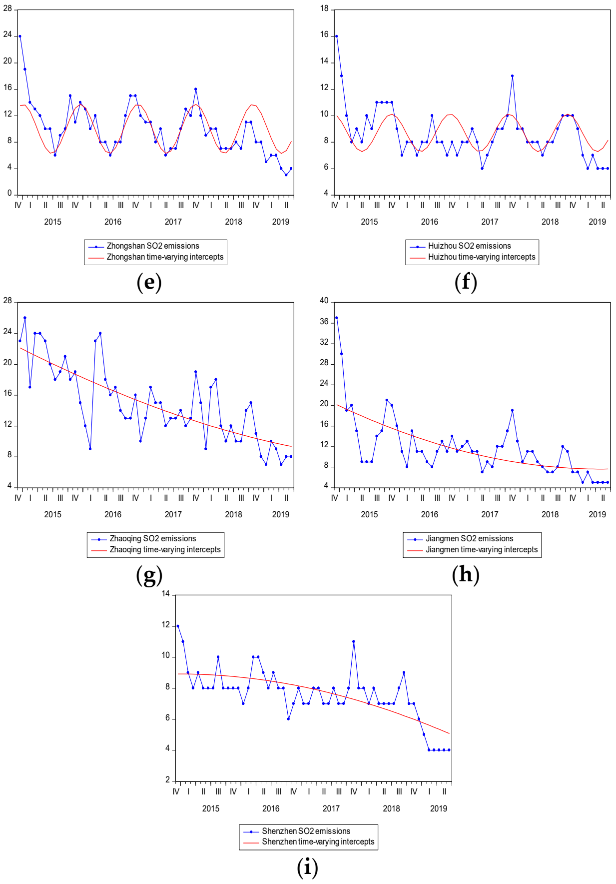
Figure 3. The plots of the SO_2 emissions per capita and fitted nonlinearities of Municipality-Chongqing.



(**a**) (**b**)

(**c**) (**d**)

Figure 4. *Cont.*

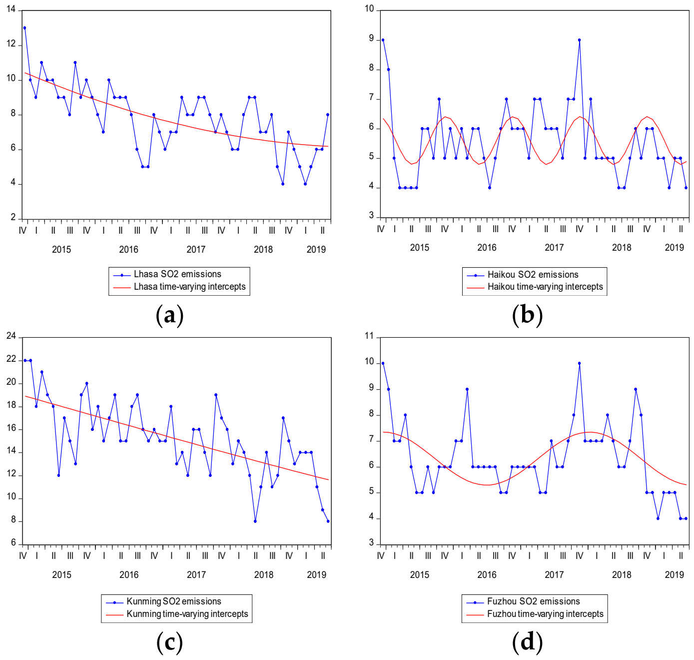


(**e**) (**f**)

(**g**) (**h**)

(**i**)

Figure 4. The plots of the SO_2 emissions per capita and fitted nonlinearities of Pearl River Delta. (**a**–**i**) respectively represent the plots of the SO2 emissions per capita and fitted nonlinearities of Guangzhou, Zhuhai, Foshan, Dongguan, Zhongshan, Huizhou, Zhaoqing, Jiangmen, and Shenzhen.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. *Cont.*

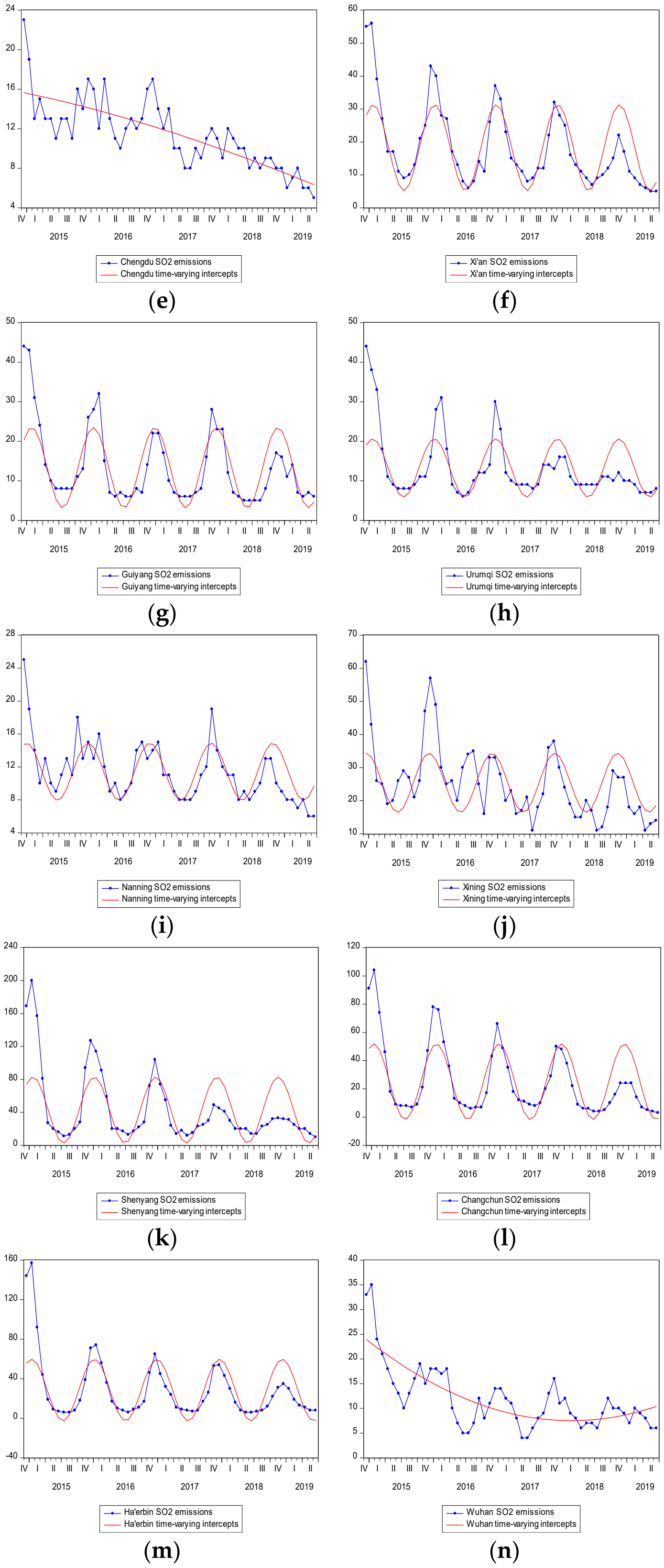
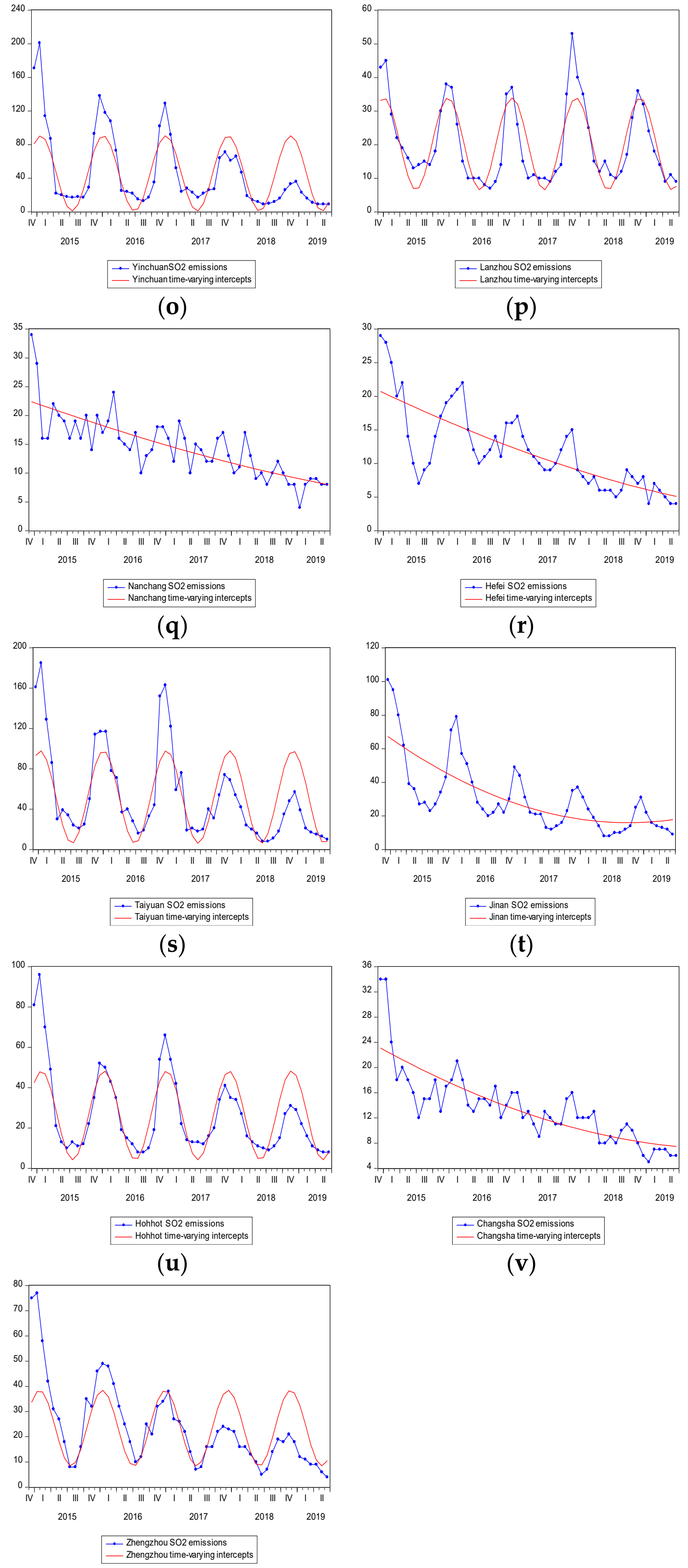


Figure 5. *Cont.*



(**o**) (**p**)

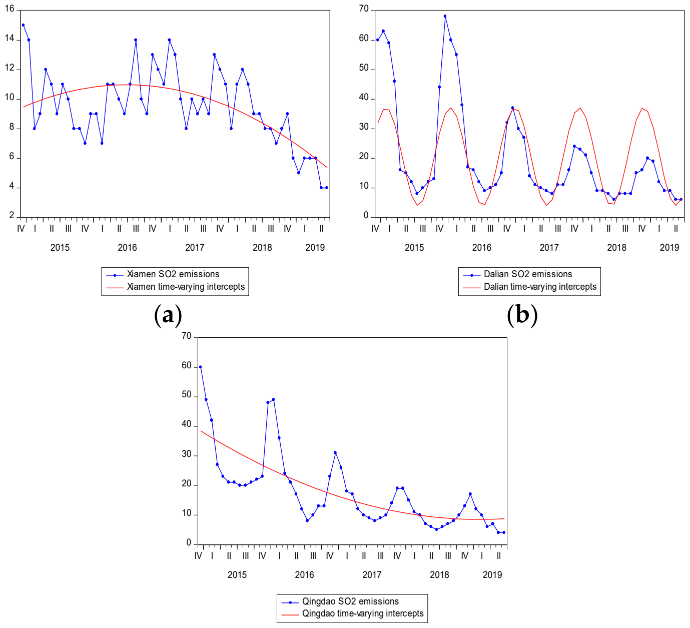
(**q**) (**r**)

(**s**) (**t**)

(**u**) (**v**)

(**w**)

Figure 5. The plots of the SO_2 emissions per capita and fitted nonlinearities of provincial capital cities. (**a**–**w**) respectively represent the plots of the SO2 emissions per capita and fitted nonlinearities of Lhasa, Haikou, Kunming, Fuzhou, Chengdu, Xi'an, Guiyang, Urumqi, Nanning, Xining, Shenyang, Changchun, Harbin, Wuhan, Yinchuan, Lanzhou, Nanchang, Hefei, Taiyuan, Ji'nan, Hohhot Changsha, and Zhengzhou.



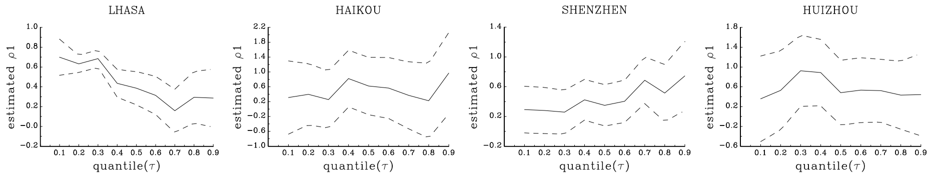
(**a**) (**b**)

(**c**)

Figure 6. The plots of the SO_2 emissions per capita and fitted nonlinearities of cities under separate state planning. (**a**–**c**) respectively represent the plots of the SO2 emissions per capita and fitted nonlinearities of Xiamen, Dalian, and Qingdao.

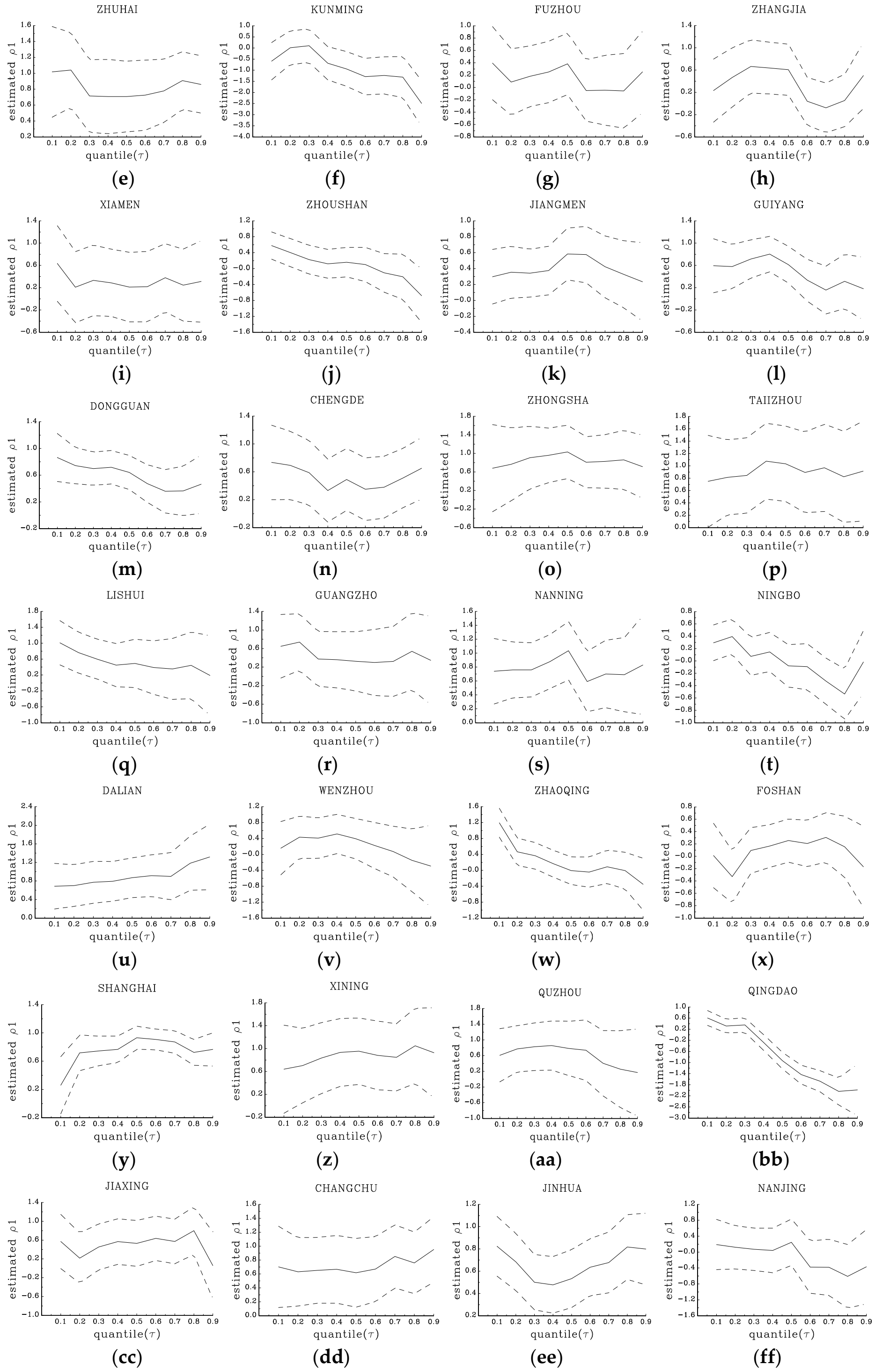
We first estimate the coefficients of the intercept $-\alpha_0(\tau)$ and autoregressive coefficient $-\rho_1(\tau)$, with the corresponding results reported in Table 5. Note that $\alpha_0(\tau)$ and $\rho_1(\tau)$ values are key indicators in determining the permanent/temporary effects of negative and positive shocks, $\alpha_0(\tau)$ refers to the size of the shocks on each quantile, while $\rho_1(\tau)$ plays a crucial role in deciding on the mean reversion of SO_2 emissions in each quantile.

To compare the degree of persistence among quantiles, we plot the aggressive coefficient $\rho_1(\tau)$ in Figure 7. In this figure, the solid line represents the values of $\rho_1(\tau)$ and dashed line represents a 95% confidence interval. Overall, we observe three types of patterns. First, the values of $\rho_1(\tau)$ for SO_2 emissions per capita series of Haikou, Shenzhen, Huizhou, Fuzhou, Ningbo, Qingdao, Jiaxing, Jinhua, and Ji'nan display concave or the straight-line upward patterns. The results indicate that the positive shocks to high quantiles of the SO_2 emissions per capita of these cities have a more persistent effect than negative shocks to low quantiles, indicating that the positive shocks to the long-run path of the urban–rural income gap will be unbound. The second type pattern can be approximated by the concave or the straight-line download pattern for Suqian and Kunming, which means positive shocks to the SO_2 emissions per capita have temporary effects while negative shocks have permanent effects for these two cities. In the third type pattern, the values of $\rho_1(\tau)$ for other cities display upward patterns in low quantiles and downward patterns in high quantiles. The results indicate that the high positive and negative shocks to SO_2 emissions per capita of these cities have a transitory effect.



(**a**) (**b**) (**c**) (**d**)

Figure 7. *Cont.*



(**e**) (**f**) (**g**) (**h**)

(**i**) (**j**) (**k**) (**l**)

(**m**) (**n**) (**o**) (**p**)

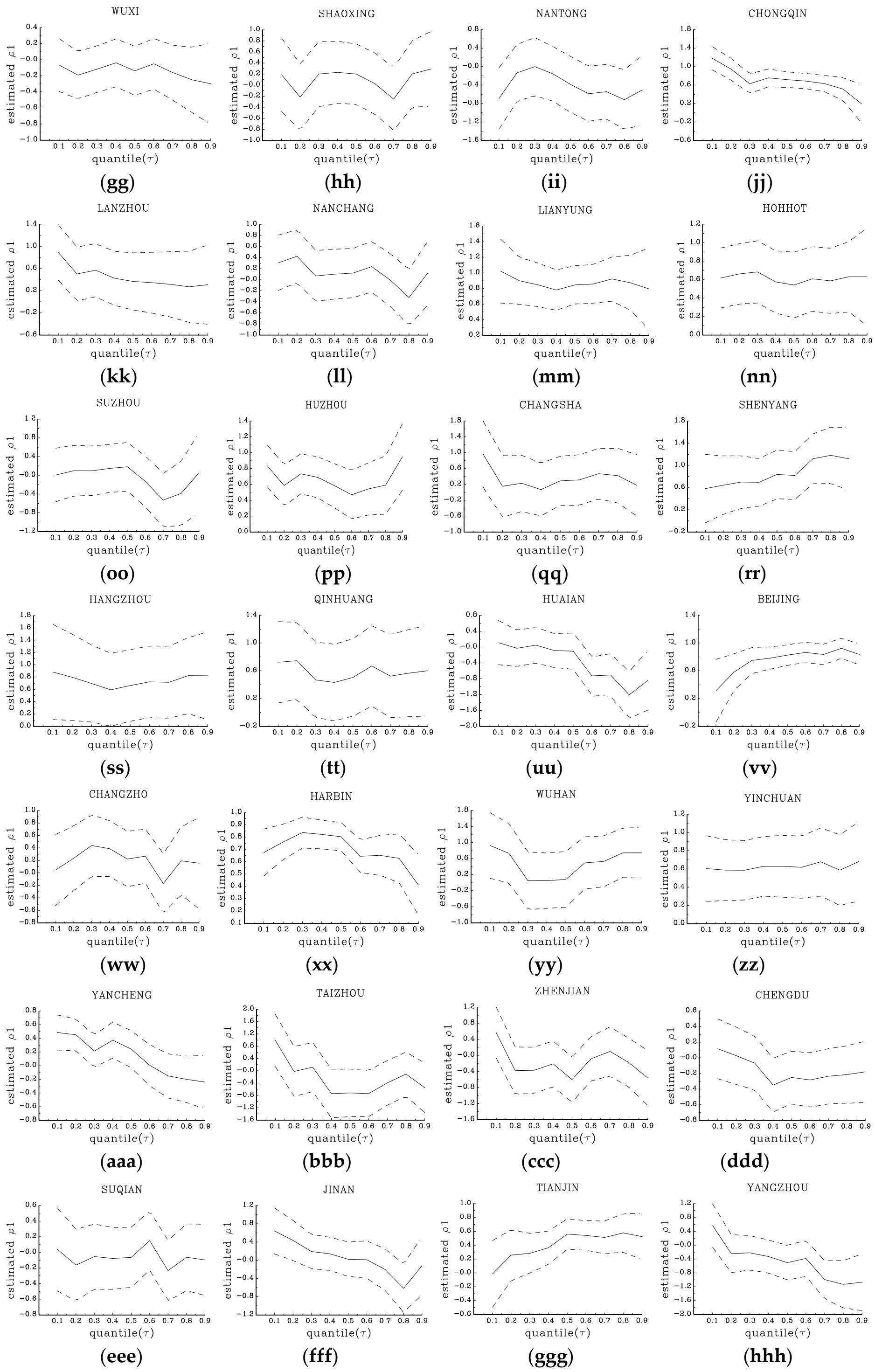
(**q**) (**r**) (**s**) (**t**)

(**u**) (**v**) (**w**) (**x**)

(**y**) (**z**) (**aa**) (**bb**)

(**cc**) (**dd**) (**ee**) (**ff**)

Figure 7. *Cont.*



(gg) **(hh)** **(ii)** **(jj)**

(kk) **(ll)** **(mm)** **(nn)**

(oo) **(pp)** **(qq)** **(rr)**

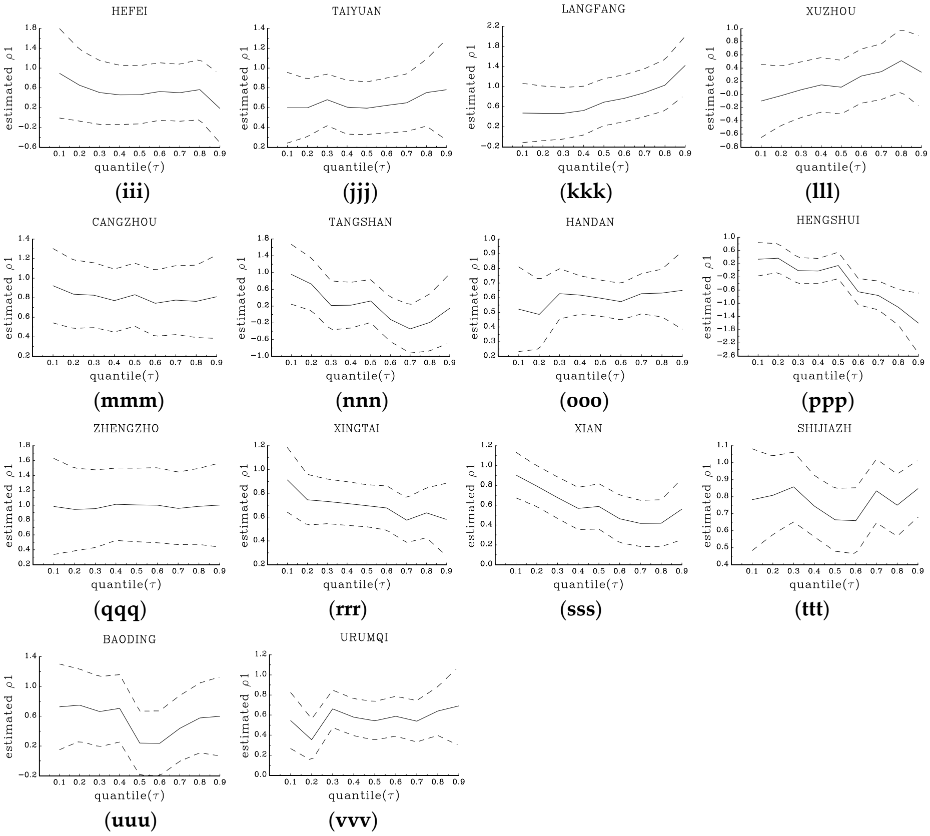
(ss) **(tt)** **(uu)** **(vv)**

(ww) **(xx)** **(yy)** **(zz)**

(aaa) **(bbb)** **(ccc)** **(ddd)**

(eee) **(fff)** **(ggg)** **(hhh)**

Figure 7. *Cont.*



(iii) **(jjj)** **(kkk)** **(lll)**

(mmm) **(nnn)** **(ooo)** **(ppp)**

(qqq) **(rrr)** **(sss)** **(ttt)**

(uuu) **(vvv)**

Figure 7. Autogressive coefficient $\rho_1(\tau)$. (**a**–**vvv**) respectively represent the autogressive coefficient of Lhasa, Haikou, Shenzhen, Huizhou, Zhuhai, Kunming, Fuzhou, Zhangjiakou, Xiamen, Zhoushan, Jiangmen, Guiyang, Dongguan, Chengde, Zhongshan, Táizhou, Lishui, Guangzhou, Nanning, Ningbo, Dalian, Wenzhou, Zhaoqing, Foshan, Shanghai, Xining, Quzhou, Qingdao, Jiaxing, Changchun, Jinhua, Nanjing, Wuxi, Shaoxing, Nantong, Chongqing, Lanzhou, Nanchang, Lianyungang, Hohhot, Suzhou, Huzhou, Changsha, Shenyang, Hangzhou, Qinhuangdao, Huaian, Beijing, Changzhou, Harbin, Wuhan, Yinchuan, Yancheng, Tàizhou, Zhenjiang, Chengdu, Suqian, Ji'nan, Tianjin, Yangzhou, Hefei, Taiyuan, Langfang, Xuzhou, Cangzhou, Tangshan, Handan, Hengshui, Zhengzhou, Xingtai, Xi'an, Shijiazhuang, Baoding, and Urumqi.

Table 5. Intercept—$\alpha_0(\tau)$ and autoregressive coefficient—$\rho_1(\tau)$.

Cities	τ	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
Beijing–Tianjin–Hebei Urban Agglomeration										
Beijing	$\alpha_0(\tau)$	−3.895 **	−2.173 ***	−1.468 ***	−0.957 **	−0.356	0.103	0.758 **	1.416 ***	1.993 ***
	$\rho_1(\tau)$	0.491 ***	0.599 ***	0.597 ***	0.639 ***	0.691 ***	0.729 ***	0.647 ***	0.599 ***	0.580 ***
Tianjin	$\alpha_0(\tau)$	−6.349 ***	−4.166 ***	−2.445 ***	−1.888 **	0.353	0.911 *	1.653 ***	2.407 ***	4.265 ***
	$\rho_1(\tau)$	0.701 ***	0.654 ***	0.662 ***	0.699 ***	0.639 ***	0.650 ***	0.609 ***	0.646 ***	0.514 ***
Zhangjiakou	$\alpha_0(\tau)$	−5.389 ***	−3.558 ***	−2.387 ***	−1.573 **	−0.348	0.150	1.177	2.776 ***	5.197 ***
	$\rho_1(\tau)$	0.615 **	0.662 ***	0.756 ***	0.725 ***	0.797 ***	0.828 **	0.829 *	0.801 **	0.563 ***
Chengde	$\alpha_0(\tau)$	−4.725 ***	−3.233 ***	−2.275 ***	−1.519 ***	−1.178 **	0.221	1.194 **	1.911 ***	3.375 ***
	$\rho_1(\tau)$	0.741 **	0.723 ***	0.609 ***	0.593 ***	0.589 ***	0.550 ***	0.526 ***	0.581 ***	0.526 ***
Qinhuangdao	$\alpha_0(\tau)$	−6.836 ***	−6.011 ***	−4.069 ***	−2.999 ***	−1.390*	0.118	1.871 **	2.635 ***	5.437 ***
	$\rho_1(\tau)$	0.714 ***	0.724 ***	0.657 ***	0.631 ***	0.594 ***	0.609 ***	0.630 ***	0.609 ***	0.676 **
Langfang	$\alpha_0(\tau)$	−6.214 ***	−3.348 ***	−1.805 **	−1.337 **	−0.722	−0.274	1.265 *	3.046 ***	3.746 ***
	$\rho_1(\tau)$	0.644 ***	0.638 ***	0.707 ***	0.730 ***	0.701 ***	0.694 ***	0.689 ***	0.755 **	0.805
Cangzhou	$\alpha_0(\tau)$	−7.181 ***	−5.402 ***	−4.145 ***	−2.558 **	−0.606	0.979	1.607 **	2.973 ***	6.390 ***
	$\rho_1(\tau)$	0.708 **	0.675 ***	0.647 ***	0.597 ***	0.629 ***	0.580 ***	0.572 ***	0.523 ***	0.650 ***
Tangshan	$\alpha_0(\tau)$	−11.385 ***	−6.315 ***	−3.173 **	−1.006	−0.015	1.121	2.256 **	3.919 ***	7.754 ***
	$\rho_1(\tau)$	0.612 **	0.526 ***	0.595 ***	0.619 ***	0.61 ***	0.638 ***	0.629 ***	0.639 ***	0.439 ***
Handan	$\alpha_0(\tau)$	−20.679 ***	−11.365 ***	−7.262 ***	−2.777 *	−1.177	0.598	4.748 ***	6.194 ***	10.815 **
	$\rho_1(\tau)$	0.522 ***	0.486 ***	0.627 ***	0.618 ***	0.597 ***	0.574 ***	0.627 ***	0.632 ***	0.651 **
Hengshui	$\alpha_0(\tau)$	−7.285 ***	−6.004 ***	−4.627 ***	−2.676 ***	−1.255 *	0.030	1.917 *	3.495 ***	6.990 ***
	$\rho_1(\tau)$	0.635 ***	0.651 ***	0.575 ***	0.577 ***	0.638 ***	0.692 ***	0.787 **	0.727 ***	0.617 ***
Xingtai	$\alpha_0(\tau)$	−14.876 ***	−11.235 ***	−6.421 ***	−3.568 **	−1.448	2.824 **	3.420 **	4.994 ***	10.098 ***
	$\rho_1(\tau)$	0.675 **	0.614 ***	0.704 ***	0.655 ***	0.614 ***	0.517 ***	0.524 ***	0.529 ***	0.591 ***
Shijiazhuang	$\alpha_0(\tau)$	−14.283 ***	−8.549 ***	−3.520 **	−2.569 **	−1.532	1.326	3.337 **	5.803 ***	11.716 ***
	$\rho_1(\tau)$	0.497 ***	0.577 ***	0.641 ***	0.611 ***	0.656 ***	0.665 ***	0.686 ***	0.725 ***	0.802 **

Table 5. *Cont.*

Cities	τ	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
Baoding	$\alpha_0(\tau)$	−12.584 ***	−8.933 ***	−5.448 ***	−2.003	−0.130	1.209	3.247 **	5.072 **	12.236 ***
	$\rho_1(\tau)$	0.669 ***	0.697 ***	0.738 ***	0.808 ***	0.797 ***	0.752 ***	0.734 ***	0.714 ***	0.647 ***
Yangtze River Delta										
Shanghai	$\alpha_0(\tau)$	−2.261 ***	−1.853 ***	−1.415 ***	−0.983 ***	−0.524 *	0.058	0.531	1.418 ***	2.234 ***
	$\rho_1(\tau)$	0.631 ***	0.677 ***	0.614 ***	0.592 ***	0.692 ***	0.724 ***	0.633 ***	0.481 ***	0.565 ***
Nanjing	$\alpha_0(\tau)$	−3.514 ***	−2.388 ***	−1.526 ***	−1.146 ***	−0.486	0.312	1.084 **	1.478 **	3.424 ***
	$\rho_1(\tau)$	0.647 **	0.512 ***	0.595 ***	0.624 ***	0.727 **	0.825	0.656 **	0.604 **	0.155 ***
Wuxi	$\alpha_0(\tau)$	−4.595 ***	−2.872 ***	−1.603 ***	−1.017 **	−0.408	0.098	0.814 *	1.826 ***	3.125 ***
	$\rho_1(\tau)$	0.352 ***	0.613 ***	0.547 ***	0.549 ***	0.624 ***	0.640 ***	0.514 ***	0.635 ***	0.697*
Nantong	$\alpha_0(\tau)$	−6.060 ***	−4.289 ***	−2.303 ***	−0.718	−0.064	0.491	1.391 ***	2.378 ***	4.946 ***
	$\rho_1(\tau)$	−0.377 ***	−0.005 ***	0.468 **	0.228 ***	0.236 ***	0.277 ***	0.238 ***	0.25 ***	0.071 ***
Lianyungang	$\alpha_0(\tau)$	−7.285 ***	−6.004 ***	−4.627 ***	−2.676 ***	−1.255 *	0.030	1.917 *	3.495 ***	6.99 ***
	$\rho_1(\tau)$	0.755 *	0.667 ***	0.729 ***	0.769 ***	0.756 ***	0.760 ***	0.741 ***	0.742 ***	0.662 ***
Suzhou	$\alpha_0(\tau)$	−3.589 ***	−2.442 ***	−1.316 ***	−0.662 *	−0.140	0.106	0.376	1.920 ***	2.907 ***
	$\rho_1(\tau)$	0.384 ***	0.451 ***	0.556 ***	0.562 ***	0.579 ***	0.562 ***	0.546 ***	0.708 **	0.677 *
Huaian	$\alpha_0(\tau)$	−3.018 ***	−2.272 ***	−1.766 ***	−1.480 ***	−0.665	−0.354	1.420 ***	2.379 ***	3.537 ***
	$\rho_1(\tau)$	0.558 ***	0.567 ***	0.620 ***	0.593 ***	0.585 ***	0.651 **	0.449 ***	0.524 ***	0.366 ***
Changzhou	$\alpha_0(\tau)$	−4.688 ***	−2.891 ***	−1.556 ***	−1.009 ***	−0.515	0.183	1.017 *	2.719 ***	4.598 ***
	$\rho_1(\tau)$	0.631*	0.505 ***	0.495 ***	0.475 ***	0.507 ***	0.480 ***	0.472 ***	0.324 ***	0.388 ***
Tàizhou	$\alpha_0(\tau)$	−4.021 ***	−3.096 ***	−1.847 ***	−1.163 **	−0.424	0.094	1.388 **	2.582 ***	3.910 ***
	$\rho_1(\tau)$	0.245 ***	0.379 ***	0.681 ***	0.554 ***	0.620 ***	0.633 ***	0.598 ***	0.419 ***	0.360 ***
Yancheng	$\alpha_0(\tau)$	−2.672 ***	−2.325 ***	−1.992 ***	−1.569 ***	−0.202	−0.087	0.687	2.492 ***	3.480 ***
	$\rho_1(\tau)$	0.534 ***	0.529 ***	0.567 ***	0.566 ***	0.682 ***	0.663 ***	0.533 ***	0.537 ***	0.312 ***
Suqian	$\alpha_0(\tau)$	−4.864 ***	−3.396 ***	−2.068 ***	−0.999	0.316	1.306 ***	1.427 ***	2.520 ***	4.080 ***
	$\rho_1(\tau)$	0.844	0.749 **	0.593 ***	0.644 ***	0.617 ***	0.629 ***	0.621 ***	0.494 ***	0.735 **
Zhenjiang	$\alpha_0(\tau)$	−4.262 ***	−2.242 ***	−1.561 ***	−0.866 *	0.027	0.416	1.416 ***	1.729 ***	2.882 ***
	$\rho_1(\tau)$	0.243 ***	0.556 **	0.526 ***	0.425 ***	0.34 ***	0.303 ***	0.448 ***	0.404 ***	0.242 ***
Yangzhou	$\alpha_0(\tau)$	−4.166 ***	−3.631 ***	−1.321 *	−0.760	−0.080	0.245	0.671	2.223 ***	4.721 ***
	$\rho_1(\tau)$	0.518 **	0.451 ***	0.356 ***	0.296 ***	0.370 ***	0.327 ***	0.265 ***	0.403 ***	0.520 *
Xuzhou	$\alpha_0(\tau)$	−6.634 ***	−3.091 ***	−2.352 ***	−2.143 ***	−0.728	0.357	1.476 **	2.485 **	6.965 ***
	$\rho_1(\tau)$	0.578 ***	0.628 ***	0.671 ***	0.685 ***	0.668 ***	0.522 ***	0.522 ***	0.588 ***	0.424 ***
Zhoushan	$\alpha_0(\tau)$	−1.796 ***	−1.012 ***	−0.739 ***	−0.476 ***	−0.213	0.073	0.284	0.624 **	1.491 ***
	$\rho_1(\tau)$	0.197 ***	0.355 ***	0.361 ***	0.511 ***	0.563 ***	0.644 ***	0.615 ***	0.561 ***	0.423 ***
Lishui	$\alpha_0(\tau)$	−2.948 ***	−1.551 ***	−0.936 ***	−0.535 **	−0.305 **	−0.070	0.494	1.129 ***	1.973 ***
	$\rho_1(\tau)$	0.065 ***	0.375 ***	0.487 ***	0.510 ***	0.493 ***	0.417 ***	0.458 ***	0.542 ***	0.403 ***
Ningbo	$\alpha_0(\tau)$	−2.599 ***	−1.508 ***	−1.299 ***	−0.850 ***	−0.324	0.189	0.636 **	1.030 ***	2.261 ***
	$\rho_1(\tau)$	0.315 ***	0.573 ***	0.538 ***	0.598 ***	0.578 ***	0.449 ***	0.472 ***	0.505 ***	0.806
Wenzhou	$\alpha_0(\tau)$	−4.207 ***	−1.840 ***	−1.056 **	−0.755 *	−0.148	0.183	0.867 ***	1.557 ***	3.457 ***
	$\rho_1(\tau)$	−0.180 ***	0.175 ***	0.374 ***	0.430 ***	0.355 ***	0.314 ***	0.197 ***	0.05 ***	−0.262 ***
Quzhou	$\alpha_0(\tau)$	−4.441 ***	−3.018 ***	−2.391 ***	−1.338 ***	−0.993 **	0.619	1.638 ***	2.631 ***	3.276 ***
	$\rho_1(\tau)$	−0.287 ***	0.077 ***	−0.027 ***	0.420 ***	0.409 ***	0.069 ***	0.212 ***	0.303 ***	0.280 ***
Jiaxing	$\alpha_0(\tau)$	−4.853 ***	−3.111 ***	−1.468 **	−0.756 *	−0.198	0.355	1.175 ***	1.621 ***	3.022 ***
	$\rho_1(\tau)$	0.259 ***	0.585 ***	0.572 ***	0.602 ***	0.592 ***	0.596 ***	0.583 ***	0.637 ***	0.809
Jinhua	$\alpha_0(\tau)$	−5.475 ***	−2.969 ***	−2.266 ***	−0.928 **	−0.494	0.134	1.088 *	2.420 ***	4.250 ***
	$\rho_1(\tau)$	−0.15 ***	0.095 ***	0.303 ***	0.432 ***	0.414 ***	0.394 ***	0.573 ***	0.578 ***	0.947
Huzhou	$\alpha_0(\tau)$	−4.768 ***	−3.213 ***	−2.02 ***	−1.215 ***	−0.558	0.164	1.200 **	2.002 ***	3.615 ***
	$\rho_1(\tau)$	0.499 **	0.533 ***	0.538 ***	0.428 ***	0.327 ***	0.363 ***	0.477 ***	0.41 ***	0.223 ***
Hangzhou	$\alpha_0(\tau)$	−2.584 ***	−1.997 ***	−0.833 **	−0.597 **	−0.237	0.173	0.876 ***	1.485 ***	2.256 ***
	$\rho_1(\tau)$	0.336 ***	0.457 ***	0.573 ***	0.586 ***	0.607 ***	0.652 ***	0.693 ***	0.566 ***	0.694 *
Shaoxing	$\alpha_0(\tau)$	−4.377 ***	−3.228 ***	−1.99 ***	−1.32 **	−0.386	0.447	1.128 ***	1.447 ***	3.420 ***
	$\rho_1(\tau)$	0.355 ***	0.401 ***	0.512 ***	0.576 ***	0.52 ***	0.277 ***	0.345 ***	0.333 ***	0.346 ***
Táizhou	$\alpha_0(\tau)$	−1.971 ***	−1.520 ***	−0.923 ***	−0.652 ***	−0.261	0.093	0.421 *	1.135 ***	1.792 ***
	$\rho_1(\tau)$	0.278 ***	0.443 ***	0.691 ***	0.656 ***	0.599 ***	0.544 ***	0.516 ***	0.594 ***	0.616 **
Pearl River Delta										
Guangzhou	$\alpha_0(\tau)$	−2.567 ***	−1.541 ***	−1.069 ***	−0.649 ***	−0.163	0.058	0.451 *	1.213 ***	2.022 ***
	$\rho_1(\tau)$	0.167 ***	0.109 ***	0.178 ***	0.095 ***	0.132 ***	0.072 ***	0.111 ***	0.212 ***	0.367 ***
Shenzhen	$\alpha_0(\tau)$	−0.951 ***	−0.799 ***	−0.613 ***	−0.439 ***	−0.343 **	0.097	0.312 *	0.564 ***	1.095 ***
	$\rho_1(\tau)$	0.474 ***	0.425 ***	0.383 ***	0.479 ***	0.470 ***	0.576 ***	0.574 ***	0.501 ***	1.013
Zhuhai	$\alpha_0(\tau)$	−1.802 ***	−1.384 ***	−0.967 ***	−0.391 *	0.064	0.408 **	0.523 **	1.271 ***	1.758 ***
	$\rho_1(\tau)$	0.521 ***	0.481 ***	0.488 ***	0.517 ***	0.561 ***	0.648 ***	0.659 ***	0.672 **	0.451 ***
Foshan	$\alpha_0(\tau)$	−3.109 ***	−2.610 ***	−1.565 ***	−0.505	−0.272	−0.009	0.942 **	1.237 ***	2.418 ***
	$\rho_1(\tau)$	−0.129 ***	0.016 ***	0.049 ***	0.279 ***	0.359 ***	0.326 ***	0.419 ***	0.427 ***	0.563 *
Jiangmen	$\alpha_0(\tau)$	−3.535 ***	−2.809 ***	−2.096 ***	−1.145 **	−0.747 *	0.525	0.954 **	1.594 **	3.832 ***
	$\rho_1(\tau)$	0.473 ***	0.492 ***	0.514 ***	0.484 ***	0.436 ***	0.411 ***	0.458 ***	0.532 ***	0.73 *
Dongguan	$\alpha_0(\tau)$	−2.202 ***	−1.819 ***	−1.338 ***	−0.728 **	−0.175	0.146	0.682 **	1.207 ***	1.739 ***
	$\rho_1(\tau)$	0.420 ***	0.409 ***	0.493 ***	0.590 ***	0.501 ***	0.453 ***	0.307 ***	0.244 ***	0.363 ***
Zhongshan	$\alpha_0(\tau)$	−2.599 ***	−1.953 ***	−1.261 ***	−0.716 **	−0.289	0.166	0.910 **	1.309 ***	2.372 ***
	$\rho_1(\tau)$	0.587 **	0.593 **	0.651 **	0.616 ***	0.621 ***	0.551 ***	0.654 **	0.654 **	0.433 **
Huizhou	$\alpha_0(\tau)$	−1.593 ***	−1.020 ***	−0.701 ***	−0.405 **	−0.034	0.227 **	0.333 ***	0.477 ***	1.412 ***
	$\rho_1(\tau)$	0.353 ***	0.637 ***	0.546 ***	0.552 ***	0.538 ***	0.521 ***	0.527 ***	0.502 ***	0.857
Zhaoqing	$\alpha_0(\tau)$	−3.788 ***	−1.768 ***	−1.518 ***	−0.709 *	0.272	0.514 *	0.923 ***	1.671 ***	3.435 ***
	$\rho_1(\tau)$	0.489 ***	0.306 ***	0.263 ***	−0.132 ***	0.033 ***	−0.005 ***	−0.064 ***	−0.179 ***	0.339 ***

Table 5. *Cont.*

Cities	τ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Municipality										
Chongqing	$\alpha_0(\tau)$	−2.920 ***	−1.251 ***	−0.954 ***	−0.607 ***	−0.391	0.107	0.497 *	1.062 **	2.354 ***
	$\rho_1(\tau)$	0.342 ***	0.593 ***	0.636 ***	0.606 ***	0.657 ***	0.509 ***	0.489 ***	0.545 ***	0.511 **
Provincial capital cities										
Lhasa	$\alpha_0(\tau)$	−1.367 ***	−1.073 ***	−0.861 ***	−0.406 **	−0.276 *	0.160	0.626 **	1.340 ***	1.722 ***
	$\rho_1(\tau)$	0.699 **	0.632 **	0.684 **	0.435 ***	0.385 ***	0.313 ***	0.158 ***	0.295 ***	0.286 ***
Haikou	$\alpha_0(\tau)$	−1.220 ***	−0.957 ***	−0.774 ***	−0.450	−0.198	0.188	0.419 **	0.626 ***	1.133 ***
	$\rho_1(\tau)$	−0.017 ***	−0.048 ***	−0.027 ***	0.168 ***	0.289 ***	0.505 **	0.417 ***	0.452 ***	0.977
Kunming	$\alpha_0(\tau)$	−2.620 ***	−2.259 ***	−1.502 ***	−0.456	0.002	0.474	1.548 ***	1.772 ***	2.606 ***
	$\rho_1(\tau)$	0.579	0.505 **	0.275 ***	−0.050 ***	−0.079 ***	0.039 ***	0.016 ***	0.054 ***	−0.119 ***
Fuzhou	$\alpha_0(\tau)$	−1.244 ***	−0.960 ***	−0.634 ***	−0.198	−0.083	0.094	0.349 ***	0.679 ***	1.151 ***
	$\rho_1(\tau)$	0.274 ***	0.401 ***	0.354 ***	0.515 ***	0.659 ***	0.592 ***	0.520 ***	0.575 ***	0.982
Chengdu	$\alpha_0(\tau)$	−2.367 ***	−1.587 ***	−1.180 ***	−0.786 **	−0.113	0.386 *	0.638 ***	1.074 **	2.254 ***
	$\rho_1(\tau)$	0.359 ***	0.446 ***	0.400 ***	0.459 ***	0.429 ***	0.419 ***	0.385 ***	0.326 ***	0.183 ***
Xi’an	$\alpha_0(\tau)$	−5.653 ***	−4.220 ***	−1.762 **	−1.169 ***	−0.679 *	0.151	1.040 *	2.106 ***	3.409 ***
	$\rho_1(\tau)$	0.599 **	0.612 ***	0.512 ***	0.542 ***	0.523 ***	0.470 ***	0.388 ***	0.302 ***	0.355 ***
Guiyang	$\alpha_0(\tau)$	−5.629 ***	−3.194 ***	−2.275 ***	−1.467 **	−0.223	0.419	1.392 ***	2.139 ***	2.955 ***
	$\rho_1(\tau)$	0.407 ***	0.566 ***	0.538 ***	0.510 ***	0.470 ***	0.432 ***	0.448 ***	0.381 ***	0.348 ***
Urumqi	$\alpha_0(\tau)$	−4.522 ***	−3.654 ***	−1.325 **	−1.101 **	−0.388	0.462	0.914 ***	1.648 ***	2.256
	$\rho_1(\tau)$	0.474 ***	0.417 ***	0.550 ***	0.533 ***	0.621 ***	0.552 ***	0.578 ***	0.744 ***	0.744
Nanning	$\alpha_0(\tau)$	−2.283 ***	−1.711 ***	−1.41 ***	−0.986 ***	−0.446 *	−0.005	0.474	1.185	2.615 ***
	$\rho_1(\tau)$	0.488 ***	0.450 ***	0.495 ***	0.509 ***	0.440 ***	0.413 ***	0.366 ***	0.296 ***	0.157 ***
Xining	$\alpha_0(\tau)$	−7.846 ***	−5.151 ***	−3.787 ***	−2.762 ***	−0.948	0.931	2.837 ***	4.156 ***	6.816 ***
	$\rho_1(\tau)$	0.541 ***	0.433 ***	0.396 ***	0.479 ***	0.542 ***	0.613 ***	0.625 ***	0.538 ***	0.385 ***
Shenyang	$\alpha_0(\tau)$	−14.438 ***	−10.199 ***	−7.654 ***	−6.133 ***	−4.659 ***	−1.774	1.842	6.919 ***	14.989 ***
	$\rho_1(\tau)$	0.678 ***	0.641 ***	0.619 ***	0.603 ***	0.609 ***	0.579 ***	0.560 ***	0.506 ***	0.479 ***
Changchun	$\alpha_0(\tau)$	−10.151 ***	−7.356 ***	−4.499 ***	−2.756 ***	−2.278 **	−0.001	2.339*	4.384 ***	8.613 ***
	$\rho_1(\tau)$	0.669 ***	0.659 ***	0.593 ***	0.592 ***	0.577 ***	0.461 ***	0.484 ***	0.480 ***	0.486 ***
Harbin	$\alpha_0(\tau)$	−11.739 ***	−9.598 ***	−4.847 ***	−3.252 **	−0.85	0.244	3.349 ***	4.392 ***	5.679 ***
	$\rho_1(\tau)$	0.470 ***	0.507 ***	0.538 ***	0.589 ***	0.510 ***	0.496 ***	0.465 ***	0.415 ***	0.329 ***
Wuhan	$\alpha_0(\tau)$	−3.777 ***	−2.607 ***	−1.693 ***	−1.141 **	−0.175	0.579	0.982 **	2.327 ***	2.983 ***
	$\rho_1(\tau)$	0.430 ***	0.676 ***	0.583 ***	0.495 ***	0.635 ***	0.640 ***	0.638 ***	0.764 *	0.813 *
Yinchuan	$\alpha_0(\tau)$	−22.699 ***	−14.753 ***	−10.862 ***	−8.093 ***	−3.529	−1.062	7.217 **	10.43 ***	18.557 ***
	$\rho_1(\tau)$	0.446 ***	0.662 ***	0.652 ***	0.626 ***	0.603 ***	0.528 ***	0.579 ***	0.594 ***	0.53 ***
Lanzhou	$\alpha_0(\tau)$	−5.699 ***	−3.987 ***	−2.576 ***	−1.838 ***	−1.227 **	−0.016	1.702 **	2.886 ***	5.694 ***
	$\rho_1(\tau)$	0.250 ***	0.167 ***	0.061 ***	0.127 ***	0.130 ***	0.305 ***	0.303 ***	0.359 ***	0.178 ***
Nanchang	$\alpha_0(\tau)$	−4.104 ***	−2.712 ***	−1.334 ***	−0.65*	−0.206	0.271	0.570	1.822 ***	3.115 ***
	$\rho_1(\tau)$	−0.127 ***	−0.101 ***	−0.086 ***	−0.115 ***	−0.13 ***	−0.102 ***	−0.077 ***	−0.243 ***	−0.569 ***
Hefei	$\alpha_0(\tau)$	−3.387 ***	−1.632 ***	−0.888 **	−0.426	−0.066	0.457	1.229 ***	1.573 ***	2.593 ***
	$\rho_1(\tau)$	0.544 **	0.613 ***	0.644 ***	0.67 ***	0.696 ***	0.718 ***	0.813 *	0.827 *	0.763 **
Taiyuan	$\alpha_0(\tau)$	−19.09 ***	−16.517 ***	−13.061 ***	−7.071 ***	−5.128 **	0.347	2.552	8.722 **	24.697 ***
	$\rho_1(\tau)$	0.580 ***	0.566 ***	0.617 ***	0.618 ***	0.638 ***	0.570 ***	0.615 ***	0.562 ***	0.111 ***
Ji’nan	$\alpha_0(\tau)$	−7.89 ***	−4.715 ***	−3.252 ***	−1.155 *	−0.366	0.549	0.986 *	1.292	8.675 ***
	$\rho_1(\tau)$	0.783 **	0.652 ***	0.623 ***	0.681 ***	0.658 ***	0.691 ***	0.678 ***	0.675 ***	0.895
Hohhot	$\alpha_0(\tau)$	−7.422 ***	−5.408 ***	−4.193 ***	−3.018 ***	−2.014 **	−0.025	2.221 **	3.253 ***	5.526 ***
	$\rho_1(\tau)$	0.554 ***	0.516 ***	0.465 ***	0.508 ***	0.538 ***	0.535 ***	0.61 ***	0.577 ***	0.473 ***
Changsha	$\alpha_0(\tau)$	−2.982 ***	−1.882 ***	−1.310 ***	−0.860 **	−0.28	0.228	0.897 **	1.632 ***	2.561 ***
	$\rho_1(\tau)$	0.404 ***	0.318 ***	0.265 ***	0.362 ***	0.317 ***	0.249 ***	0.495 ***	0.434 ***	0.360 ***
Zhengzhou	$\alpha_0(\tau)$	−6.349 ***	−4.166 ***	−2.445 ***	−1.888 **	0.353	0.911 *	1.653 ***	2.407 ***	4.265 ***
	$\rho_1(\tau)$	0.695 ***	0.685 ***	0.683 ***	0.856 **	0.801 **	0.855*	0.760 ***	0.729 ***	0.752 **
Cities under separate state planning										
Xiamen	$\alpha_0(\tau)$	−6.349 ***	−4.166 ***	−2.445 ***	−1.888 **	0.353	0.911*	1.653 ***	2.407 ***	4.265 ***
	$\rho_1(\tau)$	0.148 ***	0.217 ***	0.139 ***	0.197 ***	0.337 ***	0.154 ***	0.243 ***	0.166 ***	−0.146 ***
Dalian	$\alpha_0(\tau)$	−7.389 ***	−4.762 ***	−3.17 ***	−2.273 ***	−1.375 **	−0.702	1.407	4.213 ***	5.294 **
	$\rho_1(\tau)$	0.633 ***	0.621 ***	0.714 ***	0.698 ***	0.752 ***	0.722 ***	0.810 **	0.693 ***	0.670 *
Qingdao	$\alpha_0(\tau)$	−4.180 ***	−2.814 ***	−2.442 ***	−1.638 ***	−0.649 *	−0.239	0.442	2.310 ***	3.529 **
	$\rho_1(\tau)$	0.625 ***	0.645 ***	0.644 ***	0.647 ***	0.649 ***	0.686 ***	0.752 ***	0.839*	0.923

***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 6 reports $t_n(\tau_i)$, which are used to measure the degree of persistence in each quantile. We can clearly observe that at quantiles between 0.2 and 0.7, the statistic $t_n(\tau_i)$ is converging for 62 cities. However, at the extremely low quantile of 0.1, $t_n(\tau_i)$ cannot be rejected for Tianjin, Zhangjiakou, Chengde, Tangshan, Xingtai, Shanghai, Nanjing, Lianyungang, Changzhou, Yancheng, Suqian, Yangzhou, Zhuhai, Dongguan, Zhongshan, Zhaoqing, Chongqing, Kunming, Xi’an, Hefei, and Jinan, which means that the SO_2 emissions per capita in these 21 cities are divergent when the emissions are high. At the extremely high quantile of 0.9, the SO_2 emissions per capita are stationary for 33 cities. These results clearly show that the impact of external changes on SO_2 emissions per capita is non-linear and asymmetric and that there is more evidence to support the fact that it is more efficient when using the Fourier function in the model.

Table 6. Results for Fourier quantile unit root at particular quantiles.

Quantiles	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
Beijing–Tianjin–Hebei Urban Agglomeration									
Beijing	−4.431 ***	−3.271 ***	−3.737 ***	−3.477 ***	−3.494 ***	−2.993 **	−3.804 ***	−2.275 *	−2.192 *
Tianjin	−1.792	−2.176*	−3.486 ***	−4.336 ***	−4.995 ***	−6.152 ***	−6.389 ***	−2.676 **	−3.072 **
Zhangjiakou	−1.455	−1.751	−2.334 **	−3.408 ***	−2.264 **	−1.657	−1.554	−1.166	−1.815
Chengde	−2.104	−2.284 *	−3.933 ***	−3.476 ***	−3.858 ***	−4.152 ***	−4.027 ***	−3.220 ***	−3.189 **
Qinhuangdao	−3.920 ***	−2.846 **	−3.838 ***	−3.665 ***	−3.707 ***	−3.424 ***	−2.369 *	−2.065	−1.660
Langfang	−3.039 **	−2.926 **	−3.041 **	−3.258 ***	−3.405 ***	−3.639 ***	−3.253 ***	−1.656	−1.343
Cangzhou	−2.384 *	−2.306 *	−3.000 **	−4.256 ***	−3.755 ***	−4.407 ***	−3.947 ***	−4.273 ***	−2.579 *
Tangshan	−1.963	−2.405 *	−2.143 *	−2.209 *	−3.126 ***	−3.237 ***	−2.711 **	−1.957	−2.401 *
Handan	−2.615 **	−3.395 ***	−2.633 **	−3.772 ***	−4.095 ***	−4.523 ***	−3.969 ***	−1.637	−1.121
Hengshui	−5.771 ***	−5.049 ***	−5.887 ***	−4.646 ***	−4.101 ***	−3.560 ***	−2.051 *	−1.504	−0.967
Xingtai	−1.657	−3.367 ***	−2.715 **	−3.198 ***	−4.359 ***	−5.634 ***	−5.998 ***	−6.918 ***	−1.025
Shijiazhuang	−2.594 *	−2.357 **	−2.958 **	−3.489 ***	−3.414 ***	−3.707 ***	−2.735 **	−2.552 **	−1.798
Baoding	−4.118 ***	−2.980 **	−3.093 **	−2.277 *	−2.717 **	−2.956 **	−2.563 **	−2.217 *	−2.490 *
Yangtze River Delta									
Shanghai	−1.588	−3.965 ***	−4.744 ***	−4.276 ***	−2.743 **	−2.164 *	−3.032 **	−3.135 ***	−1.012
Nanjing	−1.974	−2.877 **	−3.037 **	−2.934 **	−2.100 *	−0.932	−1.864 *	−1.660	−2.972 *
Wuxi	−3.113 **	−2.655 **	−3.104 ***	−4.017 ***	−3.148 ***	−2.857 **	−3.066 ***	−1.095	−0.798
Nantong	−5.365 ***	−2.858 **	−2.065 *	−2.906 **	−3.299 ***	−4.075 ***	−3.517 ***	−2.597 **	−3.406 **
Lianyungang	−1.149	−2.553 **	−2.318 **	−3.214 ***	−3.126 **	−2.559 **	−2.681 **	−2.517 **	−0.971
Suzhou	−2.771 **	−4.425 ***	−3.179 ***	−3.855 ***	−3.261 ***	−3.925 ***	−3.157 ***	−1.611	−0.753
Huaian	−1.963*	−2.950 **	−3.445 ***	−3.023 **	−2.874 **	−2.355*	−3.171 ***	−2.337 *	−1.993
Changzhou	−1.025	−1.999 *	−3.275 ***	−4.541 ***	−4.067 ***	−3.817 ***	−3.531 ***	−2.461 **	−1.565
Tàizhou	−2.000 *	−4.374 ***	−2.504 **	−3.346 ***	−2.514 **	−2.468 **	−2.467 *	−3.473 ***	−2.671 **
Yancheng	−1.584	−4.341 ***	−4.339 ***	−3.880 ***	−2.110	−2.052	−2.824 **	−2.519 **	−3.229 **
Suqian	−0.815	−1.684	−2.934 **	−2.824 **	−3.120 **	−2.914 **	−3.679 ***	−5.163 ***	−1.267
Zhenjiang	−3.759 ***	−2.375*	−2.490 **	−2.910 **	−4.897 ***	−4.397 ***	−4.157 ***	−2.663 **	−2.858 **
Yangzhou	−1.890	−2.366 *	−3.512 ***	−4.960 ***	−3.608 ***	−3.986 ***	−4.269 ***	−2.519 **	−1.030
Xuzhou	−2.108 *	−2.414 **	−2.660 **	−2.473 **	−3.735 ***	−5.057 ***	−3.128 ***	−1.731	−2.120
Zhoushan	−3.741 ***	−4.082 ***	−4.145 ***	−4.317 ***	−4.024 ***	−2.339 **	−2.245 *	−1.810	−1.553
Lishui	−3.595 **	−2.676 **	−2.633 **	−3.100 ***	−3.990 ***	−4.136 ***	−3.545 ***	−2.350 **	−2.996 **
Ningbo	−3.736 **	−2.980 **	−2.968 **	−2.778 **	−3.871 ***	−3.965 ***	−3.569 ***	−2.639 **	−0.600
Wenzhou	−3.109 **	−2.816 **	−2.877 **	−3.226 ***	−4.668 ***	−4.047 ***	−4.364 ***	−3.640 ***	−4.837 ***
Quzhou	−6.526 ***	−4.819 ***	−5.251 ***	−2.836 **	−2.880 **	−4.890 ***	−3.953 ***	−3.393 ***	−3.729 ***
Jiaxing	−2.343 *	−1.994 *	−3.003 ***	−3.625 ***	−3.658 ***	−3.793 ***	−4.052 ***	−3.245 ***	−0.396
Jinhua	−5.078 ***	−4.466 ***	−4.264 ***	−3.421 ***	−4.130 ***	−4.673 ***	−2.516 **	−2.201 *	−0.271
Huzhou	−2.374 *	−2.002 *	−2.299 *	−3.767 ***	−4.522 ***	−4.303 ***	−3.126 ***	−1.984	−1.850
Hangzhou	−2.874 **	−3.534 ***	−3.045 **	−2.861 **	−2.741 **	−2.782 **	−2.308 *	−3.116 **	−1.498
Shaoxing	−2.747 **	−2.561 **	−2.134 **	−3.079 **	−3.858 ***	−4.830 ***	−4.303 ***	−2.959 **	−1.367
Táizhou	−3.735 ***	−3.460 ***	−2.353 **	−2.617 **	−3.202 ***	−2.964 **	−3.126 **	−1.606	−1.550
Pearl River Delta									
Guangzhou	−3.012 **	−3.991 ***	−4.614 ***	−5.417 ***	−5.302 ***	−6.002 ***	−4.105 ***	−3.747 ***	−1.347
Shenzhen	−2.153 *	−4.308 ***	−7.644 ***	−4.326 ***	−4.198 ***	−2.425 **	−2.448 *	−2.233 *	0.031
Zhuhai	−1.551	−2.860 **	−3.493 ***	−3.533 ***	−3.529 ***	−2.295 *	−2.443 *	−2.512 **	−4.548 ***
Foshan	−4.444 ***	−4.717 ***	−5.051 ***	−4.960 ***	−4.104 ***	−4.972 ***	−3.125 ***	−1.530	−0.987
Jiangmen	−3.066 **	−3.658 ***	−3.357 ***	−3.963 ***	−4.340 ***	−3.716 ***	−3.093 ***	−2.177 *	−1.088
Dongguan	−1.788	−2.838 **	−2.968 **	−2.966 **	−3.170 ***	−3.414 ***	−3.953 ***	−2.975 **	−2.438*
Zhongshan	−2.165	−1.994	−2.015	−2.298 *	−2.241 *	−2.678 **	−1.802	−1.648	−3.293 **
Huizhou	−3.648 ***	−2.158 *	−2.849 **	−3.160 ***	−4.163 ***	−3.686 ***	−3.491 ***	−3.225 ***	−0.379
Zhaoqing	−1.276	−2.482 **	−3.125 ***	−4.606 ***	−6.966 ***	−4.288 ***	−4.505 ***	−3.274 **	−3.464 **
Municipality									
Chongqing	−2.029	−1.866 *	−1.912 *	−3.249 ***	−3.300 ***	−3.290 ***	−3.261 ***	−1.977	−1.487
Provincial capital cities									
Lhasa	−1.646 *	−2.143 **	−1.985 **	−3.441 ***	−2.940 **	−3.140 ***	−3.740 ***	−3.868 ***	5.554 ***
Haikou	−8.688 ***	−6.417 ***	−5.434 ***	−3.652 ***	−3.344 ***	−2.061	−2.331*	−1.692	−0.057
Kunming	−0.943	−1.769	−3.106 **	−4.492 ***	−4.126 ***	−3.907 ***	−4.379 ***	−3.282 ***	−4.063 ***
Fuzhou	−5.844 ***	−3.291 ***	−4.203 ***	−3.038 **	−2.383 **	−2.482 **	−2.200	−1.659	−0.059
Chengdu	−3.663 ***	−3.027 **	−3.287 ***	−3.365 ***	−4.284 ***	−3.181 ***	−2.939 **	−3.136 **	−2.692 **
Xi’an	−1.853	−2.434 **	−4.252 ***	−4.296 ***	−4.063 ***	−6.378 ***	−4.492 ***	−5.009 ***	−1.820
Guiyang	−3.091 **	−3.001 **	−3.064 ***	−3.649 ***	−4.248 ***	−4.476 ***	−4.717 ***	−3.549 ***	−2.650*
Urumqi	−5.919 ***	−4.259 ***	−3.797 ***	−3.787 ***	−3.237 ***	−5.535 ***	−4.766 ***	−0.943	−0.601
Nanning	−2.634 **	−3.875 ***	−4.503 ***	−4.073 ***	−4.140 ***	−3.673 ***	−3.105 **	−3.200 ***	−2.547 **
Xining	−2.878 **	−4.882 ***	−4.406 ***	−3.397 ***	−3.187 ***	−2.407 *	−1.887	−2.747 **	−2.175 *
Shenyang	−3.119 **	−3.920 ***	−5.963 ***	−7.012 ***	−5.409 ***	−5.491 ***	−4.107 ***	−4.181 ***	−2.139 ***
Changchun	−4.222 ***	−3.361 ***	−4.842 ***	−4.664 ***	−4.372 ***	−5.844 ***	−4.496 ***	−3.142 **	−3.766 **
Harbin	−7.021 ***	−6.353 ***	−5.377 ***	−4.720 ***	−5.555 ***	−7.051 ***	−8.833 ***	−11.338 ***	−5.662 ***
Wuhan	−3.593 **	−2.346 **	−2.881 ***	−3.556 ***	−2.372 *	−2.495	−2.294	−1.585	−1.578
Yinchuan	−5.568 ***	−2.886 **	−2.875 **	−3.002 **	−3.638 ***	−3.667 ***	−3.143 **	−2.388 **	−2.606*
Lanzhou	−5.398 ***	−5.548 ***	−6.695 ***	−6.973 ***	−5.670 ***	−4.467 ***	−3.204 ***	−2.148 *	−2.225 *
Nanchang	−3.521 **	−3.788 ***	−4.615 ***	−6.417 ***	−5.654 ***	−6.634 ***	−4.305 ***	−4.119 ***	−4.239 ***
Hefei	−1.632	−1.905	−2.559 **	−2.273 *	−2.948 **	−2.405 *	−1.679	−1.775	−1.592

Table 6. *Cont.*

Quantiles	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Taiyuan	−4.166 ***	−3.798 ***	−3.220 ***	−4.176 ***	−3.324 ***	−3.477 ***	−2.141 *	−1.837	−1.937
Jinan	−1.435	−2.470 **	−4.412 ***	−4.649 ***	−6.768 ***	−3.981 ***	−3.028 **	−2.074 *	−0.396
Hohhot	−5.727 ***	−6.320 ***	−6.228 ***	−5.221 ***	−5.281 ***	−4.474 ***	−3.432 ***	−4.263 ***	−2.286 **
Changsha	−2.546 *	−3.002 **	−5.320 ***	−4.225 ***	−4.666 ***	−4.595 ***	−3.294 ***	−3.250 ***	−3.203 **
Zhengzhou	−3.442 **	−3.725 ***	−3.505 ***	−1.465	−2.012 *	−1.427	−2.846 **	−3.219 ***	−1.640
Cities under separate state planning									
Xiamen	−3.660 **	−3.487 ***	−4.534 ***	−4.052 ***	−3.154 ***	−4.103 ***	−3.161 ***	−2.633 **	−3.782 **
Dalian	−3.723 **	−3.632 ***	−3.379 ***	−3.240 ***	−2.766 **	−3.140 **	−2.062 *	−1.605	−0.965
Qingdao	−3.765 **	−6.113 ***	−5.171 ***	−5.241 ***	−5.403 ***	−3.669 ***	−2.444 **	−1.016	−0.142

***, **, and * indicate significance at the 1%, 5%, and 10% levels.

Table 7 reports the results of the unit root hypothesis over the whole quantiles. The optimal frequency and its *F* statistics are reported at the end of the two columns. The results of Fourier QKS test statistics indicate that the null of unit root over the range of quantiles [0.1, 0.9] is rejected for 13 cities of Beijing–Tianjin–Hebei Urban Agglomeration, 24 cities of Yangtze River Delta, 9 cities of Pearl River Delta, the Chongqing municipality, 22 provincial capital cities, and 3 cities under separate state planning. Only the SO_2 emissions per capita of Nanjing and Hefei were not stationary. The optimum frequency varies from 0.1 to 4.8, and the computed *F* statistics are in all cases greater than the critical values even at 1% significance level, indicating the validity of the choice of the optimal. Hence, the mean-reverting function with the nonlinear component is accepted in favor of the one without the nonlinear component.

Table 7. Results for overall the Fourier quantile unit root test.

City	FQKS statistic	CV 10%	CV 5%	CV 1%	Optimal Frequency	Optimal F-statistic
Beijing–Tianjin–Hebei Urban Agglomeration						
Beijing	4.431 **	3.257	3.691	4.842	4.7	21.229
Tianjin	6.389 ***	3.247	3.679	4.805	0.1	18.423
Zhangjiakou	3.408 *	3.076	3.567	4.670	0.1	28.983
Chengde	4.152 **	3.332	3.722	4.988	4.8	24.667
Qinhuangdao	3.920 **	3.302	3.681	4.771	4.8	33.107
Langfang	3.639 **	3.271	3.638	4.683	4.7	22.617
Cangzhou	4.407 **	3.311	3.723	4.838	4.7	28.438
Tangshan	3.237 *	3.223	3.659	4.704	0.1	22.792
Handan	4.523 ***	2.984	3.400	4.305	4.7	19.901
Hengshui	5.887 ***	3.160	3.682	4.959	0.1	21.210
Xingtai	6.918 ***	3.264	3.685	4.903	4.8	17.478
Shijiazhuang	3.707 **	3.188	3.602	4.602	4.7	24.438
Baoding	4.118 **	3.263	3.669	4.785	0.1	19.500
Yangtze River Delta						
Shanghai	4.744 ***	3.245	3.639	4.703	0.1	29.304
Nanjing	3.037	3.186	3.590	4.698	0.1	35.179
Wuxi	4.017 **	3.227	3.680	4.913	0.1	53.096
Nantong	5.365 ***	3.222	3.622	4.826	0.1	60.307
Lianyungang	3.214 *	3.090	3.463	4.317	4.7	28.714
Suzhou	4.425 **	3.210	3.678	4.744	0.1	47.641
Huaian	3.445 *	3.215	3.631	4.730	0.1	45.100
Changzhou	4.541 ***	3.087	3.475	4.320	0.1	59.147
Tàizhou	4.374 ***	3.121	3.484	4.308	0.1	71.957
Yancheng	4.341 **	3.289	3.663	4.788	0.1	40.810
Suqian	5.163 ***	3.351	3.767	4.971	0.1	22.540
Zhenjiang	4.897 ***	3.134	3.483	4.291	0.5	122.378
Yangzhou	4.960 ***	3.237	3.662	4.692	0.1	48.814
Xuzhou	5.057 ***	3.236	3.643	4.738	0.1	47.864

Table 7. *Cont.*

City	FQKS statistic	CV 10%	CV 5%	CV 1%	Optimal Frequency	Optimal F-statistic
Zhoushan	4.317 **	3.136	3.518	4.383	0.1	17.966
Lishui	4.136 **	3.103	3.489	4.850	0.1	14.357
Ningbo	3.965 **	3.253	3.686	4.929	0.1	28.160
Wenzhou	4.837 ***	3.229	3.652	4.793	0.1	20.234
Quzhou	6.526 ***	3.187	3.650	4.798	0.1	40.906
Jiaxing	4.052 **	3.098	3.611	4.933	0.1	29.824
Jinhua	5.078 ***	3.163	3.583	4.842	0.1	35.089
Huzhou	4.522 **	3.242	3.675	4.846	4.7	11.500
Hangzhou	3.534 *	3.259	3.737	4.924	0.1	27.361
Shaoxing	4.830 **	3.174	3.646	4.984	0.1	58.567
Táizhou	3.735 **	3.131	3.495	4.395	4.8	18.381
Pearl River Delta						
Guangzhou	6.002 ***	3.210	3.633	4.669	0.1	19.932
Shenzhen	7.644 ***	3.228	3.574	4.449	0.1	24.866
Zhuhai	4.548 ***	3.114	3.416	4.178	4.7	40.026
Foshan	5.051 ***	3.294	3.749	4.870	0.1	24.451
Jiangmen	4.340 **	3.305	3.707	4.884	0.1	19.891
Dongguan	3.953 **	3.240	3.703	4.822	4.7	20.705
Zhongshan	3.293 *	3.231	3.621	4.699	4.8	25.200
Huizhou	4.163 **	3.146	3.461	4.322	4.7	10.425
Zhaoqing	6.966 ***	3.244	3.657	4.755	0.1	39.582
Municipality						
Chongqing	3.300 *	3.198	3.632	4.869	0.1	32.420
Provincial capital cities						
Lhasa	5.554 ***	3.066	3.413	4.275	0.1	23.913
Haikou	8.688 ***	3.224	3.673	4.609	4.6	8.313
Kunming	3.593 **	3.183	3.577	4.709	0.1	35.461
Fuzhou	5.844 ***	3.113	3.514	4.388	1.5	9.918
Chengdu	4.284 **	3.162	3.491	4.312	0.1	42.587
Xi’an	6.378 ***	3.273	3.699	4.886	4.8	40.747
Guiyang	4.717 **	3.259	3.620	4.855	4.8	38.941
Urumqi	5.919 ***	3.183	3.637	4.823	4.8	19.204
Nanning	4.503 ***	3.140	3.517	4.398	4.8	25.52
Xining	4.882 ***	3.257	3.670	4.726	4.7	13.739
Shenyang	7.012 ***	3.252	3.695	5.056	4.8	22.382
Changchun	5.844 ***	3.260	3.662	4.762	4.7	42.081
Harbin	11.338 ***	3.232	3.705	5.126	4.7	27.913
Wuhan	3.593 **	3.183	3.577	4.709	0.1	35.461
Yinchuan	5.568 ***	3.223	3.612	4.856	4.8	29.116
Lanzhou	6.973 ***	3.264	3.664	4.734	4.7	70.174
Nanchang	6.634 ***	3.282	3.683	4.630	0.1	43.119
Hefei	2.948	3.255	3.659	4.850	0.1	37.914
Taiyuan	4.176 **	3.222	3.703	4.793	4.7	32.412
Jinan	6.768 ***	3.348	3.767	4.830	0.1	30.034
Hohhot	6.320 ***	3.267	3.725	4.987	4.8	44.381
Changsha	5.320 ***	3.260	3.659	4.782	0.1	52.570
Zhengzhou	3.725 **	3.238	3.672	4.615	4.8	21.613
Cities under separate state planning						
Xiamen	4.534 **	3.266	3.642	4.737	0.1	16.879
Dalian	3.723 **	3.264	3.722	4.856	4.8	25.841
Qingdao	6.113 ***	3.136	3.599	4.807	0.1	31.960

***, **, and * indicate significance at the 1%, 5%, and 10% significant levels. The critical value for QKS statistics generated by bootstrap techniques with 5000 iterations.

Several important policy implications emerge from our study. First, the convergence of the SO_2 emissions per capita for those 72 out of 74 cities does not mean that the environmental improvement goals have been achieved; it only suggests that the past environmental protection work has been effected. More to the point, stationarity indicates that the impact from the SO_2 emissions per capita reduction policy is temporary and the SO_2 emissions per capita series would revert to a trend path in the long run. Especially for 13 cities in Beijing–Tianjin–Hebei Urban Agglomeration, though the SO_2 emissions per capita are converging, the SO_2 emission levels are still larger than the levels of the Yangtze River and Pearl River Deltas. Therefore, the policymakers should find more creative and effective ways to curb the SO_2 emissions, given that shifting the SO_2 emissions from the current level to another would eventually return to its equilibrium level. The environmental situation is not optimistic. A large number of high-pollution industries, such as cement, steel, refining, and petrochemicals, are gathered and the industrial energy consumption is still dominated by coal. Therefore, it is still necessary to actively implement pollution control measures and adjust the structure of industrial sectors.

Second, Nanjing and Hefei are the only two cities where the SO_2 emissions per capita are divergent. The environmental protection must be further strengthened because the environmental protection can leave permanent effects. The electricity, heat production and supply industries produce the largest amount of SO_2 in these two cities. For a long time, there has been a phenomenon of uncoordinated development of light and heavy industries. The local government should appropriately adjust the industrial structure, increase the proportion of the tertiary industry, and reduce the proportion of the secondary industry, especially the proportion of low-end manufacturing, high-consumption, and high-pollution industries, so that its energy efficiency can be significantly improved and to reduce the SO_2 emissions per capita.

Last, our findings suggest that the negative/positive shocks to the SO_2 emissions per capita can produce three different effects. Negative shocks to the SO_2 emissions per capita in Haikou, Shenzhen, Huizhou, Fuzhou, Ningbo, Qingdao, Jiaxing, Jinhua, and Ji'nan have transitory effects, while positive shocks have permanent effects. On the contrary, positive shocks to the SO_2 emissions per capita in Suqian and Kunming have temporary effects, while negative shocks have permanent effects. For the other cities, neither positive nor negative shocks have permanent effects since the SO_2 emissions per capita for these cities show stationary behavior. In light of the evidence, local governments should formulate environmental protection policies that are consistent with local practices based on the permanent or transient characteristics of the shocks to the SO_2 emissions. This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

4. Conclusions

In this study, we mainly utilized the Fourier quantile unit root test to survey the convergence of the SO_2 emissions per capita in 74 cities of China from December 2014 to June 2019, by conducting five traditional unit root tests and a quantile root unit test as a comparative analysis. The empirical results indicate that the SO_2 emissions per capita in 72 out of 74 cities in China are converged in the sample period. Only the SO_2 emissions per capita in Nanjing and Hefei are divergent. The results also suggest that unit root behavior of the SO_2 emissions per capita in these cities is asymmetrically persistent at different quantiles.

Our findings have great implications for the environmental improvement of all cities in China. For the cities with the converging SO_2 emissions, the government should consider the asymmetric mean-reverting pattern of SO_2 emissions when implementing environmental protection policies at different stages. Moreover, it is worth noting that the environmental protection policies in these cities will not always make a consistent impact on SO_2 emissions moving from lower to upper quantiles. For Hefei and Nanjing, the local governments need to enact stricter environmental protection policies to control the emission of sulfur dioxide. In addition, given that the old industrialization route is not desirable, it is thus necessary to implement an energy-saving and material-saving recycling industrial system, which reduces waste discharge per unit of economic output, improves resource utilization efficiency, and achieves low resource consumption and less environmental pollution. Only when the SO_2 emissions per capita from cities reach convergence can the SO_2 emissions per capita from the country reach convergence.

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