Asymmetric Persistence in Convergence for Carbon Dioxide Emissions based on Quantile Unit Root Test with Fourier Function

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Abstract

Figuring out the convergence and persistence of per capita CO2 emissions matters much for environmental policy makers in both developed and developing countries. The Kyoto Protocol aims at avoiding threat from climate warming for human beings. CO2 emissions have been viewed as the main cause of climate change in recent decades. Thus, loads of empirical studies contribute to investigate the convergence of per capita CO2 emissions by implementing various econometric models including as many sample countries as possible. By applying a battery of univariate unit root tests, quantile unit root test, and a newly developed quantile unit root test with Fourier function, we re-investigate the convergence, mean-reverting properties and asymmetric behavior of per capita CO2 emissions in 21 OECD countries. The findings show that per capita CO2 emissions of Austria, Finland, Japan, Netherlands, New Zealand, Norway, Sweden, Switzerland and the US perform converging as a whole from the perspective of the FQKS statistics. Besides, mean-reverting properties are identified for Austria, Finland, Japan, Netherlands, Norway, Sweden, Switzerland and the US when economy is in recession. Finally, asymmetric behaviors of per capita CO2 emissions are detected at selected quantiles. All of the results provide impressive environmental economic implications for policy makers.

Keywords: Per capita CO2 emissions, Quantile unit root test, Fourier function, Mean-reverting properties.

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1. Introduction

Figuring out the convergence and persistence of per capita CO2 emissions matters much for environmental policy makers in both developed and developing countries. The Kyoto Protocol aims at avoiding threat from climate warming for human beings. CO2 emissions have been viewed as the main cause of climate change in recent decades. Thus, loads of empirical studies contribute to investigate the convergence of per capita CO2 emissions by implementing various econometric models including as many sample countries as possible. Normally, if per capita CO2 emissions are converging, we could infer that the greenhouse gas effects would gradually mitigated for the mean-reversion properties in the series without any necessities to implement policy tools. In contrast, policy makers should promulgate rules and laws to restrict the trend of per capita CO2 emissions with considering the unit roots contained in the time-series.

The main purpose is to examine whether external shocks would result in permanent impacts on emissions. If such persistence is confirmed, only with timeous and strict environmental policies will be beneficial in the emissions reduction. However, if the emissions were tested to be stationary, then environmental policies would only transitorily affect the path. Thus, investigating the characteristics and internal dynamics of emissions would assist in proposing and implementing appropriate policies.

The environmental convergence hypothesis has been widely discussed in existing studies (Presno et al., 2015; Wu et al., 2016; Apergis and Payne, 2017); while the concept of energy convergence in general has attracted some attention in the literature recently (Gozgor and Demir, 2017; Solarin et al., 2018). Relevant studies could be divided into three strands by considering the research methods (Pettersson et al., 2014), i.e., β and σ convergence test (Panopoulou and Pantelidis, 2009); distributional dynamics analysis (Wu et al., 2016) and stochastic convergence test (Apergis and Payne, 2017). In this paper, we make use of a newly proposed quantile based unit root test with Fourier function to revisit the convergence of per capita CO2 emissions from the perspective of both particular quantiles and overall conditions. Although the previous quantile unit root test proposed by Koenker and Xiao (2014) could also achieve the same goal, the conventional method neglects the structural breaks in the series.

Indeed, many econometricians have revealed that structural breaks are main disturbances to correct inference of previous unit root tests. Specifically speaking, Perron (1989) accurately points out that conventional tests often fail to reject the null hypothesis of unit root with a structural break in a series and further deals with the structural breaks by employing dummy variables. However, most of the series perform smooth breaks other than sharp shifts. Given that, Lee and Enders (2004) develop a Fourier unit root test with unknown structural breaks and functional forms. Thus, previous difficulties in selecting specific breaking dates, the number of breaks and the form of breaks are solved by only emphasizing on choosing optimal frequency in the Fourier function. Besides, Koenker and Xiao (2014) focus on testing the stationarity of macroeconomic variables under a quantile auto-regression based unit root test.

Unlike past studies only emphasizing on convergence of series, the quantile unit root test provides more insights on mean-reversion properties and persistence at particular quantiles.[2] Besides, they develop QKS statistic to survey the convergence over the whole sample. After taking all of the advantages of the method stated into account, Bahmani-Oskooee et al. (2017) develop a new quantile unit root test with Fourier function to approximate the smooth breaks in the series which could consider persistence and stationarity at particular quantiles, but also overall stationarity based on FQKS statistic. Besides, the new approach including Fourier function could solve inaccurate inference generated by structural breaks. Lastly, to the best of our knowledge, it is the first time to survey the convergence of per capita CO2 emissions through quantile auto-regression based unit root test with considering the smooth breaks solved by Fourier function.

This paper revisits the stochastic convergence of the per capita CO2 emissions among

[2] Koenker and Xiao (2004) present that lower quantiles represent sluggish economy, and upper quantiles represent booming economy.

21 OECD countries and contribute to the existing knowledge in the following: first, the smooth breaks in the per capita CO2 emission are first approximated in smooth transition with unknown breaking dates; second, the unit root hypothesis is tested with and without considering structural breaks; third, the persistency is investigated at each quantile; forth, the unit root hypothesis is investigated at each quantile. In fact, existing studies ignore the asymmetric performance of the unit root behavior at different situation. In other words, the mean-reverting properties would be highly changed when CO2 emissions are located at different quantile. Besides, the quantile regression based unit root test could efficiently test on the series that is not subjected to normal distribution. Koenker and Xiao (2004) note that the non-normality of the series would directly result to the bias of the unit root behavior through traditional unit root tests.

The OECD countries are all industrialized which also account for the most of the GDP share in the world. Since Kyoto Protocol, those economies are committed to cut CO2 emissions at request level to curb the soaring global mean temperature. Recently, those developed countries have come up with many environmental protection policies. According to Climate Change Policies and Measures Databases of International Energy Agency (IEA), Australia, Austria, Belgium, Canada, Denmark, France, Germany, Italy, Japan, Netherlands, Poland, Portugal, Sweden, the UK and the US have on average 35 climate change policies each in force since 2005 in the year of Kyoto protocol.[3] Those environmental protection policy shocks would significantly affect the path of CO2 emissions. Such means that the properties of stochastic convergence of CO2 emissions in these OECD countries would be highly affected by those environmental protection policies. Besides, such countries like Australia, the US and Germany are all leaders in curbing the CO2 emissions in the world. At the same time, those OECD countries are the main CO2 emitters in the word. According to the Key World Energy report (2017), the share of CO2 emissions from fuel combustion in OECD

[3] Climate Change Policies and Measures Databases of International Energy Agency (IEA) reports the policy types including economic instruments, information and education, policy support, regulatory instruments, research, RD&D and voluntary approaches.

group decline from 66.7% to 36.3% in the world. It means that the share of CO2 emissions of the OECD group has dramatically declined since 1973. The decreasing share could be attributed to the raising share of the emerging market countries. It is still worthy to figure out the stochastic convergence of CO2 emissions for selected OECD countries. After the long-run policy regulation, the stochastic convergence of CO2 emissions is also worth to be re-examined.

The rest of the paper proceeds as follows. Section 2 reviews the literatures in testing the convergence of per capita CO2 emissions. Section 3 presents datasets and descriptive statistics. Section 4 introduces the econometric methodology. Section 5 discusses the empirical results and provide economic implications. The last section concludes the paper.

2. Literature Review

Loads of literatures contribute to test the convergence for per capita CO2 emissions by various econometric models. However, figuring out whether per capita CO2 emissions are converging matters about not only the cointegration and causality test between CO2 emissions and other macroeconomic variables, but also shed new light on economic implications. To our knowledge, if the per capita CO2 emissions are converging with mean reverting properties, any environmental protecting policy would be in vein. However, when the per capita CO2 emissions are non-converging, any shocks (including business cycle shocks, policy shocks and technical shocks) would permanently affect the move trend of per capita CO2 emissions in the long run without any mean-reverted properties. Besides, understanding whether the per capita CO2 emissions contain unit roots would be a key step for further model specifications related to per capita CO2 emissions.

Briefly speaking, all studies could be divided into two strands by surveying the convergence through various unit root tests and modelling the distribution for per capita CO2 emissions. In this first group by implementing unit root tests, per capita CO2 emissions are converging as a whole (Strazicich and List, 2003; Westerlund and

Table 1 A survey of existing literature by unit root tests.

Literatures	Country	Period	Methodology	Main Findings
Strazicich and List (2003)	21 industrial countries	1960-1997	Panel unit root tests and cross-section regressions	1. CO_2 emissions converge over the sample period.
Westerlund and Basher (2008)	Selected developed and developing countries	1870-2002	Panel unit root test allowing dependence	1. The per capita CO_2 emissions converge as a whole.
Lee and Chang (2008)	21 OECD countries	1960-2000	Panel seemingly unrelated regressions augmented Dickey–Fuller tests	1. Per capita CO emissions in OECD countries are a mixture of I(0) and I(1) processes, in which 14 out of 21 OECD countries exhibit divergence. 2. Conventional panel unit-root tests can lead to misleading inferences biased towards stationarity.
Romero-Ávila (2008)	23 countries	1960-2002	Panel unit root test with multiple breaks (Carrion-I Silvestre et al., 2005)	1. The per capita CO_2 emissions are both stochastic and deterministic convergence.
Chang and Lee (2008)	Industrialized countries	1960-2000	LM unit root test with structural breaks (Lee and Strazicich, 2003; 2004)	1. Per capita CO_2emissions for industrialized countries stochastically converge with considering breaks 2. Structural breaks always occur to energy crisis.
Chang (2008)	21 OECD countries	1960-2000	Unit root test with a break (Sen, 2003)	1. Stationary for 21 OECD countries. 2. Stochastically converging for 21 OECD countries.
Lee and Lee (2009)	109 countries	1971–2003	SURADF test (Breuer et al. 2001)	1. Mixture of (0) and (1) processes for CO_2 emissions. 2. Traditional panel unit-root tests could lead to misleading inferences.
Lee and Chang (2009)	21 OECD countries	1950-2002	Panel unit root test with multiple breaks (Carrion-I Silvestre et al., 2005)	1. Per capita carbon dioxide (CO_2) emissions stochastically converge. 2. Per capita CO_2 emissions is stationary.
Yavuz et al. (2013)	G7 countries	1960-2005	TAR panel unit root test	1. Per capita CO_2 emissions converge in the first regime, but diverge in the second regime. 2. Per capita CO_2 emissions conditionally converge in the first regime.
Christidou et al. (2013)	36 countries	1870-2006	Nonlinear panel unit root test	1. Per capita CO_2 emissions are stationary.

Li et al. (2014)	50 U.S. states	1990-2010	Panel KSS unit root test (Ucar and Omay, 2009)	1. CO_2 emissions converge in 12 out of the 50 U.S. states.
Runar et al. (2014)	124 countries	1985-2010	Narametric and nonparametric panel data techniques	1. Per capita CO_2 emissions are β-convergence for global sample including OECD and non-OECD countries.
Tiwari et al. (2016)	35 countries in Sub-Saharan Africa	1960-2009	Nonlinear unit root test (Becker et al., 2006) and Panel Unit Root test	1. Stationary for 27 countries by nonlinear unit root test. 2. Stationary for 15 of these countries are stationary by panel unit root test without Fourier Function. 3. Stationary for all countries by panel unit root test with Fourier function.

Basher, 2008; Romero-Ávila, 2008; Chang and Lee, 2008; Chang, 2008; Lee and Chang, 2009; Lee and Chang, 2008; Christidou et al., 2013; Li et al., 2014; El- Montasser et al., 2015). Besides, some studies supporting the convergences for per capita CO2 emissions depend on different countries and econometric methodology (Lee and Chang, 2008; Yavuz et al., 2013; Kaivo-oja et al., 2014; Tiwari et al.,2016). Besides, Lee and Chang (2009) also present that conventional panel unit root tests could result to misleading inferences biased towards convergence. Tiwari et al. (2016) state per capita CO2 emissions are converging for only 15 countries without Fourier function and for all countries with considering Fourier function (see Table 1).

The second group investigates the convergence of per capita CO2 emissions by modelling the distribution of the series. Some studies could not confirm per capita CO2 emissions converge as a whole (Van, 2005; Aldy, 2006; Panopoulou and Pantelidis, 2009; Wang and Zhang, 2014). Besides, Van (2005) and Burnett (2016) indicate that advanced economies exhibit converging pattern. Besides, Panopoulou and Pantelidis (2009) identify two separate convergence clubs to different steady states. Criado and Grether (2011) point out that the convergence for per capita CO2 emissions contains time-varying properties. Wu et al. (2016) also find multimodality in the ergodic distribution as a whole and more persistence for cities with low per capita CO2 emissions. Besides, the geographical, environmental and income factors are also poured into the model, which significantly affect the dynamic distribution of per capita CO2 emissions (see Table 2).

After combing the existing literatures, we could summarize that scholars are more likely to survey the detailed information about per capita CO2 emissions with considering different samples. Besides, in the field of unit root tests, existing literatures consider more structural breaks to survey the convergence of CO2 emissions. Furthermore, Tiwari et al. (2016) present different conclusions with and without Fourier function, which is utilized to deal with smooth breaks.

Table 2 A survey of existing literature by modelling distribution.

Literatures	Country	Period	Methodology	Conclusion
Van (2005)	100 countries	1966-1996	Nonparametric methods	1. Industrial countries show a convergence patter. 2. Little evidence is found for the whole sample.
Aldy (2006)	23 OECD countries	1960-2000	Markov chain transition matrix	1. Little evidence to support the per capita CO2 emissions converge. 2. Per capita CO2 emissions diverge in the near term.
Ezcurra (2007)	87 countries	1960-1999	Non-parametric convergence analysis	1. Cross-country disparities in per capita CO2 emissions decreased throughout the ample period.
Panopoulou and Pantelidis (2009)	128 countries	1960-2003	Club convergence test (Phillips and Sul, 2007a)	1. Per capita CO2 emissions are converged. 2. Two separate convergence clubs are identified to different steady states.
Criado and Grether (2011)	166 world areas	1960-2002		1. Before the oil shocks in 1970s, the per capita CO2 emissions are non-stationary. 2. In the latter group, the per capita CO2 emissions show convergence pattern. 3. From the perspective of the whole sample period, no multimodality is detected.
Herrerias (2012)	25 EU countries	1920-2007	Distribution dynamics approach	1. Unweighted analysis supports converged pattern with significant difference before and after Would War II. 2. The economic size and population plays significant role on the convergence for 25 EU countries.
Wu et al. (2016)	286 cities	2002-2011	Continuous dynamic distribution approach	1. Multimodality is found in the ergodic distribution of the full sample. 2. Cities with low per capita CO2 emissions perform more persistence, one with high per capita CO2 emissions experience more mobility. 3. Geographical, environmental factors and income all significantly affects the dynamics of per capita CO2 emissions.
Burnett (2016)	U.S. states	1960-2010	Two-stage procedure	1. Twenty-six states converge to a unique steady-state equilibrium. 2. The per capita CO2 emissions for the rest of countries diverge.

3. Datasets and Descriptive Statistics

The dataset in this paper include 21 OECD countries, including Austria, Belgium, Canada, Finland, France, Greece, Hungary, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, UK and US. Annual per capita CO2 emission is employed covering the period from 1950 to 2014. All of the data used are retrieved from Carbon Dioxide Information Analysis Center (website: http://cdiac.ornl.gov).

Table 3 Descriptive statistics for per capita CO2 emissions

	Mean	Max	Min	Skewness	Kurtosis	Jarque-Bera	Observations
Australia	3.66	4.95	1.83	-0.53	1.87	6.47**	65
Austria	1.82	2.46	0.82	-0.84	2.48	8.32**	65
Belgium	3.01	3.89	2.27	0.50	2.78	2.89	65
Canada	4.10	4.97	2.88	-0.79	2.11	8.91**	65
Finland	2.31	3.62	0.45	-0.82	2.25	8.74**	65
France	1.87	2.71	1.29	0.78	2.64	6.90**	65
Greece	1.35	2.42	0.15	-0.27	1.61	6.06**	65
Hungary	1.60	2.34	0.54	-0.26	2.61	1.15	65
Italy	1.53	2.22	0.24	-0.90	2.37	9.77***	65
Japan	1.90	2.73	0.34	-0.86	2.16	9.84***	65
Korea	1.33	3.26	0.03	0.40	1.66	6.63**	65
Netherlands	2.65	3.66	1.40	-0.81	2.43	8.02**	65
New Zealand	1.72	2.40	1.14	0.09	1.57	5.59*	65
Norway	2.02	3.35	0.71	-0.34	2.00	3.95	65
Poland	2.40	3.56	1.23	0.15	2.36	1.35	65
Portugal	0.86	1.75	0.17	0.22	1.66	5.34*	65
Spain	1.27	2.22	0.32	-0.28	1.88	4.24	65
Sweden	1.90	3.13	1.12	0.78	2.43	7.52**	65
Switzerland	1.43	1.98	0.58	-1.04	3.13	11.86***	65
UK	2.71	3.22	1.78	-0.73	3.05	5.78*	65
US	4.96	5.96	3.97	-0.18	2.00	3.10	65

Note: ***, ** and * denote 1%, 5% and 10% significant levels.

The descriptive statistics are presented in Table 3. The maximum for per capita CO2 emissions belongs to the US with 5.96, but the minimum of that is from Korea with only 0.03. Besides, the skewness for Australia, Austria, Canada, Finland, Greece, Hungary, Italy, Japan, Netherlands, Norway, Spain, Switzerland, UK and US. The kurtosis for Switzerland and UK are over 3, which means leptokurtic for per capita CO2 emissions in these two countries. Finally, in terms of the Jarque-Bera statistic, we could infer that per capita CO2 emissions for Australia, Austria, Canada, Finland, France, Greece, Italy, Japan, Korea, Netherlands, New Zealand, Portugal, Sweden, Switzerland and UK are not subjected to normal distribution. Given that, Koenker and Xiao (2004) point out that the quantile auto-regression based unit root test would provide more robust and accurate empirical results rather than the least square methodology with the appearance of non-Gaussian and heavy-tailed datasets.

4. Econometric Methodology

Koenker and Xiao (2004) first proposed the unit root test based on quantile regression. However, this method does not fully consider the impacts of structural breaks, which would result to lower testing efficiency. Perron (1989) first suggests that the ignorance of structural breaks would significantly lead to estimation bias. In other words, the failure to capture the structural breaks would result to the failure of unit root tests. Given that, Bahmani-Oskooee et al. (2017) first propose a quantile based unit root test with smooth breaks, which could approximate the unknown breaks in the series. Code was written by one of authors, Omid Ranjbar. The econometric model is built upon a time series, which is composed by a deterministic trend, $d(t)$ and a stationary error term with variance δ^2 and zero mean. The $d(t)$ could be expressed as follows,

$$y_{t=} = d(t) + \varepsilon_t \quad (1)$$

Enders and Lee (2012) and Bahmani-Oskooee et al. (2017) suggest using Fourier function to capture the time-varying smooth process. Specifically, the terms of $\alpha_k \sin\left(\frac{2\pi kt}{T}\right)$ and $\beta_k \cos\left(\frac{2\pi kt}{T}\right)$ are served to approximate the unknown breaks in the series. Here, α_k and β_k measure the amplitude and displacement of the frequency component. After considering the constant and trend, the term $d(t)$ could be expressed, as follows,

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

where, c, k, t and T represent the constant, frequency of the Fourier function, time trend and sample size by sequence. Besides, $\pi = 3.1416$ is as usual. Then, equation (1) could be rewritten as following form,

$$\mathrm{y}_t = c + at + \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \beta_k \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \tag{3}$$

where, $\alpha_k = \beta_k = 0$ is a special case of standard linear specification. Becker et al. (2006) create 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^*.4 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 k^* is set as optimum frequency at the minimum of SSR. After searching the optimal frequencyk^*, Bahmani-Oskooee et al. (2018) obtain the adjusted y_t^{ad} series, which excludes the deterministic trend$d(t)$,

$$\mathrm{y}_t^{ad} = \mathrm{y}_t - \hat{c} - \hat{a}t - \hat{\alpha}_k \sin\left(\frac{2\pi kt}{T}\right) - \hat{\beta}_k \cos\left(\frac{2\pi kt}{T}\right) \tag{4}$$

where, $\hat{c}$, $\hat{a}$, $\hat{\alpha}_k$ and $\hat{\beta}_k$ are obtained through the OLS after searching the optimal frequency k^*. Then, Bahmani-Oskooee et al. (2018) pour the series y_t^{ad} after adjusted is poured into the ADF regression model (Dickey and Fuller, 1979), which is presented as follows,

$$\mathrm{y}_t^{ad} = \alpha_0 \mathrm{y}_{t-1}^{ad} + \sum_{i=1}^{p} \alpha_i \Delta \mathrm{y}_{t-i}^{ad} + \varepsilon_t \tag{5}$$

where, p is the lag order of the ADF regression model. Besides, α_0 is used to measure the persistency of the y_t^{ad}. As usual, if $\alpha_0 = 1$, y_t^{ad} contains a unit root with persistency, and if $|\alpha_0| < 1$, y_t^{ad} is stationary with mean-reverting properties. The

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[4] The optimal frequency k^* is determined by the following equation: $F(k^*) = \frac{\frac{SSR_{unrestricted}(k^*) - SSR_{restricted}(k^*)}{2}}{\frac{SSR_{restricted}(k^*)}{T-q}}$. Where, $SSR_{unrestricted}(k^*)$ and $SSR_{restricted}(k^*)$ are the sum of squared residuals from equation (3) with and without nonlinear component (structural breaks and Fourier function). Becker et al. (2006) suggest that the F statistic has no standard distribution due to the presence of nuisance parameters. Here, we implement Monte Carlo simulations to generate the critical values with 20000 replications.

equation (5) could be re-written based on quantile regression, as follows,

$$Q_{y_t^{ad}}\left(\tau \middle| y_{t-1}^{ad}, \dots, y_{t-p}^{ad}\right)$$

$$= Q_{\varepsilon}(\tau) + \theta(\tau) y_{t-1}^{ad} + \sum_{i=1}^{p} \varphi_i \Delta y_{t-i}^{ad} \tag{6}$$

where, $Q_{y_t^{ad}}\left(\tau \middle| y_{t-1}^{ad}, \dots, y_{t-p}^{ad}\right)$ denotes the τth conditional quantile of y_t conditional on the information set $(y_{t-1}^{ad}, \dots, y_{t-p}^{ad})$. $Q_{\varepsilon}(\tau)$ is the τth conditional quantile of ε_t. $\theta(\tau)$ is used to capture the mean-reverting speed of y_t at different quantiles. Here, the quantiles is set to be $\tau_i \in (0.1, 0.25, 0.5, 0.75, 0.9)'$. To obtain the coefficient $\theta(\tau)$ and $\sum_{i=1}^{p} \varphi_i$, we could minimize the following equation,

$$\min \sum_{t=1}^{n} \left(\tau - I_t \left(y_t^{ad} < Q_{\varepsilon}(\tau) + \theta(\tau) y_{t-1}^{ad} + \sum_{i=1}^{p} \varphi_i \Delta y_{t-i}^{ad} \right) \right) \left| y_t^{ad} - Q_{\varepsilon}(\tau) - \theta(\tau) y_{t-1}^{ad} - \sum_{i=1}^{p} \varphi_i \Delta y_{t-i}^{ad} \right|$$

here, $I_t(\cdot) = 1$ if $y_t^{ad} < Q_{\varepsilon}(\tau) + \theta(\tau) y_{t-1}^{ad} + \sum_{i=1}^{p} \varphi_i \Delta y_{t-i}^{ad}$, otherwise $I_t(\cdot) = 0$. Koenker and Xiao (2004) further propose t–ratio statistic with the null non-stationary hypothesis $\alpha(\tau) = 1$ against different alternative hypothesis: $\alpha(\tau) < 1$, $\alpha(\tau) > 1$ and $\alpha(\tau) \neq 1$ to check the unit root hypothesis at specific quantiles, which could be expressed as,

$$t_n(\tau_i) = \frac{f\left(\hat{F}^{-1}(\tau_i)\right)}{\sqrt{\tau_i(1-\tau_i)}} \left(Y_{-1}' P_{(1, \Delta y_{t-1}^{ad}, \dots, \Delta y_{t-p}^{ad})} Y_{-1}\right)^{\frac{1}{2}} \left(\hat{\theta}(\tau) - 1\right) \tag{8}$$

where $f(\cdot)$ is probability functions of y_t^{ad}, and $F(\cdot)$ is cumulative density function of series y_t^{ad}. Y_{-1} is the vector of lagged dependent variables (y_{t-1}^{ad}) and P_X is the projection matrix onto the space orthogonal to $X = \left(1, \Delta y_{t-1}^{ad}, \dots, \Delta y_{t-p}^{ad}\right)$. $f\left(\hat{F}^{-1}(\tau_i)\right)$ is a consistent estimator of $f\left(F^{-1}(\tau_i)\right)$ indicated by Koenker and Xiao (2004), which can be expressed as,

$$f\left(F^{-1}(\tau_i)\right) = \frac{(\tau_i - \tau_{i-1})}{G'(\omega(\tau_i) - \omega(\tau_{i-1}))} \tag{9}$$

here $\omega(\tau_i) = (c(\tau_i), \theta(\tau_i), \varphi_1(\tau_i), \dots, \varphi_p(\tau_i))$ and $\tau_i \in [\underline{\lambda}, \overline{\lambda}]$. We set $\underline{\lambda} = 0.1$ and $\overline{\lambda} = 0.9$. Obviously, we test the unit root hypothesis at different quantiles in comparison with traditional ADF test, which only emphasizes on the conditional central tendency.

To assess the performance of Quantile Unit Root test, Koenker and Xiao (2004) suggested a quantile auto-regression based Kolmogorov-Smirnov (QKS) test which could be presented as,

$$QKS = Sup_{\tau_i \in [\underline{\lambda}, \overline{\lambda}]} |\mathrm{t}_n(\tau_i)| \tag{10}$$

In this paper, we select the maximum of $\mathrm{t}_n(\tau_i)$ to build the QKS-Fourier statistics over the quantiles$\tau_i \in (0.1, 0.25, 0.5, 0.75, 0.9)'$. Although the limiting distributions of both $t_n(\tau_i)$ and QKS tests are nonstandard, Koenker and Xiao (2004) suggest to use re-sampling procedure to generate the critical values. In this paper, 10000 bootstrap iterations are used to accurate the critical values.

5. Empirical Results and Economic Implications

Unit root tests are widely used to examine the stochastic convergence of per capita CO2 emissions. Both time series and panel data analysis are widely used in existing studies testing on the macroeconomic series. This section contains three parts, which utilize different econometric models to examine the convergence of per capita CO2 emissions among the OECD countries. The first part presents the results from some classical unit root tests. The second part presents the results of quantile unit root test without smooth breaks. The last part utilizes quantile unit root test with smooth breaks to re-examine the stochastic convergence of per capita CO2 emissions.

5.1 Results for univariate unit root test

For comparative purpose, we firstly implement standard unit root tests including ADF test (Dickey and Fuller, 1982), DF-GLS test (Mackinnon, 1995), PP test (Phillips and Perron, 1988), KPSS test (Kwiatkowski et al., 1992) and MZ_a test (Ng and Perron, 2001) to revisit the stochastic convergence of per capita CO2 emissions.

Table 4 Results for univariate unit root test

	ADF test	DF-GLS test	PP test	KPSS test	MZ_a test
Australia	-2.1763	0.0512	-2.1915	0.9621***	0.2789
Austria	-2.3340	-0.5427	-2.3964	0.8244***	-0.4125
Belgium	-1.5657	-1.2029	-1.5657	0.2417	-2.8423
Canada	-1.5894	-0.6556	-1.6037	0.6239**	-0.7158
Finland	-2.0410	-0.7017	-2.0729	0.7791***	-0.7908
France	-1.0945	-0.8503	-1.2599	0.2584	-1.3500
Greece	-1.9137	-1.4402	-1.5737	0.9508***	-9.8745**
Hungary	-1.6476	-0.7678	-2.3050	0.2984	-1.2984
Italy	-2.2973	-1.1700	-2.3530	0.8103***	-3.4834
Japan	-2.2251	0.1458	-1.9558	0.8804***	0.3970
Korea	0.7977	2.3804**	1.0394	1.0026***	1.8247
Netherlands	-2.1145	-0.6751	-2.1160	0.6259**	-0.7253
New Zealand	-1.0946	-0.3149	-1.0658	0.9421***	-0.3286
Norway	-1.5772	-0.3020	-1.8118	0.8521***	-0.4924
Poland	-1.9945	-0.6974	-1.9478	0.3040	-0.5519
Portugal	-1.5081	-0.7906	-1.1709	0.9322***	-1.7479
Spain	-1.7147	-0.5404	-1.6358	0.8833***	-0.5198
Sweden	-1.2401	-0.8958	-1.3948	0.2878	-1.4056
Switzerland	-2.4048	-0.7847	-2.4206	0.4075	-0.7526
UK	0.5272	0.2376	1.0638	0.8848*	0.5921
US	-1.5941	-1.2715	-1.5206	0.3126	-3.3151

Note: ***, ** and * denote 1%, 5% and 10% significant levels.

Table 4 reports convergence of per capita CO2 emissions by employing univariate unit root test for 21 OECD countries. Obviously, the ADF test indicates per capita CO2 emissions are not converging at any significant levels. Similar to the results from ADF, the empirical results of PP test (Phillips and Perron, 1982) are non-converging for all 21 OECD countries. Next, the DF-GLS test indicates that only per capita CO2 emission for Korea is converged for the null hypothesis is rejected at 5% significant level. Besides, the MZ_a test developed by Ng and Perron (1990) support converging conclusion only for Greece at 5% significant level. However, the unit root test results for KPSS test are various, e.g., the null hypothesis is rejected in Australia, Austria, Canada, Finland, Greece, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, Spain and the UK. For the rest of the countries, no evidence by the KPSS test supports the per capita CO_2 emissions are mean-reverting or in other words, it confirms convergence for per capita CO_2 emissions.

Comparing with past studies, we reaffirm that per capita CO_2 emissions are non-converging. Besides, the standard unit root tests could only provide the convergence over the whole sample. The detailed information about the mean-reverting properties and the convergence at particular conditions of the series cannot be revealed by these conventional unit root tests. As Koenker and Xiao (2004) note "In addition, it also provides a more robust and efficient approach than the least squares method when the data is non-Gaussian or is contaminated by outliers". The results obtained through the traditional unit root tests may be biased by the non-normality of the datasets. The economic implications behind may be less reliable.

5.2 Results for quantile unit root test proposed by Koenker and Xiao (2004)

Koenker and Xiao (2004) present that the merits of the quantile unit root tests, which could be listed in the following aspects: first, the quantile unit root tests are more suitable to test on the unit root hypothesis for the non-Gaussian series; second, the quantile unit root test provides unit root behavior not only on the whole quantiles, but also at each selected quantiles; third, the asymmetric persistency could be witnessed through the quantiles; forth, economic implications would be suggested not only reply on whole quantiles, but also at each quantile. To run the procedure beforehand, some parameters should be declared. Specifically, as mentioned earlier, the quantiles are determined by the range of $\tau_i \in (0.1,0.25,0.5,0.75,0.9)'$.

The reason why we determine the quantiles as these five figures mainly considers the sample size and to provide more unit root behaviors at different cases. Besides, $\theta(\tau)$ is reported to describe the persistency of per capita CO_2 emissions. As Koenker and Xiao (2004) suggested, $\theta(\tau)$ would be different through various quantiles. Besides, this method also reports unit root behavior at different quantiles which could be obtained through the $t_n(\tau_i), \tau_i \in (0.1,0.25,0.5,0.75,0.9)'$.

In fact, following results suggest that the asymmetric unit root behaviors are different at different quantiles. Besides, the QKS statistics are utilized to check the stochastic convergence over the whole quantiles covering τ_i∈(0.1,0.25,0.5,0.75,0.9)^'. However, no standard distribution of t_n (τ_i) and QKS statistics are available. Given that, we get help from bootstrap techniques with 5000 replications to generate the critical values.

Besides, the Kolmogorov-Smirnov class tests are developed under the quantile analysis framework.

Table 5 reports all the results from the quantile unit root tests in Panel A, B and C. First, Panel A presents the persistency of per capita CO2 emissions at specific quantiles. Some interesting findings could be summarized as following aspects. For countries like Australia, Austria, Belgium, Finland, Greece, Hungary, Japan, Korea, Netherlands, Norway, Poland, Portugal, Spain, Sweden, UK and US, the persistency $\theta(\tau)$ is increasing straightforward with the quantiles increasing from 0.1 to 0.9 indicating explosive trend across the quantiles. For the rest of the countries, the $\theta(\tau)$ is decreasing first and then rebound presenting a U curve shape. In other words, the persistency is asymmetric over different quantiles. Panel B reports the results of unit root hypothesis across particular quantile. In obvious, the $\mathrm{t}_n(\tau_i)$ is rejected only for some minor cases. Specifically, for countries like Canada, Finland, Netherlands, Portugal, Spain, Switzerland and US, the unit root hypothesis is rejected only at lower quantiles indicating the asymmetric unit root behaviors of per capita CO2 emissions at different quantiles. In other words, per capita CO2 emissions are stationary for countries like Canada, Finland, Netherlands, Portugal, Spain, Switzerland and US at lower quantiles. When testing on the whole quantiles, we could find that the QKS statistics are significant for Greece, Korea, Netherlands, Spain and Switzerland, and US. It means that the per capita CO2 emissions are stationary for these countries. Shocks from energy protection policies, wars, crisis only transitorily affect the per capita CO2 emissions through this method. However, for the rest of the economies, shocks would permanently affect the path of per capita CO2 emissions.

Table 5 Results for linear quantile unit root test proposed by Koenker and Xiao (2004)

Panel A Results for persistence at particular quantiles

Quantiles	0.1	0.25	0.5	0.75	0.9
Australia	0.918*	0.934*	0.961	0.948	0.971
Austria	0.835*	0.924	0.940	0.986	1.043
Belgium	0.665**	0.822*	0.939	0.970	0.937
Canada	0.914*	0.895**	0.838***	0.859**	0.936
Finland	0.845**	0.902**	0.930	1.036	1.083
France	0.905	0.864**	0.943	1.028	1.079
Greece	0.935**	0.963	0.998	1.005	0.989
Hungary	0.900*	0.911*	0.945	0.992	0.998
Italy	0.987	0.959	0.960	0.956	0.972
Japan	0.938	0.955	0.971	0.989	1.050
Korea	0.949	1.000	1.023	1.049	1.090
Netherlands	0.903**	0.903***	0.941*	1.000	1.069
New Zealand	0.974	0.958	0.982	1.007	1.021
Norway	0.693	0.934	0.992	1.060	1.168
Poland	0.770***	0.900***	0.991	0.993	1.012
Portugal	0.946	0.949	0.983	1.021	1.042
Spain	0.905**	0.965	0.982	1.008	0.989
Sweden	0.884	0.841*	0.927	1.014	1.013
Switzerland	0.813**	0.818**	0.778***	0.828**	0.831*
UK	0.936	1.035	0.986	1.056	1.096
US	0.807***	0.844**	0.879**	0.891**	1.028

Panel B Results for unit root at particular quantiles

Quantiles	0.1	0.25	0.5	0.75	0.9
Australia	-3.223	-1.804	-1.140	-1.682	-1.674
Austria	-2.806	-1.487	-1.309	-0.301	1.056
Belgium	-3.464	-1.401	-0.672	-0.318	-0.983
Canada	-5.718*	-2.459*	-2.916**	-2.531*	-2.808
Finland	-2.549**	-2.061*	-1.648	0.656	1.522
France	-1.467	-1.806	-1.051	0.550	4.306
Greece	-4.951**	-2.086	-0.122	0.313	-1.506
Hungary	-2.691	-2.268	-1.458	-0.198	-0.135
Italy	-0.599	-1.786	-1.898	-1.618	-0.236
Japan	-2.856	-1.874	-1.124	-0.340	1.391
Korea	-1.223*	0.000	2.207	3.102	7.497
Netherlands	-0.768	-3.559***	-1.824	0.000	0.524
New Zealand	-0.421	-0.694	-0.427	0.125	0.182

Norway	-2.549**	-0.606	-0.229	1.046	1.848
Poland	-1.232	-1.499	-0.303	-0.323	0.417
Portugal	-4.393*	-2.783**	-0.894	0.804	2.471
Spain	-3.304**	-1.207	-0.710	0.434	-0.326
Sweden	-3.528	-2.528*	-1.139	0.251	0.334
Switzerland	-10.312**	-2.445*	-3.317***	-1.878	-1.178
UK	-0.546	0.417	-0.234	0.592	0.150
US	-7.969**	-2.351	-1.975	-2.333	0.654

Panel C Results for overall unit root test

	QKS statistic	CV 10%	CV 5%	CV 1%
Australia	3.223	7.194	9.179	17.438
Austria	2.806	4.303	5.267	7.949
Belgium	3.464	5.443	6.811	10.769
Canada	5.718	7.115	9.221	14.876
Finland	2.549	2.875	3.247	4.105
France	4.306	5.262	6.765	10.733
Greece	4.951**	3.791	4.426	6.344
Hungary	2.691	5.434	6.753	10.416
Italy	1.898	3.602	4.25	6.103
Japan	2.856	4.024	4.806	6.998
Korea	7.497***	2.608	3.015	3.935
Netherlands	3.559**	2.737	3.099	4.154
New Zealand	0.694	3.073	3.488	4.509
Norway	2.549*	2.507	2.832	3.898
Poland	1.499	2.723	3.099	4.057
Portugal	4.393	4.704	5.779	8.782
Spain	3.304*	3.248	3.785	5.084
Sweden	3.528	8.606	11.272	21.242
Switzerland	10.312**	6.385	8.255	14.42
UK	0.592	3.347	3.921	5.475
US	7.969**	6.324	7.983	12.988

Note: ***, ** and * denote 1%, 5% and 10% significant level. The critical values are generated by bootstrap techniques for 5000 iterations.

5.3 Results for quantile unit root test with Fourier function proposed by Bahmani-Oskooee et al. (2017)

To overcome the drawbacks from structural breaks, Lee and Enders (2004) indicate that Fourier function could better deal with smooth breaks in time-series. However, breaking numbers, specific breaking dates and breaking forms are all required when estimating a conventional function with considering breaks. However, Lee and Enders (2004) point out that these problems under the standard breaking models are all solved by only estimating the optimal frequency k. Bahmani-Oskooee et al. (2017) firstly pour the Fourier terms into the quantile auto-regression based unit root tests and get novel empirical findings in comparison with quantile unit root test proposed by Koenker and Xiao (2004).

Table 6. Results for quantile unit root test with fourier function proposed by Bahmani-Oskooee et al. [11].

Quantiles	0.1	0.25	0.5	0.75	0.9
Panel A Results for persistence at particular quantiles					
Australia	0.709*	0.784*	0.707***	0.661**	0.702***
Austria	0.414***	0.711***	0.677***	0.814*	0.962
Belgium	0.649**	0.785**	0.860*	0.912	0.999
Canada	0.886	0.898	0.862*	0.800**	0.795*
Finland	0.510***	0.667***	0.738***	0.662***	0.777
France	0.754**	0.844**	0.963	0.846	0.959
Greece	0.859	0.888	0.836**	0.916	0.865
Hungary	0.907	0.833*	0.876*	0.959	1.009
Italy	0.726	0.925	0.927	0.939	1.004
Japan	0.829**	0.808***	0.823**	0.867	0.881
Korea	0.424***	0.767***	1.006	0.915	0.918

Quantiles	0.1	0.25	0.5	0.75	0.9
Netherlands	0.822**	0.754***	0.753***	0.935	1.188
New Zealand	0.898	0.691***	0.760**	0.687***	0.609***
Norway	0.299***	0.651***	0.881	0.895	1.275
Poland	0.734**	0.847**	0.972	0.949	0.971
Portugal	0.721*	0.870	0.910*	0.908	0.834
Spain	1.003	0.888	0.926*	1.024	0.840**
Sweden	0.735**	0.706***	0.843**	0.904	0.994
Switzerland	0.681***	0.656***	0.971	0.873	0.906
UK	0.692*	0.805	0.690***	0.785**	0.759*
US	0.725***	0.667***	0.826**	0.960	1.007
Panel B Results for unit root at particular quantiles					
Australia	−1.172	−1.203	−2.205*	−1.924	−2.671
Austria	−3.302**	−2.011	−2.539**	−1.523	−0.340
Belgium	−1.413	−1.748	−1.250	−0.657	−0.007
Canada	−1.069	−1.109	−1.726	−2.010	−1.693
Finland	−2.608**	−2.537**	−2.248*	−1.993	−0.875
France	−1.052	−1.396	−0.341	−1.145	−0.181
Greece	−0.436	−0.871	−1.653	−0.775	−0.951
Hungary	−0.778	−1.404	−1.773	−0.540	0.092
Italy	−2.223*	−0.792	−0.996	−0.773	0.044
Japan	−1.593	−3.116***	−2.417*	−1.571	−0.909
Korea	−1.858*	−1.330	0.071	−0.503	−0.312
Netherlands	−0.533	−3.151***	−3.605***	−0.441	0.634
New Zealand	−0.400	−2.055*	−2.210	−2.985**	−3.092**
Norway	−2.095**	−1.463*	−1.148	−0.598	0.831

Quantiles	0.1	0.25	0.5	0.75	0.9
Poland	−0.756	−1.027	−0.522	−0.901	−0.321
Portugal	−1.450	−1.374	−1.685	−0.694	−0.566
Spain	0.019	−0.901	−1.102	0.287	−1.573
Sweden	−1.801	−2.677**	−1.569	−0.718	−0.037
Switzerland	−3.473***	−2.864**	−0.247	−1.137	−0.220
UK	−1.697	−0.774	−1.963	−1.587	−1.771
US	−2.845**	−4.186***	−2.070*	−0.621	0.066

Panel C Results for overall unit root test

	FQKS statistic	CV 10%	CV 5%	CV 1%	Optimal Frequency	Optimal F-statistic
Australia	2.671	2.812	3.127	4.010	0.4	1418.729
Austria	3.302**	2.846	3.204	4.079	0.1	283.138
Belgium	1.748	2.893	3.233	4.210	0.8	44.210
Canada	2.010	2.874	3.263	4.253	0.4	125.181
Finland	2.608	2.809	3.186	4.132	0.3	268.609
France	1.396	2.810	3.129	4.085	1.2	111.675
Greece	1.653	2.807	3.154	3.970	0.6	1699.528
Hungary	1.773	2.868	3.188	4.067	0.5	195.965
Italy	2.223	2.896	3.253	4.171	0.4	696.113
Japan	3.116*	2.954	3.332	4.188	0.1	488.187
Korea	1.858	2.555	3.003	4.163	0.4	3077.136
Netherlands	3.605**	2.669	3.088	4.199	0.1	131.139
New Zealand	3.092*	2.874	3.227	4.043	0.7	312.033
Norway	2.095	2.667	3.081	3.979	0.1	138.193
Poland	1.027	2.421	2.733	3.462	1	152.763
Portugal	1.685	2.654	3.115	4.090	0.7	549.345

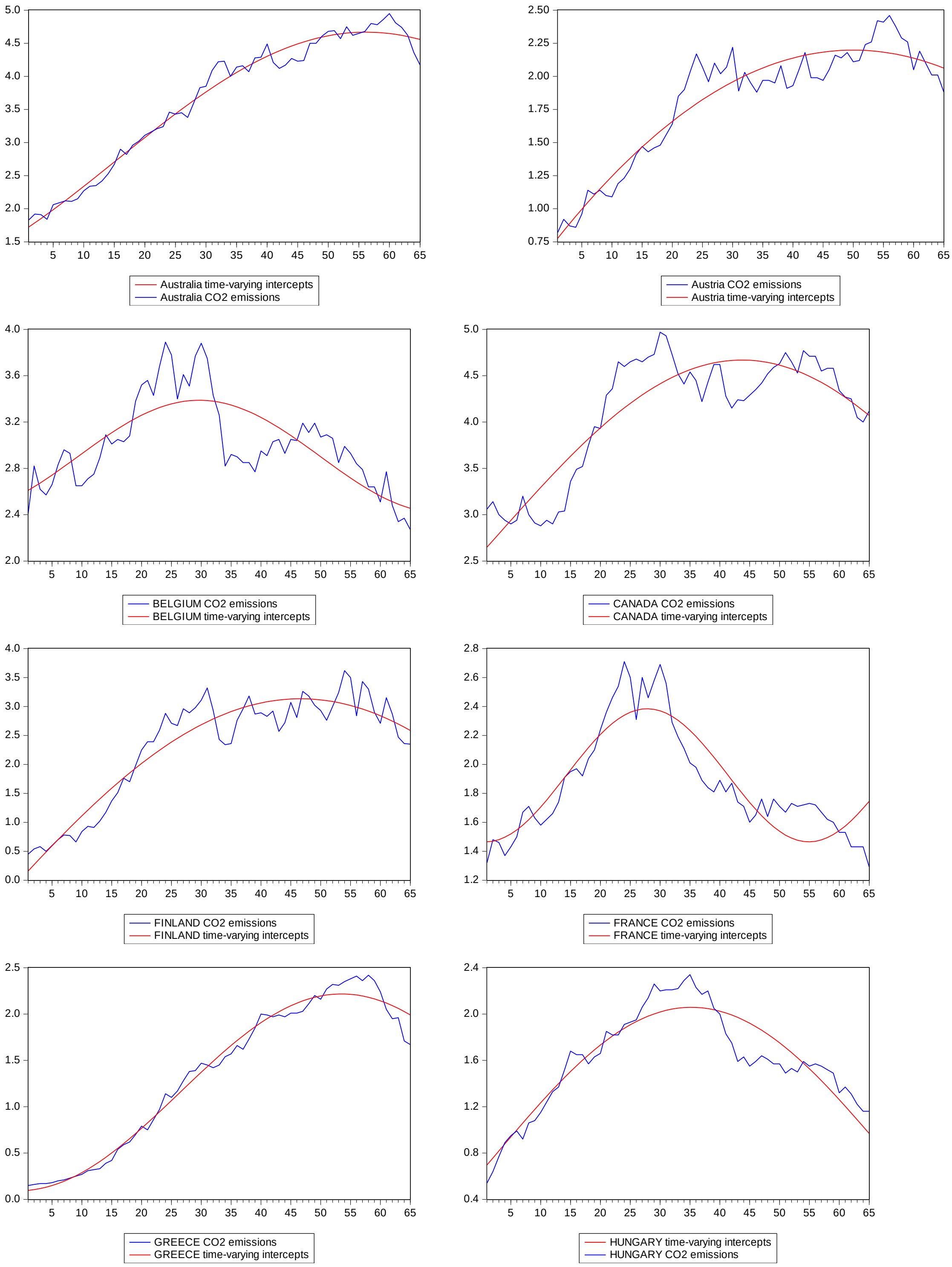
Panel C Results for overall unit root test

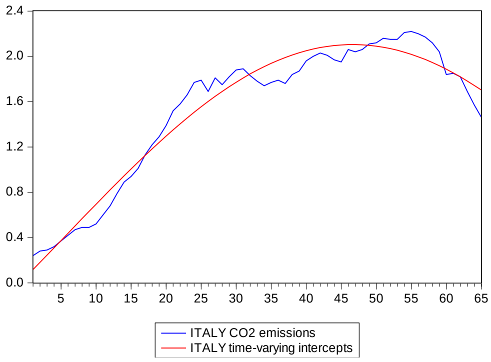
	FQKS statistic	CV 10%	CV 5%	CV 1%	Optimal Frequency	Optimal F-statistic
Spain	1.573	2.815	3.174	4.018	0.6	295.311
Sweden	2.677	2.832	3.171	3.878	1.1	111.846
Switzerland	3.473**	2.828	3.222	4.153	0.1	136.988
UK	1.963	2.874	3.199	4.139	0.3	247.894
US	4.186**	2.879	3.262	4.228	0.5	56.211

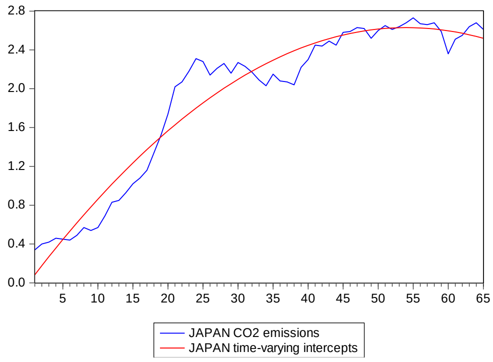
Note: ***, ** and * denote 10%, 5% and 1% significant level. The critical value for QKS statistic is generated by bootstrap techniques with 5000 iterations.

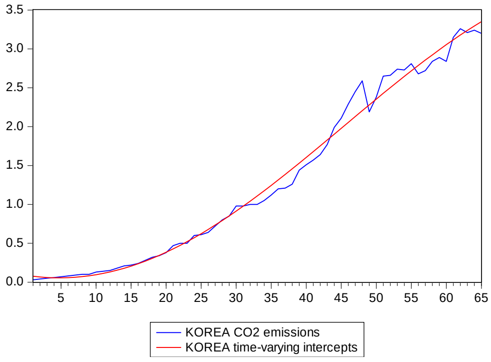
Like the results generated from quantile unit root test without smooth breaks (Koenker and Xiao, 2004), Table 6 reports the persistency at each quantile in Panel A, unit root behavior at each quantile in Panel B and unit root behavior across the quantiles in Panel C. After getting rid of the effects of smooth structural breaks, we find $\theta(\tau)$ shows increasing trend for Austria, Belgium, Finland, France, Italy and Norway without rebounds. For the rest of the countries, the $\theta(\tau)$ shows fluctuations around the mean. In other words, only 6 of 21 OECD countries show explosive performance than 16 of 21 OECD countries after approximating the smooth breaks through Fourier function. Besides, the fluctuations in $\theta(\tau)$ also indicate the persistency is asymmetric, which has been ignored in existing studies focusing on the convergence of CO2 emissions. Panel B reports unit root hypothesis at each quantile. For each quantile, the statistic $\mathrm{t}_n(\tau_i)$ is significant level of Australia, Austria, Finland, Japan, Netherlands and the US at median quantile 0.5, indicating the stationarity of per capita CO2 emissions. However, at extreme low quantile 0.1, the $\mathrm{t}_n(\tau_i)$ is significant for Austria, Finland, Italy, Korea, Norway, Switzerland and the US. At quantile 0.25, the per capita CO2 emission is stationary for Finland, Japan, Netherlands, New Zealand, Norway, Sweden, Switzerland and the US. However, we only find stationarity for New Zealand at upper quantile 0.75 and 0.9 rejecting the null non-stationary hypothesis. Panel C reports the results of unit root hypothesis over the whole quantile. Bahmani-Oskooee et al. (2018) propose the revised QKS statistics with Fourier function, which is called FQKS statistic. The null non-stationary hypothesis is rejected for Austria, Japan, Netherlands, New Zealand, Switzerland and the US at significant level. Besides, the critical values are generated through bootstrap technique with 5000 replications. It means that per capita CO2 emission is stationary for Austria, Japan, Netherlands, New Zealand, Switzerland and the US, which means that the shocks such as environmental protection policies would only transitory impacts on the path across the whole quantiles from 0.1 to 0.9. For the rest of the countries including Australia, Belgium, Canada, Finland, France, Greece, Hungary, Italy, Korea, Norway, Poland, Portugal, Spain, Sweden and UK, the per capita CO2 emission is non-stationary indicating those shocks would permanently affect the path of per capita CO2 emission. The optimal frequency and its F statistics are reported at the end of the two columns in Panel C. In obvious, the F statistics are significantly large enough indicating the validity of choice of the optimal frequency. To reveal the accuracy of the estimations, the deterministic trend in equation (2) is plotted in Figure 1. In obvious, the deterministic trend plotted in color red is closely fitted to the path of per capita CO2 emission at unknown breaking dates. Unlike the structural breaks

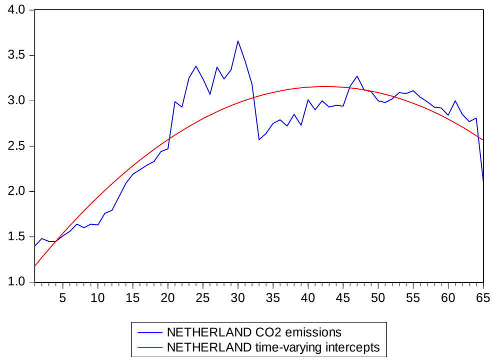
Figure 1 Plots of per capita CO2 emissions and fitted nonlinearities

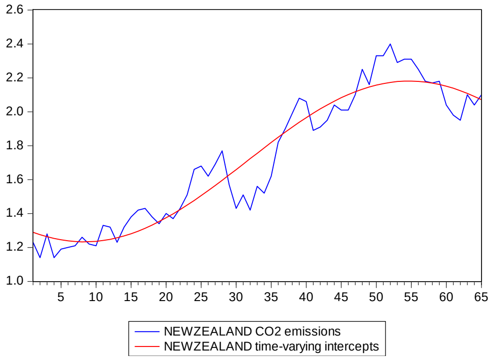


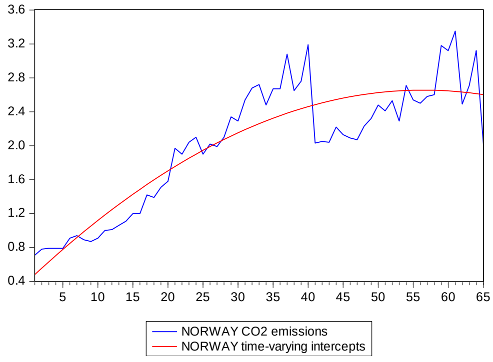

ITALY CO2 emissions
ITALY time-varying intercepts

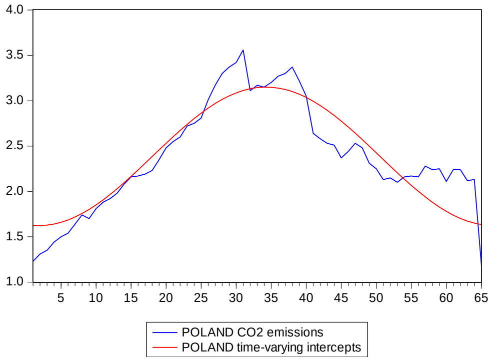

JAPAN CO2 emissions
JAPAN time-varying intercepts

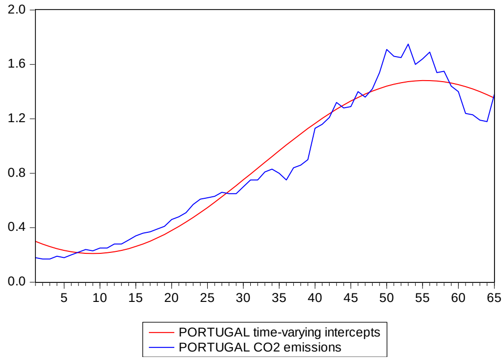

KOREA CO2 emissions
KOREA time-varying intercepts

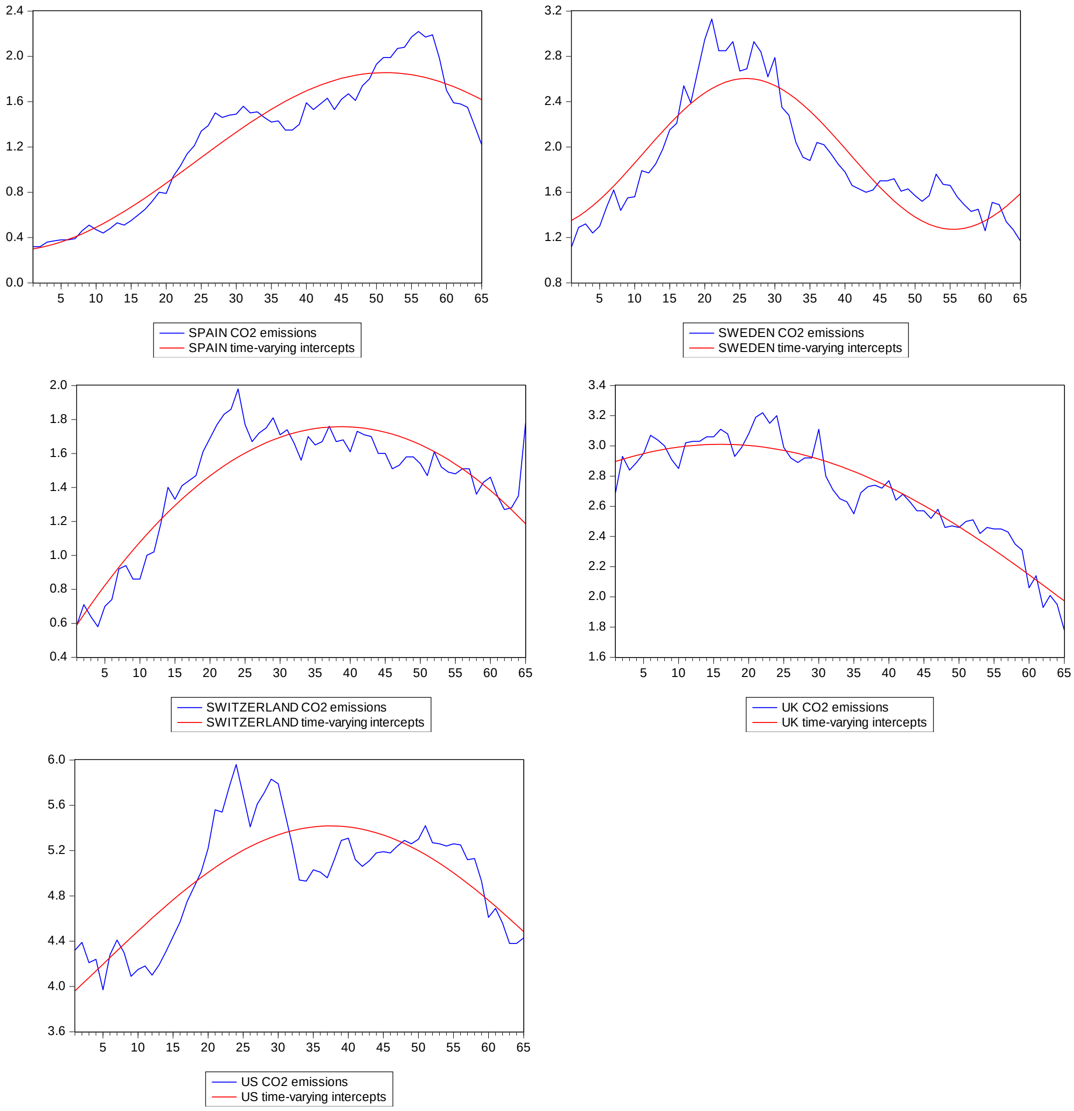

NETHERLAND CO2 emissions
NETHERLAND time-varying intercepts


NEWZEALAND CO2 emissions
NEWZEALAND time-varying intercepts


NORWAY CO2 emissions
NORWAY time-varying intercepts


POLAND CO2 emissions
POLAND time-varying intercepts


PORTUGAL time-varying intercepts
PORTUGAL CO2 emissions



approximated by sharp breaks such as dummies, the smooth transition in the deterministic trend shows our estimations considering smooth breaks are persuasive.

As mentioned in the empirical results, we could conclude asymmetric behavior of per capita CO2 emission for 21 OECD countries, which has not revealed in existing literatures after considering structural breaks at specific condition. The short-term mean reverting properties are figured out by quantile auto-regression methodology, which makes upper quantiles to represent economic expansion and lower quantiles to indicate economic recession (Koenker and Xiao, 2004).

6. Conclusion

As mentioned in Lee and Chang (2008), the conventional unit root tests always perform low efficiency in testing the convergence of per capita CO2 emissions. This paper employing a newly developed quantile auto-regression based unit root test with Fourier function to revisit the convergence of per capita CO2 emissions in 21 OECD countries. For the comparable purposes, we also make use of a battery of univariate unit root tests and quantile unit root test proposed by Koenker and Xiao (2004). Unlike previous studies only checking the convergence as a whole, we shed new light on mean-reverting properties and persistence at selected quantiles, which are able to provide impressive economic implications to environmental policy makers. In line with Lee and Chang (2008), these conventional univariate unit root tests always perform low efficiency and ignoring smooth breaks may get inaccurate empirical results. In this paper, these gaps mentioned are filled by quantile unit root test with Fourier function proposed by Bahmani-Oskooee et al. (2017).

Specifically speaking, after approximating the smooth breaks in deterministic trend, the per capita CO2 emissions in 21 OECD countries is less explosive at each quantile in comparable to the results without smooth breaks. The persistency in per capita CO2 emission is crucial to policy makers due to the explosive behavior. For a further step, the persistency would be asymmetric across the quantiles. Except for the asymmetry in persistency, the unit root behavior is also asymmetric at different quantiles. Furthermore, after approximating the structural breaks in smooth process, the per capita CO2 emission is more likely to be stationary at each quantile in comparable to the results without smooth breaks. The time-varying fitted intercepts are more fitted to the path of the per capita CO2 emissions.

Due to the asymmetric performance of the persistency and unit root behavior over different quantiles, some innovative economic implications are provided in the end. Since Kyoto Protocol, Doha Amendment and Paris Agreement, many countries come out environmental protection policies. However, the impacts of those policies are heterogenous across different countries. However, the heterogeneity in the CO2 emission for a specific country is not revealed in the existing knowledge. The empirical results from quantile unit root test with smooth breaks suggest that both persistency and unit root behavior are asymmetric across different quantiles. In other words, the heterogeneity of stochastic convergence should be realized by policy authorities at different quantiles. The stochastic convergence is not constant, but varies across different situation. Such suggests the government should care about the asymmetry by implementing different environmental protection policies at different stages. Specifically, countries like Australia, Austria, Finland, Japan, Netherlands and the US should realize the stochastic convergence of per capita CO2 emission at lower quantiles. Besides, Austria, Finland, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Sweden, Switzerland and the US should realize that per capita CO2 emission is stochastic convergence at lower quantiles. However, the per capita CO2 emissions of New Zealand is also converging at upper quantiles. For the rest of the countries, we support divergence of per capita CO2 emissions, any shocks would permanently affect the path of per capita CO2 emissions. Governments in these countries should realize the asymmetry in capita CO2 emissions. Some discretionary policies should be paid more attention with considering different situations. The environmental protection policies would not always make consistent impacts on CO2 emission moving from lower to upper quantiles. Besides, the non-normality of the CO2 emission should be also cared when implementing unit root tests.

All of the empirical results could indeed provide impressive economic implications for the environmental authorities in 21 OECD countries. From the perspective of the whole sample, the policy makers in Austria, Finland, Japan, Netherlands, New Zealand, Norway, Sweden, Switzerland and the US should notice that per capita CO2 emissions have mean-reverting properties without any necessary to implement policy tools to curb the emissions. Finally, the policy authorities should pay more attention to asymmetric behaviors in specific quantiles for 21 OECD countries.

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