CO2 Emissions Converge in China and G7 Countries? Further Evidence from Fourier Quantile Unit Root Test

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Abstract

G7 countries and China are considered both the highest energy producers globally, but also the largest CO_2 emission groups of countries among the world. In this study we apply the Fourier Quantile Unit Root test to investigate whether CO_2 emissions converge in China and G7 countries using per capita CO_2 emissions data over 1950-2013. While traditional unit root test results indicate per capita CO_2 emissions, do not converge among these G7 countries and China, empirical results from the Fourier Quantile Unit root test point out that the CO_2 emissions *did* converge in Germany, Italy and the United Kingdom three countries. Although the results of this study *do not find* strong CO_2 emissions converge in the other five countries (i.e., Canada, France, Japan, US, and China), however the CO_2 emissions did converge in certain quantiles for these five countries. Our empirical results have important policy implications for the governments of G7 countries and China to implement the effective energy policy to reduce the CO_2 emissions.

Keywords: Per Capita CO2 Emissions; China; G7 Countries; Fourier Function; Convergence; Quantile Unit Root Test

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1. Introduction

G7 countries and China are not only the biggest energy producers globally but also the largest CO_2 emission groups of countries among the world and as pointed by Gil-Alana et al., (2015) that more than 60% total CO_2 emissions around the world come from these eight countries in 2014. The reduction of greenhouse gas emissions is a global imperative, making thus each country responsible in the fight of the global warming phenomenon. In order to shape the effective energy policy to reduce the CO_2 emissions, policy makers from G7 countries and China should know and understand the time series properties of CO_2 emissions. The main property in our interest is to investigate whether or not the CO_2 emissions are converging in these countries, without future interventions. Understanding the business as usual scenario, the emissions time series properties as well as future distributions, while policy makers debate policies to might climate changes, would benefit the discussion.

If CO_2 emissions are converged, then the policymakers can continue with the same approaches and policy implementations as currently. Otherwise, it means that the policymakers must reduce carbon dioxide emission rigidly according to the difference of emission amount. Policy proposals in these economies must reexamine the existing reducing policies and put forward some reasonable suggestions to obtain sustainable development (Sun et al., 2016).

To investigate the magnitude of emissions convergence empirically, recently researchers have relied on unit root tests to assess if shocks to CO_2 emissions are persistent, a feature to be evident against convergence. However, previous studies usually focus on the average converging behavior of CO_2 emissions without considering the influence of various sizes of shocks on CO_2 emissions. In other words, the speed of convergence in CO_2 emissions is usually assumed constant, no matter how big or what sign the shock is. As a result, the commonly used conventional unit root tests possibly lead to a widespread failure in the rejection of unit-root null hypothesis of convergence.

This paper aims to employ a newly developed more powerful Quantile Unit Root test to enhance its estimation and testing accuracy. However, in the case of ignoring structural breaks, Quantile Unit Root test presents its own drawbacks. Perron (1989) and Bahmani-Oskoee *et al.* (2015) stress that failure to account for structural break in testing contributes to the failure of the rejection of unit-root null convergence. This paper proceeds in improving possible predicaments by employing a newly developed Quantile-based Unit Root test with Fourier Function as proposed by Bahmani-Oskoee *et al.* (2015) to enhance and assure its estimation and testing accuracy. Both Chang *et al*. (2011) and Bahmani-Oskoee *et al*. (2015) point out that for low frequency data it is more likely that structural changes take the form of large swings, which cannot be captured well using only dummies.

Breaks should therefore be approximated as smooth and gradual processes (Leybourne *et al.*, 1998; Chang *et al.,* 2011; and Bahmani-Oskoee *et al.,* 2015). These arguments motivate the use of a recently developed set of unit root and stationary tests that avoid this problem. Both Becker *et al.* (2004, 2006), Enders and Lee (2012), and Bahmani-Oskoee *et al.* (2015) develop tests which model any structural break of an unknown form as a smooth process via means of Flexible Fourier transforms.

This study contributes to this line of research by determining whether CO_2 emissions convergence in China and G7 countries. We test the convergence hypothesis of CO_2 emissions using a more powerful Quantile Unit Root test with Fourier Function as proposed by Bahmani-Oskoee *et al* (2016) to consider smooth breaks. Our empirical findings indicate a support of convergence hypothesis in Germany, Italy and the United Kingdom. Although we do not find strong CO_2 emission converge in the other five countries (i.e., Canada, France, Japan, US, and China), the CO_2 emissions did converge in certain quantiles for those. Apparently, the empirical findings from our study have important policy implications for the governments of G7 countries and China to implement the effective energy policy to reduce the CO_2 emissions.

The remainder of this paper is organized as follows. Section 2 briefly describes previous studies Section 3 first briefly describes the convergence test and then the Quantile Unit Root test with Fourier Function proposed by Bahmani-Oskoee *et al* (2016). Section 4 presents the data used in our study. Section 5 first presents the empirical results and then its policy implications. Section 6 concludes our paper.

2. Literature review

Strazicich and List (2003) demonstrate significant evidence of convergence in per capita CO_2 emissions, using annual data for 21 OECD nations between 1960 and 1997, Lee and Chang (2008) find that only 7 out of 21 OECD countries in their sample converge to the average emissions level. Jobert et al. (2010) also confirmed the CO_2 emissions existence hypothesis for the EU countries until 2006 although they observed slow convergence. The speed of convergence was also discussed in Barassi et al. (2011), where the convergence was proven to be achieved in particularly slow rates within 13 out of 18 OECD countries.

By contrast, Aldy (2006b) reports no evidence of convergence for his global sample comprising 88 countries during the period 1960–2000, although some evidence of convergence is discovered for a subsample of 23 OECD countries. Barassi et al. (2008) also disagreed with the existence of convergence in emissions in OECD countries. Sun and Wang (1996) test the stationarity of global CO_2 emissions based on 129-year historical data using the augmented Dickey-Fuller (ADF) (1979) unit root test and their result shows that CO_2 emissions is not stationary. Nguyen-Van (2005) employs non-parametric methods to examine the convergence in CO_2 emissions per capita on a sample of 100 countries for the period from 1966 to 1996. He reports that industrialized countries exhibit a convergence pattern, but shows little evidence of convergence for the whole sample. Panopoulou and Pantelidis (2009) examined a sample of 128 countries for the years 1960–2003. They did confirm the existence of convergence in the overall time period for all countries but also for two subsamples of countries. Li and Lin (2013) examined the topic for 110 countries over the period 1971–2008. Their results showed that there was convergence within subgroups of countries with similar income levels but no overall convergence was achieved.

However, an important point worth noting is that structural breaks were not taken into account in any of those previous studies. By identifying the points of structural change, we are able to discover specific economic factors that caused CO_2 emissions to fluctuate significantly in individual regions during the sample period. Kanjilal and Ghosh (2002) reported that industrial CO_2 emissions are non-stationary in India. Unlike traditional unit root test results, the empirical results from Lee et al., (2008) provide additional evidence that relative per capita CO_2 emissions are stationary, stochastically converge and mean reversion when controls for some breaks. Lee et al. (2008) and Chang and Lee (2008) also provide further evidence that relative per capita CO_2 emissions in 21 OECD countries are stationary and stochastically converging, when structural breaks are incorporated into their testing model.

Romero-Ávila (2008) examines the existence of stochastic and deterministic convergence of CO_2 emissions in 23 countries over the period 1960–2002 by employing the recently developed panel stationarity test of Carrion-i-Silvestre et al (2005). Their empirical results provide strong evidence supporting both stochastic and deterministic convergence in CO_2 emissions, thus confirming the findings of those Strazicich and List (2003) and Westerlund and Basher (2007). Lee and Chang (2009) also applied a panel stationarity test developed by Carrioni-Silvestre et al. (2005) for 21 OECD countries from 1950 to 2002 and found evidence for stochastic convergence. They also emphasized that the structural breaks that occurred in the 1960s and over the 1970–1982 period corresponded to time periods when fossil fuel became the main source of productivity.

Jobert et al. (2010) use a Bayesian shrinkage estimation method to test the convergence of per capita CO_2 emissions in the European Union (EU) and find that the hypothesis of absolute convergence in per capita CO_2 emissions is supported and a slight upward convergence is observed in the EU. Ordas Criado and Grether (2011) provide the most comprehensive analysis out of the convergence studies. They apply non-parametric dynamic distributional analysis and find that between 1960 and 2002 national per capita CO_2 emissions have actually diverged globally and predict that emissions will continue to diverge into the future. However, they do find evidence that the per capita emissions of developed countries have converged conditional on macroeconomic variables. Yavuz and Yilanci (2013) employ a recently proposed TAR panel nonlinear unit root test to test the convergence of per capita carbon dioxide emissions of the G7 countries during the 1960–2005 period. They found that the emissions are nonlinear, which shows that testing nonlinearity for the convergence hypothesis should be considered before reaching any conclusions about convergence. Li et al. (2014) also reach the same conclusion that they find CO_2 emission converge in 12 out of 50 US states after considering nonlinearity for the convergence hypothesis test. Sun et al., (2016) also examine the validity of carbon dioxide emission from the nonlinear point of view and provide clear evidence indicates that carbon dioxide emission is convergence in most countries, not depending on their development pattern. This implies that the existing policies in most countries are rational, and the United States, Japan, and Germany need more efforts in reducing the carbon dioxide emission.

Sun et al., (2016) find that their approximation has higher power to detect smooth breaks than the linear method, as the true data generating process of carbon dioxide emission convergence is in fact a stationary nonlinear process.

Regarding the China study, Huang and Meng (2013) analyze CO_2 emissions in urban China based on our spatio-temporal model shows that overall, per capita CO_2 emissions in these areas increased and converged from 1985 to 2008. Their results reveal the dynamics of spatial effects in the convergence model, thus identifying the role of spatial effects in a disaggregated manner. The convergence rate increases when considering its spatio-temporal dependency. This 'catching-up' in the convergence of CO_2 emissions indicates an increasing trend in such emissions in China, although the Chinese government has taken many measures to reduce CO_2 emissions. Empirical results further motivate policy makers to reflect on whether current policies actually reduce carbon emissions in China. Wang and Zhang (2014) analyze differences in per capita carbon dioxide emissions from 1996 to 2010 in six sectors across 28 provinces in China and examine the σ -convergence, stochastic convergence and β convergence of these emissions and their results show that per capita carbon dioxide emissions in all sectors converged across provinces from 1996 to 2010. Wang *et al.*, (2014) also empirically investigate the convergence behavior of carbon dioxide emissions in China based on provincial data for the period of 1995–2011. They use the log t-test developed by Phillips and Sul (2007) and find evidence of divergence at the country level and convergence to three steady state equilibriums at provincial level. Hao et al., (2015) investigate the existence of convergence in per capita sulfur dioxide emissions across Chinese cities using city-level panel data between 2002 and 2012. Dynamic panel data estimators are utilized and their empirical results indicate that there were absolute and conditional convergences in per capita sulfur dioxide emissions across cities within the whole nation as well as in the eastern, western and central regions of China.

On the other hand, Zhao *et al.* (2015) also investigate the convergence of province-level carbon dioxide emission intensities among a panel of 30 provinces in China over the period 1990–2010. They use a novel spatial dynamic panel data model to evaluate an empirical hypothesis of convergence among provinces and their empirical results suggest that CO_2 emission intensities are converging across provinces in China. However, the rate of convergence found is higher for the dynamic panel data model than that of the cross-sectional regression models. Zhao et al. (2015) also find that province-level CO_2 emission intensities are spatially correlated and the rate of convergence, when controlling for spatial autocorrelation, is higher with the non-spatial models.

Our study here fills two gaps in the existing literature by examining the CO_2 convergence in China and G7. Firstly, employing the specific methodology, we take into account structural breaks and secondly, we focus our investigation to some of the highest contributors to the world aggregate emissions.

3. Methodology

3.1. Convergence Tests

Our methodology is rooted in the work of Evans (1998), who introduces a particular notion of convergence, which implies that the long-run CO_2 gap between any two regions must be stationary. To formalize the idea empirically, suppose that y_{it} the log of CO_2 emissions for state *i = G7 countries and China* at time $t = 1, . . . , T$, is non-stationary, and thus exhibits a unit root. Then a pair-wise convergence is said to occur if, for any pair of states *i* and *j*, the difference, $y_{it} - y_{jt}$, is stationary so that y_{it} and y_{jt} are cointegrated. Specifically, this notion of pair-wise convergence is equivalent to the condition that the difference between the individual series and their mean value at each point in time is stationary.

This hypothesis could be tested using the following regression

$$\tilde{y}_{it} = \alpha_i + \tau_i t + \varphi_i \tilde{y}_{it-1} + u_{it} \tag{1}$$

where $\tilde{y}_{it} = y_{it} - \frac{1}{N}\sum_{j=1}^{N} y_{jt}$ (relative per capita CO2 emissions), α_i and τ_i are state specific intercept and trend terms, and u_{it} is a disturbance term that may by correlated across both i and t . The key parameter is φ_i which measures the degree of the convergence. If $\varphi_i = 1$ then state *i* has a unit root and is thus non-convergent, whereas, if $\varphi_i < 1$ then state *i* is convergent. The exact hypothesis to be tested is given as follows.

$$H_0 : \varphi_i = 1 \text{ for all } i \text{ versus } H_1 : \varphi_i < 1 \text{ for some } i. \tag{2}$$

A rejection of the null should therefore be taken as evidence in favor of convergence for at least one state, whereas a non-rejection should be taken as evidence of non-convergence for the whole panel.

3.2. Fourier Quantile Unit Root Test

Following Bahmani-Oskooee *et al., (*2016) that we can assume that a series $\tilde{y}_{it}$ follows the data generating process (DGP) as

$$\tilde{y}_{it} = Z_t \lambda + \sum_{k=1}^{n} \gamma_{1,k} \sin(\frac{2\pi kt}{T}) + \sum_{k=1}^{n} \gamma_{2,k} \cos(\frac{2\pi kt}{T}) + e_t \tag{3}$$

In order to obtain a global approximation from the smooth transition and unknown number and to equip deterministic components with breaks, we follow Gallant (1981) approach by employing the Fourier approximation and putting both terms of $\sum_{k=1}^{n} \gamma_k \sin(\frac{2\pi kt}{T})$ and $\sum_{k=1}^{n} \gamma_k \cos(\frac{2\pi kt}{T})$ into the model. The reason to select both

$\sin(\frac{2\pi kt}{T})$ and $\cos(\frac{2\pi kt}{T})$ 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. Where k, T, and t are the number of frequencies of the Fourier function, sample size, and a trend term, respectively, and $\pi = 3.1416$. Z is an optional exogenous regressor which consists of a constant term in our case; n denotes the number of frequencies contained in the approximation and $n \leq \frac{T}{2}$ should be satisfied.

The estimation of equation (3) involves two parameters choice - the choice of n and the choice of k. As noted by Becker et al. (2004), it is reasonable to restrict n=1 because the joint null hypothesis of γ s is rejected for one frequency (i.e., $\gamma_{1,k} = \gamma_{2,k} = 0$), and time invariance hypothesis is also rejected. Similarly, Enders and Lee (2012) note that the restriction n=1 is useful to save the degrees of freedom and prevents the over-fitting problem. Hence, we re-specify equation (3) as follows:

$$\tilde{y}_t = Z_t\lambda + \gamma_1 \sin(\frac{2\pi kt}{T}) + \gamma_2 \cos(\frac{2\pi kt}{T}) + e_t \qquad (4)$$

where $\gamma = [\gamma_1, \gamma_2]'$ measures the amplitude and displacement of the frequency component. Particularly the standard linear specification is a special case of equation (4) while setting $\gamma_1 = \gamma_2 = 0$. There must be at least one of the both frequency components existed if a structural break is appeared. Becker et al. (2004) utilize this property of equation (4) to develop a more powerful test to detect structural breaks under an unknown form than that of Bai and Ng (2004) test.

In determining an optimal k, we set the maximum of k equal to 5. For any $K=k$, we estimate equation (4) employing ordinary least squares (OLS) method and save the sum of squared residuals (SSR). Frequency k^* is setting as optimum frequency at the minimum of SSR. With above assumption and respect to the deterministic components, we test the following null hypothesis:

$$H_0 : e_t = \upsilon_t , \upsilon_t = \upsilon_{t-1} + u_t \tag{5}$$

where u_t is assumed to be an I(0) process with zero mean. To test the null hypothesis, we follow Christopoulos and Leon-Ledesma (2010) to calculate the statistic *via* three steps shown in following.

First step: we set a maximum k equals to 5, and then find out the optimal frequency of k^* by employing the methodology described above. We compute the OLS residuals as that:

$$e_t = \tilde{y}_{it} - \hat{\alpha}(t) \tag{6}$$

$$\hat{\alpha}(t) = Z_t \hat{\lambda} + \hat{\gamma}_1 \sin(\frac{2\pi \overset{*}{k} t}{T}) + \hat{\gamma}_2 \cos(\frac{2\pi \overset{*}{k} t}{T}) \tag{7}$$

Second step: a unit root on the OLS residuals given from equation (6) is tested by using Quantile regression frameworks which was introduced by Koenker and Xiao's (2004). The test is an extension of Augmented Dickey-Fuller (ADF) type unit root test and has much more power than 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. To illustrate the test, we start with standard ADF test:

$$e_t = \rho_1 e_{t-1} + \sum_{k=1}^{k=1} \rho_{1+k} e_{t-k} + \varepsilon_t \tag{8}$$

where stochastic variable of concern, e_t is estimated residuals from equation (6). In (8) ρ_1 is the AR coefficient and reflect the persistence degree. $|\rho_1| < 1$ is required for mean reverting properties of real exchange rate (hereafter, RER) and for ruling out explosive behavior. Koenker and Xiao (2004) define the τ_{th} conditional quantile of e_t as follows:

$$Q_{e_t}(\tau \mid \xi_{t-1}) = \alpha_0(\tau) + \rho_1(\tau) e_{t-1} + \sum_{k=1}^{k=1} \rho_{1+k}(\tau) \Delta e_{t-k} + \vartheta_t \tag{9}$$

where $Q_{e_t}(\tau \mid \xi_{t-1})$ is τth quantile of e_t conditional on the past information set, $\xi_{t-1} \cdot \alpha_0(\tau)$ is τth conditional quantile of ϑ_t and its estimated values captures the magnitude of RER shock in each quantile. $\rho_1(\tau)$ measures the speed of mean reversion of e_t within each quantile. Optimum lags are selected by the AIC information criteria.

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

$$\min \sum_{t=1}^{n} (\tau - I(e_t < \alpha_0(\tau) + \rho_1(\tau)e_{t-1} + \sum_{k=1}^{k=1} \rho_{1+k}(\tau)\Delta e_{t-k})) \left| e_t - \alpha_0(\tau) + \rho_1(\tau)e_{t-1} + \sum_{k=1}^{k=1} \rho_{1+k}(\tau)\Delta e_{t-k} \right| \tag{10}$$

where I=1 if $e_t < (\alpha_0(\tau) + \rho_1(\tau)e_{t-1} + \sum_{k=1}^{k=1} \rho_{1+k}(\tau)\Delta e_{t-k})$ and I=0, otherwise. As sugested by Koenker and Xiao (2004), after solving equation (10), we can test the stochastic properties of e_t within the τth quantile by using the following *t ratio* statistic:

$$t_n(\tau_i) = \frac{\hat{f}(F^{-1}(\tau_i))}{\sqrt{\tau_i(1-\tau_i)}} (E'_{-1} p_x E_{-1})^{1/2} (\hat{\rho}_1(\tau_i) - 1) \tag{11}$$

In (11) E_{-1} is the vector of lagged dependent variable e_{t-1}, P_x is the projection matrix onto the space orthogonal to $X = (1, \Delta e_{t-1}, \ldots, e_{t-k})$. $\hat{f}(F^{-1}(\tau_i))$ is a consistent estimator of $f(F^{-1}(\tau_i))$. Koenker and Xiao (2004) suggest that it can be expressed as :

$$\hat{f}(F^{-1}(\tau_i)) = \frac{(\tau_i - \tau_{i-1})}{x'(\beta(\tau_i) - \beta(\tau_{i-1}))} \tag{12}$$

where $\beta(\tau_i) = (\alpha_0(\tau_i), \rho_1(\tau_i), \rho_2(\tau_i), \ldots, \rho_{1+k}(\tau_i))$ and $\tau_i \in [\underline{\lambda}, \overline{\lambda}]$ In this paper, we set $\underline{\lambda} = 0.1$ and $\overline{\lambda} = 0.9$. As can be seen, using $t_n(\tau_i)$ statistics, we are able to test the unit root hypothesis in each quantile while ADF and other conventional unit root tests examine the unit root only on the conditional central tendency.

To assess the unit root behavior over a range of quantiles, Koenker and Xiao (2004) recommend following the Quantile Kolmogorov–Smirnov (QKS) test:

$$QKS = \sup_{\tau_i \in [\underline{\lambda}, \bar{\lambda}]} |t_n(\tau)| \tag{13}$$

In this paper, we construct the QKS statistics by choosing maximum $|t_n(\tau)|$ statistics over range $\tau_i \in [0.1, 0.9]$. As noted by Koenker and Xiao (2004), the limiting distributions of $t_n(\tau_i)$ and QKS test statistics are nonstandard and depend on nuisance parameters. Hence, to derive critical values for the above mentioned test, we implement the re-sampling procedures of Koenker and Xiao (2004). To construct the 95% confidence intervals for both the $\alpha_0(\tau)$ and $\rho_1(\tau)$ that we can use their empirical distribution functions.

4. Data Sets

In our study that we use per capita CO_2 emissions from the CDIAC (http://cdiac.ornl.gov/CO2Emission/times/national - Carbon Dioxide Information Analysis Center) with the data ending in 2013 for all G7 countries and China. Due to data availability for all G7 countries and China, that we start our sample in 1950 (Figure 1).

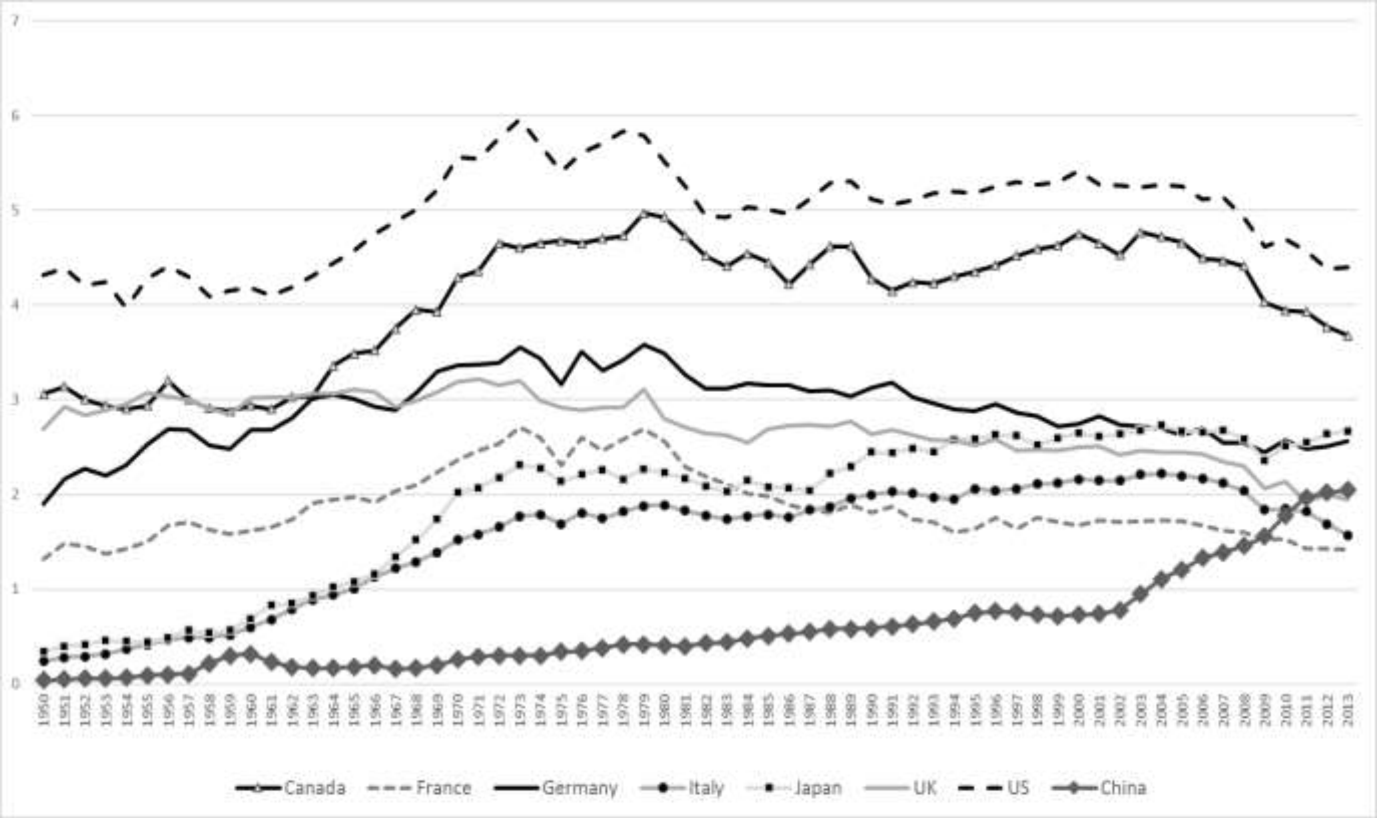

Figure 1. Per capita CO2 Emissions in G7 and China (1950-2013)

The necessity of using per capita measures in the analysis of CO_2 emissions has been emphasized by Soz (1997) in the Kyoto Protocol that per capita basis is a direct measure of human welfare. McKibbin and Stegman (2005) also mention that individual activities such as car use cause greenhouse gases, so it can be assured that a per capita measure is necessary. In addition, by using a per capita indicator, we incorporate vast differences in population amongst the countries examined. Table 1 reports summary statistics of CO_2 emissions for G7 countries and China. We find that the United States and China have the highest and lowest mean CO_2 emissions per capita of 5.965 and 0.583, respectively. Jarque-Bera statistics also indicate that CO_2 emissions are non-normal for most the G7 countries and China with the exception of Germany and the United States. As pointed by Koenker and Xiao (200), the QAR-based unit root test has higher power than conventional unit root tests, because the QAR-based unit root test is superior to standard unit root tests in case of departure from Gaussian residuals and these further confirm the use of our quantile unit root test.

Table 1. Summary Statistics of Per Capita CO2 Emissions in G7 and China

Countries	Mean	Max.	Min.	Std. Dev.	Skew.	Kurt.	J.-B.
China	0.583	2.050	0.04	0.505	1.432	4.428	27.341***
Canada	4.064	4.97	2.88	0.665	-0.672	1.961	7.701**
France	1.874	2.71	1.32	0.68	0.803	2.628	7.248**
Germany	2.892	3.58	1.90	0.371	-0.219	2.625	0.888
Italy	1.529	2.222	0.24	0.623	-0.894	2.343	9.693***
Japan	1.893	2.73	0.34	0.803	-0.834	2.122	9.481***
United Kingdom	2.727	3.22	1.93	0.32	-0.622	2.818	4.221*
United States	4.965	5.96	3.97	0.516	-0.222	2.023	3.044

Note:

1. The sample period is from 1950 to2013.
2. * , **, and *** indicate significance at the 0.1, 0.05, and 0.01 levels, respectively.

5. Empirical Results and Policy Implications

5.1. Empirical Results from Univariate Unit Root Tests

For comparison, several univariate unit root tests are first employed to examine the null hypothesis of a unit root in $\tilde{y}_{it}$ (relative per capita CO_2 emissions) for these 8 countries that we study. Table 2 reports the results of the three univariate unit root tests—the Augmented Dickey and Fuller (1981, ADF), the Phillips and Perron (1988, PP) and the Kwiatkowski *et al.* (1992, KPSS) tests. Results from Table 2 clearly indicate that both the ADF and PP tests fail to reject the unit root null hypothesis for most of the countries under study. The KPSS also rejects the stationary null hypothesis for most of the countries. Based on the results from Table 2, there is no question that three univariate unit root tests—the ADF, PP, and KPSS tests all fail to reject the null of non-stationary relative per capita CO_2 emission for most of the countries. This result is consistent with that of existing literature and is due to the low power of these three univariate unit root tests when relative per capita CO_2 emissions are highly persistent. This result implies that relative per capita CO_2 emissions do not converge in China and G7 countries following the random walk processes during the sample period.

Table 2: Univariate Unit Root Tests.

	Level			First differences		
Country	ADF	PP	KPSS	ADF	PP	KPSS
Canada	-1.267[0]	-1.229[2]	0.497(6)	-8.098(0) ***	-8.106(2) ***	0.250(1)
China	0.466[1]	0.986[4]	0.362(6)	-4.200(0) ***	-4.170(2) ***	0.647(5)
France	-0.233[1]	-0.256[4]	0.920(6)	-10.848(0) ***	-10.848(2) ***	0.198(3)
Germany	-1.029[1]	-1.029[0]	0.802(6)	-8.550(0) ***	-8.667(2) ***	0.301(2)
Italy	-1.550[0]	-1.538[3]	0.940 (6)	-6.371(0) ***	-6.353(3) ***	0.378(2)
Japan	-0.282[0]	-0.260[3]	0.993(6)	-8.310(0) ***	-8.299(3) ***	0.053(4)
United Kingdom	-0.954[1]	-0.572[3]	0.935(6)	-10.38(0) ***	-10.635(1) ***	0.134(3)
United States	-1.427[1]	-1.322[2]	0.194(5)	-7.06184(0) ***	-7.062(0) ***	0.153(1)

Notes: ***, ** and * indicate the null hypothesis is rejected at the 1%, 5% and 10% levels, respectively. The number in brackets indicates the lag order selected based on Schwarz information criterion. The number in the parenthesis indicates the truncation for the Bartlett Kernel, as suggested by the Newey-West test (1987).

Table 3: Empirical results of quantile estimation and unit-root tests for each quantile (without considering smooth breaks)

	τ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Canada	$\rho_1(\tau)$	**0.864***	0.892	0.958	0.979	0.974	0.931	0.978	0.894	0.909
	QKS for quantiles of 10–90%:			1.734						
France	$\rho_1(\tau)$	0.967	1.012	0.992	0.977	1.002	1.011	0.997	0.986	1.014
	QKS for quantiles of 10-90%			0.805						
Germany	$\rho_1(\tau)$	0.961	0.954	0.946	0.985	0.905	0.952	0.977	0.985	1.025
	QKS for quantiles of 10–90%:			1.734						
Italy	$\rho_1(\tau)$	0.974	1.014	0.998	0.972	0.954	0.948	0.950	0.967	0.942
	QKS for quantiles of 10–90%:			2.045						
Japan	$\rho_1(\tau)$	1.003	0.992	0.981	0.968	0.983	1.001	1.006	0.989	0.986
	QKS for quantiles of 10–90%:			1.323						
UK	$\rho_1(\tau)$	0.922	0.938	0.975	0.976	0.969	0.972	0.994	1.008	1.025
	QKS for quantiles of 10–90%:			2.229						
USA	$\rho_1(\tau)$	0.943	0.897	0.813	0.892	0.909	0.978	1.036	1.061	1.089
	QKS for quantiles of 10–90%:			1.886						
China	$\rho_1(\tau)$	1.025	1.007	1.016	1.015	0.996	0.974	0.968	0.991	0.991
	QKS for quantiles of 10–90%:			0.736						

Notes: ** and ***denote significance at 5% and 1% levels, respectively. Numbers in parenthesis denote bootstrap p-values with the bootstrap replications set to be 10000. The lag length p are selected based on robust Schwarz information criterion as suggested by Koenker and Xiao (2004) with a maximum lag set to be 12. For α1(τ), the unit-root null is examined with the tn(τ) statistic. The number in parenthesis is p-value.

5.2. Empirical Results from the Quantile Unit Root Tests

As we know that the univariate unit root tests might have lower power when they are applied to a finite sample. The previous studies usually focus on the average converging behavior of relative per capita CO_2 emissions without considering the influence of various sizes of shocks on relative per capita CO_2 emissions. As a result, the commonly used conventional unit root tests possibly lead to a widespread failure in the rejection of unit-root null hypothesis of convergence. Quantile Unit Root test provide a good tool to enhance its estimation and testing accuracy.

Results for Quantile Unit Root test are provided in Table 3. The QKS statistics from Table 3 indicate that relative CO_2 emissions do not converge in both G7 countries and China under study. However, as we know that Quantile Unit Root tests have some drawback if we fail to consider breaks as indicated by Perron (1989) and Bahmani-Oskoee *et al.* (2015) that failure to account for structural break in testing is said to contribute to the failure of the rejection of unit-root null convergence. To reduce this deficiency, we apply a newly developed Quantile-based Unit Root test with Fourier Function as proposed by Bahmani-Oskoee *et al.* (2016) to further enhance and assure its estimation and testing accuracy. Therefore, we go for the Fourier Quantile Unit Root Test. First, a grid-search is performed to find the best frequency, as there is no a priori knowledge concerning the shape of the breaks in the data. We estimate Equation (9) for each integer $k = 1, ...5,$ following the recommendations of Enders and Lee (2004, 2012) that a single frequency can capture a wide variety of breaks. The residual sum of squares (RSSs) indicates that a single frequency *(k=0.8, 0.7, 0.7, 0.6, 0.3, 0.2, 2.5, and 0.1)* work best for G7 countries and China.

Table 4: Empirical results of quantile estimation and unit-root tests for each quantile (with considering smooth breaks)

	τ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Canada	$\rho_1(\tau)$	0.842	**0.780****	**0.753****	**0.819****	**0.779****	**0.791****	**0.651*****	**0.671*****	**0.744*****
	QKS for quantiles of 10–90%:	2.973								
	Optimal Frequency	0.8	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**66.542*****						
France	$\rho_1(\tau)$	0.763	0**.650****	**0.607****	**0.537*****	**0.550*****	**0.629****	0.792	**0.615****	**0.663***
	QKS for quantiles of 10-90%	2.854								
	Optimal Frequency	0.7	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**681.423*****						
Germany	$\rho_1(\tau)$	0.899	**0.993**	**0.779***	**0.703****	**0514*****	**0.606*****	**0.581*****	**0.652****	**0.699****
	QKS for quantiles of 10–90%:	**3.804****								
	Optimal Frequency	0.7	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**205.775*****						
Italy	$\rho_1(\tau)$	1.03	0.946	**0.789****	**0.725*****	**0.655*****	**0.605*****	**0.556*****	**0.567*****	**0.593*****
	QKS for quantiles of 10–90%:	**4.461*****								
	Optimal Frequency	0.6	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**600.4*****						
Japan	$\rho_1(\tau)$	**0.613****	**0.731****	0.877	**0.812****	**0.786****	**0.733*****	**0.733*****	**0.804****	0.838
	QKS for quantiles of 10–90%:	2.862								
	Optimal Frequency	0.3	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**508.645*****						
UK	$\rho_1(\tau)$	1.094	1.058	0.856	**0.851***	**0.849****	**0.794*****	**0.763*****	**0.687*****	**0.760***
	QKS for quantiles of 10–90%:	**3.154***								
	Optimal Frequency	0.2	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**44.648*****						
USA	$\rho_1(\tau)$	**0.728*****	**0.700*****	**0.772****	**0.693*****	**0.773****	**0.809****	**0.795****	**1.005**	**1.058**
	QKS for quantiles of 10–90%:	3.074								
	Optimal Frequency	2.5	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**170.613*****						
China	$\rho_1(\tau)$	1.050	0.965	0.897**	**0.888****	**0.884****	**0.823*****	**0.791*****	**0.729*****	**0.755****
	QKS for quantiles of 10–90%:	3.028								
	Optimal Frequency	0.1	F-Statistics for $\gamma_1 = \gamma_2 = 0$	**3200.569*****						

Notes: ** and ***denote significance at 5% and 1% levels, respectively. Numbers in parenthesis denote bootstrap p-values with the bootstrap replications set to be 10000. The lag length p are selected based on robust Schwarz information criterion as suggested by Koenker and Xiao (2004) with a maximum lag set to be 12. For α1(τ), the unit-root null is examined with the tn(τ) statistic. The number in parenthesis is p-value.

Table 4 reports the results of our Fourier Quantile Unit Root Test. Results from Table 4 clearly indicate that relative per capita CO2 emissions did converge in Germany, Italy and the United Kingdom when Fourier Quantile Unit Root test is applied. If we look at the coefficients (of $\rho_1(\tau)$ – a measure of persistence) that we find that they are significant at 0.2-0.9 for Germany, 0.3-0.9 for Italy, and 0.4-0.9 for the United Kingdom. These results indicate that shocks to relative per capita CO_2 emissions are nonlinear and asymmetric. These results are not shown in previous studies. For the rest of 5 countries (i.e., Canada, China, France, Japan, the United States) that we find the coefficients (of $\rho_1(\tau)$) are significant at some certain quantiles. These results clearly indicate that relative per capita CO_2 emissions did converge in some quantiles among G7 countries and China. Empirical results lead us to the conclusions that relative per capita CO_2 emissions did converge in some G7 countries (i.e., Germany, Italy and the United Kingdom). Our empirical findings suggest that allowing for structural breaks results in more rejection of the unit root null hypothesis. The results point to the importance of proper modelling of structural breaks in relative per capita CO_2 emissions.

6. Conclusion

This study applies the Fourier Quantile Unit Root test to investigate whether CO_2 emissions converge in China and G7 countries using relative per capita CO_2 emissions data over 1950-2013. Our empirical findings suggest that allowing for structural breaks results in more rejection of the unit root null hypothesis. The results point to the importance of proper modelling of structural breaks in relative per capita CO_2 emissions.

Within the extensive literature examining the existence of convergence of CO2 emissions in various country groups, our study's results specifically on the G7 and China are consistent with studies such as Aldy (2006b) that concluded divergence for the full country sample, but some convergence for the OECD countries (highly industrialized and mostly developed economies). In addition, the hypothesis of CO2 lack of convergence was confirmed by Strazicich and List (2003), Westerlund and Basher (2007), Lee *et al.,* (2008), Chang and Lee (2008), and Lee and Chang (2009) which indicate that relative per capita CO_2 emissions are stationary, stochastically converge and mean reversion in several panels of OECD countries when controls for some breaks. For specifically the case of China, Wang and Zhang (2014), Wang *et al.*, (2014), Hao *et al.,* (2015), and Zhao *et al.* (2015) have concluded some level of convergence; however their analysis focused in within China CO2 emissions of various provinces or economic sectors – and not on the country's convergence with other countries.

Except for the differences in country groups and datasets employed, the use of a newly proposed Fourier Quantile model might also be proven more useful and accurate in testing for the hypothesis of convergence, due to it being considered more reliable than conventional unit root tests. Koenker and Xiao (2004) state the same in the case of departure from Gaussian residuals – see summary statistics Table 1. Hence, our study also finds stronger evidence in support to relative per capita CO_2 emissions convergence.

The convergence of carbon dioxide emission means that the markets can equilibrium actively and the policymakers can stick to current policies, and this means that the policymakers can reduce carbon dioxide emission rigidly according to the difference of emissions amount. Regarding the divergence economies such as Canada, China, France, Japan, and the United States can take some measures to reduce emission amounts to release the burden of massive usage of fossil energy and to adjust economic instruments. Policy proposals in these countries must reexamine the existing carbon-reducing policies and propose some reasonable suggestions to obtain sustainable development (Sun et al., 2016).

The main reason for testing the hypothesis of emission convergence is that if the hypothesis is confirmed, it increases the ability for future projections and hence, promotes the implementation of more appropriate policies (McKibbin and Stegman, 2005). Under the current global conditions, all various socioeconomic and environmental indicators tend to move unpredictably and hence their forecasting is a difficult task. Confirming convergence gives some robustness to policy makers to expect certain levels of emissions in a business as usual scenario and hence, implement environmental policies at the right timing.

Based our empirical results, the projection for these five economies' CO_2 emissions (such as Canada, China, France, Japan, and the United States) cannot be estimated with precision, due to lack of convergence.

El-Montasser et al. (2015) also stresses the importance of convergence differences between developed and developing countries, especially with regards the future common strategies to tackle the negative consequences of climate change. They also confirm that non-convergence in developed countries such as the five here (with non-convergence results) is an indication that the international environmental system of countries is not ready to promote common strategies and one-fits-all policies. As a result, the policies should also be country-specific and will depend on the socio-economic characteristics of each country (El-Montasser et al., 2015). For the other three countries such as Germany, Italy and the United Kingdom where relative CO_2 emissions converge and this implies the existing policies in these three countries are rational. The policymakers of these economies can stick to the current carbon-reduction policies. All in all, the existence or not of emission convergence in the world is a concept that has been underestimated in the global negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) where the common climate future is discussed.

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References

Aldy, J.E. (2006a) Divergence in State-Level Per Capita Carbon Dioxide Emissions, Discussion Paper, RFF DP 06-07.

Aldy, J.E (2006b) Per capita carbon dioxide emissions: convergence or divergence? *Environmental Resource Economics,* 33:533–555

Bai, J. and Ng, S. (2004) A PANIC attack on unit roots and cointegration, *Econometrica*, 72, 4, 1127-1177.

Bahmani-Oskooee, M. Chang, T., and Wu, .-P. (2015) Purchasing Power Parity in Transition Countries: Panel Stationary Test with Smooth and Sharp Breaks. *International Journal of Financial Studies, MDPI, Open Access Journal*, 3(2), 1-9.

Bahmani-Oskooee, M., Chang, T. and Lee, K.-C. (2016) Purchasing power parity in emerging markets: A panel stationary test with both sharp and smooth breaks. *Economic Systems*, 40(3), 453-460.

Barassi, M. R., Cole, M. A. and Elliott, R. J. R. (2008) Stochastic divergence or convergence of per capita carbon dioxide emissions: re-examining the evidence,

Environmental and Resource Economics, 40, 121–37.

Barassi, M. R., Cole, M. A. and Elliott, R. J. R. (2011) The stochastic convergence of CO2 emissions: a long memory approach, *Environmental and Resource Economics*, 49, 367–85.

Becker, R., Enders, W., and Lee, J. (2004) A general test for time dependence in parameters, J*ournal of Applied Econometrics*, 19, 899-906.

Becker, R., Enders, W, and Lee, J. (2006) A stationarity test in the presence of an unknown number of smooth breaks, *Journal of Time Series Analysis*, 27, 3, 381-409.

Carrion-i-Silvestre, J.L., Del Barrio-Castro, T and López-Bazo, E (2005) Breaking the panels: an application to the GDP per capita. *Economic Journal*, 8:159–175.

Chang, C. P and Lee, C. C. (2008) Are per capita carbon dioxide emissions converging among industrialized countries? New time series evidence with structural breaks, *Environment and Development Economics*, 13, 4, 497-515.

Chang, C.P., Lee, C.C., Hsieh, M.-C. (2011) Globalization, Real output and Multiple Structural Breaks. Global Economic Review, 40, 421-444.

Christopoulos, D., Leon-Ledesma, M. (2010). Smooth breaks and non-linear mean reversion: Post-Bretton Woods real exchange rates. Journal of International Money and Finance, 29(6), 1076-1093.

Dickey, D. A. and Fuller, W. A. (1979) Likelihood ratio statistics for autoregressive time series with a unit root, *Econometrica*, 49: 1057-1072.

El-Monstasser, G., Inglesi-Lotz, R. and Gupta,R. (2015) Convergence of Greenhouse Gas Emissions among G7 Countries, *Applied Economics*, 47, 60, 6543-6552.

Enders, W. and Lee, J. (2012) A unit root test using a Fourier series to approximate smooth breaks, *Oxford Bulletin of Economics and Statistics*, 74(4), 574-599.

Evans, P. (1998) Using panel data to evaluate growth theories, *International Economic Review*, 39:295–306

Gallant, R. (1981) On the basis in flexible functional form and an essentially unbiased form: the flexible Fourier form. *Journal of Econometrics*, 15:211–353.

Gil-Alana, L.A., Perez de Garcia, F., Gupta, R. (2015) Modeling Persistence of carbon emission allowance prices. University of Pretoria, Department of Economics Working Paper Series 2015-15.

Hao, Y. Zhang, Q. Zhong, M. and Li, B (2015) Is there convergence in per capita SO2 emissions in China? An empirical study using city-level panel data, *Journal of Cleaner Production*, 108, 944-954.

Huang, B and Meng, Lina (2013) Convergence of per capita carbon dioxide emissions in Urban China: a spatio-temporal perspective, *Applied Geography*, 40, 21-29.

Jobert, T., Karanfil, F. and Tykhonenko, A. (2010) Convergence of per capita carbon dioxide emissions in the EU: Legend or reality? *Energy Economics*, 32, 1364-1373.

Kanjilal, K. and Ghosh, S. (2002) Future industrial CO_2 emission and consequences of CO_2 abatement strategies on the Indian economy, *Pacific and Asian Journal of Energy*, 12, 123–128.

Koenker, R., Xiao, Z. (2004) Unit Root Quantile Autoregression Inference. *Journal of the American Statistical Association*, 99, 775-787.

Kwiatkowski, D., Phillips, P., Schmidt, P., and Shin, Y (1992), “Testing the Null Hypothesis of Stationarity Against the Alternative of a Unit Root: How Sure Are We That Economic Time Series Have a Unit Root?” *Journal of Econometrics,* 54, 159-178.

Lee, C.C., and Chang, C.P. (2008) Energy consumption and economic growth in Asian economies: a more comprehensive analysis using panel data, R*esource and Energy Economics*, 30, 50–65.

Lee, C.C., Chang, C.P., and Chen, P.F. (2008) Energy-income causality in OECD countries revisited: the key role of capital stock. *Energy Economics,* 30, 2359–2373

Leybourne, S., Newbold, P and Vougas, D. (1998) Unit roots and smooth transitions, *Journal of Time Series Analysis,* 19, 83-97.

Li, X-L., Tang, D.P and Chang, TY (2014) CO2 emissions converge in the 50 U.S. states — Sequential panel selection method, *Economic Modelling*, 40, 320-333.

Li, X. and Lin, B. (2013) Global convergence in per capita CO2 emissions, *enewable and Sustainable Energy Reviews*, 24, 357–63.

McKibbin,W. J. and Stegman, A. (2005) Convergence and per capita carbon emissions, *Brooking Discussion papers in International Economics* No 167.

Nguyen -Van, P (2005) Distribution Dynamics of CO_2 Emissions. *Environmental and Resource Economics,* 32: 495–508.

Ordas Criado, C. and Grether, J.M., (2011) Convergence in per capita CO2 emissions: a robust distributional approach. *Resource Energy Economics*. 33, 637–665

Panopoulou, E. and Pantelidis, T. (2009) Club convergence in carbon dioxide emissions, *Environmental and Resource Economics*, 44, 47–70

Perron, P. (1989) The great crash, the oil price shock and the unit root hypothesis, *Econometrica, 57,* 1361-1401.

Phillips, P.C.B. and Sul, D. (2007) Transition modeling and econometric convergence tests. *Econometrica*, 75 (6), 1771–1855.

Phillips, P. C. B., and P. Perron (1988) Testing for a Unit Root in Time Series Regression." *Biometrika* 75, 335-346.

Romero-Ávila, Diego (2008) Convergence in carbon dioxide emissions among industrialised countries revisited, *Energy Economics*, 30, 2265-2282.

Sun, J., Chi-Wei Su and Gui-lan Shao (2016) Is carbon dioxide emission convergence in ten largest economies? *International Journal of Green Energy*, 13,5,454-461.

Strazicich, M.C. and List, J.A. (2003) Are CO2 emission levels converging among industrial countries? *Environmental and Resource Economics*, 24, 263–271.

Wang, J. and Zhang, K. (2014) Convergence of carbon dioxide emissions in different sectors in China, *Energy*, 65, 605-611.

Wang, Y. Zhang, P. Huang, D. and Cai, C. (2014) Convergence behavior of carbon dioxide emissions in China, *Economic Modelling*, 43, 75-80.

Westerlund, J. and Basher, S.A. (2007) Testing for convergence in carbon dioxide emissions using a century of panel data. *Environmental and Resource Economics*,

Yavuz, Nilgun Cil and Yilanci, Veli. (2013) Convergence in Per Capita Carbon Dioxide Emissions among G7 Countries: A TAR Panel Unit Root Approach. *Environmental and Resource Economics*, February 2013, 54:2, pp. 283-91.

Zhao, X. Burnett, J. W. and Lacombe, D. J (2015) Province-level convergence of China’s carbon dioxide emissions, *Applied Energy*, 150, 286-295.