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Are C02 Emission Levels Converging Among Industrial Countries?

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ABSTRACT

Time paths of carbon dioxide emissions in twenty-one industrial countries are examined from 1960-1997 to test for stochastic and conditional convergence. Both panel unit root tests and cross-section regressions are performed. Overall, we find significant evidence that C02 emissions have converged.

I. INTRODUCTION

An important prediction of Solow's (1956) growth model is that controlling for savings rates, population growth rates, rates of technological progress and other economy characteristics, per capita incomes among nations should converge. Numerous empirical studies have presented results that support this premise for industrial countries and their regions: Baumol (1986), Barro (1991), Barro and Sala-i-Martin (1991, 1992), Mankiw, Romer and Weil (1992), and Evans and Karras (1996), among others, find evidence that per capita incomes are "conditionally converging". 1 A much different stylized fact has emerged in the environmental literature, which posits that an inverted-U relationship exists (frequently termed the environmental Kuznets curve, or EKC) between a measure of wealth and environmental degradation (Grossman and Krueger 1995). While separately these lines of research provide significant positive and normative insights, considering them jointly points to a potential gap in the literature: have spatial emissions converged ?2

In this paper, we attempt to fill this gap in the literature by examining whether emissions converged among the industrialized countries. To accomplish this task, we perform a battery of convergence tests on country-level emissions of carbon dioxide (C02).3 First, we use familiar cross-sectional regression tests, conditional on income and other variables, to test for emissions convergence across twenty-one industrial countries for the period 1960-1997. Second, we employ the panel unit root test recently developed by 1m, Pesaran and Shin (2002) to examine emission convergence in a time series framework. The panel unit root test provides a convenient methodology to test our hypothesis and has a significant advantage over single country tests in terms of greater power to reject the null. Nevertheless, both sets of empirical results clearly reject the null of divergence and provide significant evidence that per capita CO2 emissions have conditionally converged.

II. THEORY, DATA, AND EMPIRICAL METHODS

To date, the theoretic literature has examined the growth/pollution relationship using several different modeling techniques. For example, making use of returns to scale assumptions, Andreoni and Levinson (2001) postulate a technical relationship between consumption and abatement of pollution and demonstrate that an inverted-U shape relation between pollution and income exists. Bulte, List and Strazicich (2001) extend the Andreoni and Levinson analysis by combining their static model with Solow's growth model. While their primary interest is not the EKC, their approach allows an exploration of the notion of pollution convergence in an analytically convenient manner. They find that in the standard Solow growth model, pollution convergence may be expected on theoretical grounds. They consider both the case of local and supra-national authority, and conclude that while the institutional context affects the *level* of the pollution/income path, it does not affect its *"shape".* We use their model as a theoretical platform to motivate the empirical analyses below.

A. Data

The primary data employed in this paper are annual emissions of CO2 measured in metric tons per capita. The data set forms a balanced panel of twenty-one industrialized countries from 1960-1997.4 Our data come from *World Development Indicators* as published by the World Bank (2001) (hereafter, World Bank).
The data were originally developed by Marland et al. (1989) as estimates of CO2 emissions from fossil fuel burning and manufacturing cement. Fuel data come from the UN Statistical Division's database, while data on cement manufacturing are from the U.S. Department of Interior, Bureau of Mines. The database omits carbon emissions caused by deforestation, land-use changes, and wood burning for energy; but suitable data on these measures are not currently available. Emissions data have an error of uncertainty of 6-10 percent at the global level. In spite of potential shortcomings, our data provide a consistently defined measure of pollution across a large group of countries.

B. Empirical methods

Cross-sectional approach

Our first testing methodology uses the per capita CO2 data to test for emissions convergence by employing a cross-section regression test that has been used extensively in the literature as a test for income convergence. The average annual rate of growth in per capita CO2 emissions is regressed on the initial level of per capita emissions and a vector of other control variables in a cross-section of countries:

$$1/(\mathrm{T}-1)\sum_{t=1961}^{\mathrm{T}}(\ln \mathrm{CO_2pc_{it}} - \ln \mathrm{CO_2pc_{it-1}}) = \alpha + \beta \ln \mathrm{CO_2pc_{i1960}} + \gamma \ln \mathrm{z_i} + \mathrm{v_i}. \quad (1)$$

The dependent variable in (1) is the average annual rate of growth of CO2 per capita for country i over the sample period (1960-1997). T is the number of time periods in the sample, ex is a constant term, *,B* is a parameter testing the null hypothesis of divergence, C02PCil960 is the initial value of per capita emissions in country i, *y* is a parameter testing the null that convergence is absolute, and Vi is an independent and identically distributed error term with zero mean and finite variance.

A few noteworthy aspects of (1) are worthy of brief mention. First, inference from the empirical estimates of (1) is quite straightforward-an estimate of $\beta < 0$ implies convergence, while failure to reject the null of $\beta = 0$ cannot reject divergence. The intuition behind this notion is that countries beginning with high per capita emissions should have lower growth in their emissions than countries beginning with low emissions in order for convergence to occur. Second, in order to allow for the possibility of persistent country differences in the time path of emissions, or country-specific "compensating differentials", we include a vector of other variables (Zi) that might be hypothesized to affect long-run emissions rates. First, we follow the suggestion of the EKC literature and include real per capita

GDP and real per capita GDP squared in 1978 US$ adjusted for purchasing power parity (Heston and Summer et al. 1995). 1978 was chosen to serve as a midpoint in our sample. Next, we include a measure of energy prices that may be closely related to CO2 emissions, namely the average price of gasoline (US$ average price per liter of super gasoline in 1998, World Bank 2001).5 One may hypothesize that higher gasoline prices (due primarily to higher taxes) will, in the long-run, lead to lower rates of pollution emissions. Two other variables are also examined for effects on conditional convergence: population density in 1978 (approximate midpoint in the sample; World Bank 2001) and an estimate of the average winter temperature (www.weather.com). One might hypothesize that countries with greater population density will tend to make more efforts to reduce air pollutants and thus converge to lower emissions rates. The relation of climate to CO2 emissions is less clear. One could hypothesize that countries having colder climates will tend to converge to higher emissions rates due to greater heating demands.6 Contrary to this, countries with warmer climates could be hypothesized to have greater automobile use and converge to higher emissions rates. The hypotheses tested in (1) can be summarized as follows: $y = 0$ and $\beta < 0$ implies absolute convergence; if $y \neq 0$ and $\beta < 0$ this suggests conditional convergence.?

Time series approach

Our second testing methodology is that suggested by Carlino and Mills (1993). They examine the log of the ratio of per capita income relative to average U.S. per capita income for eight regions of the U.S. and test for a unit root. A unit root in the log ratio implies a non stationary time series in which shocks to per capita income relative to the average per capita income are permanent: following a shock to relative income in region i there is no tendency for per capita income to converge toward the average (i.e., to its compensating differential). As such, a unit root in the log relative series supports divergence and rejection of a unit root implies a stationary or mean reverting series. The intuition is as follows. A stationary series implies that shocks to per capita income in country i relative to average per capita income in all countries will be temporary-following an exogenous shock, per capita income "converges stochastically" back toward the average.

We make use of Carlino and Mills' (1993) methodology in our time series test for convergence in per capita C02 emissions. Akin to Carlino and Mills (1993), we generate our variable of interest using a two-step procedure. First, we calculate a yearly sample average for our twenty-one industrial countries. Second, we compute the natural logarithm of relative per capita pollution for each country as follows:

$$x_{it} = \ln(CO_2pc_{it}/averageCO_2pc_t). \quad (2)$$

Log relative values from equation (2) form our twenty-one countries, thirty-eight year balanced panel consisting of 798 observations.

To analyze the log-relative emissions data, we use the panel unit root test of 1m, Pesaran, and Shin (2002, IPS hereafter). The IPS test has significantly greater power to reject the unit root null as compared to tests with a single time series. In contrast to univariate ADF tests, IPS derive the asymptotic properties of their panel test statistic and show that it converges to a standard normal distribution. The panel testing procedure can be described as follows. Begin by performing augmented Dickey and Fuller (ADF) tests separately for each country. To correct for possible higher-order serial correlations, we include first-differenced lagged (i.e., "augmented") terms .0.Xt-k on the right-hand side of each test equation. To determine the optimal number of augmented terms to include for each country, we employ the "general to specific" procedure suggested in Perron (1989).8 The ADF regression test for each country looks accordingly:

$$\Delta x_{it} = \alpha_i + \gamma_i t + \beta_i x_{it-1} + \sum_{k=1}^{m} \theta_{ik} \Delta x_{it-k} + \varepsilon_{it}, \qquad (3)$$

where X_{it} is as described in (2) and is the log ratio of per capita CO2 in country i, α_i is a country-specific constant term, or compensating differential, that allows for conditional convergence, and Y_{it} is a linear time trend. β_i is the parameter that tests the null of a unit root, m is the maximum number of lagged terms ΔX_{it-k} and θ_{ik} is a parameter estimated for each first-differenced lagged term. ε_{it} is the contemporaneous error term and is assumed independent and identically distributed with zero mean and finite variance. After estimating equation (3) for each country, the average t-statistic (t) is calculated. A modified t statistic is then calculated as follows:

$$\text{IPS statistic} = N^{\frac{1}{2}}\{\bar{t}_{NT} - E(t_T|\beta_i = 0)\}/\{\text{Var}(t_T|\beta_i = 0)\}^{\frac{1}{2}}, \qquad (4)$$

where N is the number of countries, t is the average t-statistic from the N = 21 estimates of β_i, and E is the expectation operator. Values of E(h I β_i = 0) and Var(h I β_i = 0) are provided in IPS for different values of T and k, where T is the number of years, and k is the number of ΔX_{it-k} lagged terms included in equation (3).9 Note that country-specific fixed effects are included in the panel test, since α_i is allowed to vary for each country. As such, stochastic convergence is consistent with the notion of conditional convergence. Time-specific fixed effects are included, since the variable tested is $X_{it} = \ln C0_{2it} - \ln C0_{2t}$, which is equivalent to demeaning the data for common time effects.

The hypothesis tested using the IPS panel unit root test is given by:

$$\textit{Null Hypothesis}: \beta_i = 0 \textit{ for all } i$$
$$\textit{Alternative Hypothesis}:$$
$$\beta_i < 0, i = 1, 2, \ldots, N_1, \beta_i = 0, i = N_1 + 1, N_1 + 2, \ldots, N.$$

Failure to reject the null hypothesis implies a nonstationary series where shocks to relative per capita CO_2 emissions have permanent effects and per capita emissions diverge. Rejection of the null supports the alternative hypothesis of a stationary series where shocks to a country's relative per capita CO_2 emissions have temporary effects and per capita emissions stochastically converge.

III. EMPIRICAL RESULTS

We present our cross sectional regression test results in Table I. To provide insights about the nature of the empirical estimates across various specifications, we present results from models including and excluding the conditional variables, Z_i. In all cases, *f3* is less than zero and strongly significant at less than the $p < 0.01$ level, implying that emissions have converged. Moving on to the conditional variables, we first note that neither per capita income nor per capita income squared is significant in any case. While these results may seem in contrast to previous empirical EKC findings, it is important to note that our dependent variable (i.e., the average growth rate) differs from these tests. The price of gasoline is negative and significant at the $p < 0.05$ level, suggesting an inverse relationship exists between emissions growth and gasoline prices. Population density is statistically insignificant in all of the seven specifications. The temperature regressor is negative and marginally significant at the $p < 0.10$ level in regression (1.7). This result suggests that countries with colder climates experienced higher growth rates of CO_2 emissions during our sample period. However, estimation results for this variable should be considered with caution, as the estimate of average winter temperature in one city is only a rough approximation for the country, especially in large countries.

Table I. Cross-section tests for conditional convergence in per capita CO_2 emissions among twenty-one industrial countries from 1960–1997

	α	β	*lnpcGDP*	*(lnpcGDP)*^{2}	*PriceGas*	*Pop.Density*	*Temp.*
(1.1)	0.049	–0.020	–	–	–	–	–
	(10.60)***	(–7.27)***	–	–	–	–	–
$\overline{R}^2 = 0.722$			F = 52.89***			N = 21	
(1.2)	0.057	–0.019	–0.001	–	–	–	–
	(0.50)	(–3.91)***	(–0.07)	–	–	–	–
$\overline{R}^2 = 0.706$			F = 25.06***			N = 21	
(1.3)	0.052	–0.019	–	–0.00004	–	–	–
	(0.94)	(–3.92)***	–	(–0.05)	–	–	–
$\overline{R}^2 = 0.706$			F = 25.06***			N = 21	
(1.4)	0.064	–0.021	–	–	–0.014	–	–
	(7.53)***	(–8.14)***	–	–	(–2.07)**	–	–
$\overline{R}^2 = 0.763$			F = 33.13***			N = 21	
(1.5)	0.050	–0.020	–	–	–	–0.00001	–
	(9.98)***	(–7.21)***	–	–	–	(–0.78)	–
$\overline{R}^2 = 0.716$			F = 26.19***			N = 21	
(1.6)	0.057	-0.021	–	–	–	–	–0.0004
	(5.15)***	(–6.75)***	–	–	–	–	(–0.86)
$\overline{R}^2 = 0.718$			F = 26.44***			N = 21	
(1.7)	–1.309	–0.020	0.324	–0.019	–0.026	0.00002	–0.0005
	(–0.72)	(–4.61)***	(0.80)	(–0.84)	(–2.61)**	(0.93)	(–1.94)*
$\overline{R}^2 = 0.836$			F = 11.93***			N = 21	

Notes. Dependent variable is the average annual growth rate of CO_2 emissions in country i. β is the coefficient that tests for convergence as described in equation (1). lnpcGDP and (lnpcGDP)^2 are the natural logarithm of per capita real GDP (US$) adjusted for purchasing power parity and per capita real GDP squared, respectively. PriceGas is the average price per liter of super gasoline (US$), Pop.Density is the population density, and Temp. is the average temperature in January (July in Australia and New Zealand), respectively. N = the number of countries included in the cross-section regression. t-statistics are shown in parentheses. *, **, and *** denote significant at the 10%, 5%, and 1% levels, respectively.

Table II. IPS Panel Unit Root Test of Stochastic Convergence in Per Capita CO_2 Emissions among Twenty-One Industrial Countries from 1960–1997

Sample	*Estimated IPS test statistic*
21 Countries	–2.016**

Notes. Dependent variable is the natural logarithm of the ratio of annual per capita CO_2 emissions for country i in year t divided by the average per capita CO_2 emissions of all countries in year t. IPS test statistic is estimated as in equation (4). The null hypothesis is a unit root in all countries implying that emissions diverge. Critical values are asymptotic standard normal and are –2.326, –1.645, and –1.282, at the 1%, 5%, and 10% levels, respectively. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Our panel unit root test results are displayed in Table II. Consistent with the cross-sectional results, we reject the null hypothesis of a unit root and, thus, reject divergence at the $p < 0.05$ level ($t = -2.016$). Taken together, these findings suggest that per capita emissions of CO2 have converged, both conditionally and stochastically (since our panel test includes country-specific constant terms, these findings are also consistent with conditional convergence).

Our finding of emissions convergence provides a link between the empirical literature that correlates pollution and incomes and the literature that finds spatial incomes have converged through time. For example, using the intuition in the theoretical model of Bulte, List, and Strazicich (2001), if we are on the downward sloping portion of the EKC and income is below equilibrium income: (i) income growth will be greater than along the balanced growth path, and (ii) pollution will be reduced less than along the balanced growth path. Of course, these growth projections are reversed if income exceeds income on the balanced growth path or if the economy is located on the upward portion of the EKe. While certainly many factors may lead to emissions divergence - including dysfunctional governmental regulatory bodies, heterogeneous preferences, or if relative prices are non stationary and price elasticities systematically differ across space, our results indicate that through time these factors have not led to emissions divergence across industrialized economies.

IV. CONCLUSION

This paper combined both cross-sectional and time series tests for convergence using data on CO2 emissions from twenty-one industrial countries over the period 1960-1997. In both tests the null hypothesis that emissions have diverged is strongly rejected. Overall, these empirical findings provide significant evidence that per capita emissions of CO2 have spatially converged. Future research is warranted. Numerous indicators of environmental quality are important, and in this paper we focused on one global pollutant. An examination of whether amenity bases across countries have converged would require an empirical analysis of other measures of environmental quality, such as local pollution concentration levels. This would move us in the appropriate direction if our goal was to examine if overall welfare levels are converging.

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NOTES

1. Given persistent country differences in population growth, savings rates, technological progress and other factors, per capita incomes are not hypothesized to converge "absolutely", but instead "conditionally", to a country-specific constant differential. We use this same definition in our tests below.

2. List (1999) presents results testing whether S02 and NOx emissions have conditionally converged across U.S. Environmental Protection Agency regions. His evidence is mixed.

3. We should stress, however, that while a plethora of studies find that many pollutants adhere to the inverted-U hypothesis, evidence suggests that C02 emissions have not followed this pattern (see, e.g., Holtz-Eakin and Selden 1995).

4. The twenty-one countries are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States. Germany was excluded due to the significant boundary changes in 1990.

5. The price includes all taxes. The price of gasoline in 1998 was utilized, as a consistent time series of earlier data was not available.

6. Average winter temperature was chosen as the mean temperature in the capital city during January, except during July in Australia and New Zealand.

7. Recently, a number of papers have criticized the .B-convergence test (see, e.g., Evans 1996; Evans and Karras 1996; Quah 1996). Nevertheless, given that we are interested in long-run paths of emissions, estimating (1) may provide useful information when combined with our time series findings.

8. The procedure to determine the optimal number of augmented terms suggested in Perron (1989) can be described as follows. We begin with eight lagged first-differenced terms for each ADF test. If the absolute value of the t-statistic on the eight lagged term is less than 1.645 (i.e., approximate 10% significance level in an asymptotic normal distribution), then this term is dropped and the procedure is repeated for the seventh lagged term. The procedure is stopped when the last lagged term is significant, in which case all lesser first-differenced lagged terms remain in the test, or zero lagged terms will result. This general to specific procedure has been shown to perform well in terms of size and power as compared to similar procedures (see, e.g., Ng and Perron 1995).

9. Since we allow for heterogeneous numbers of first-differenced lagged terms in the single equation ADF tests, we estimate E(tT I *.Bi* = 0) and Var(tT I *.Bi* = 0) in equation (4) as weighted averages of the values shown in Table 2 of IPS. We thank Kyung 1m for suggesting this procedure.

REFERENCES

Andreoni, J. and A. Levinson (2001), 'The Simple Analytics of the Environmental Kuznets Curve', *Journal of Public Economics* 80, 269-286.

Barro, R. J. (1991), 'Economic Growth in a Cross Section of Countries', *Quarterly Journal of Economics* 106, 407-443.

Barro, R. J. and X. Sa1a-i-Martin (1991), 'Convergence Across States and Regions', *Brookings Papers on Economic Activity* 1,107-182.

Barro, R. J. and X. Sala-i-Martin (1992), 'Convergence', *Journal of Political Economy* 100, 223-251.

Baumo1, W. J. (1986), 'Productivity Growth, Convergence and Welfare: What the Long-Run Data Show', *American Economic Review* 76, 1075-1085.

Bulte, E., J. A. List and M. C. Strazicich (2001), *Regulatory Federalism and the Distribution of Air Pollutant Emissions.* Working paper, University of Maryland.

Carlino, G. and L. Mills (1993), 'Are U.S. Regional Economies Converging? A Time Series Analysis', *Journal of Monetary Economics* 32,335-346.

Evans, P. (1996), 'Using Cross-Country Variances to Evaluate Growth Theories', *Journal of Economic Dynamics and Control* 20, 1027-1049.

Evans, P. and G. Karras (1996), 'Convergence Revisited', *Journal of Monetary Economics* 37,249-265.

Grossman G. and A. Krueger (1995), 'Economic Growth and the Environment', *Quarterly Journal of Economics* 3,53-77.

Heston, A. and R. Summers et al. (1995), *The Penn World Tables, Version 5.6.*

Holtz-Eakin, D. and T. Selden (1995), 'Stoking the Fires? C02 Emissions and Economic Growth', *Journal of Public Economics* 57,85-101.

1m, K., M. Pesaran and Y. Shin (2002), 'Testing for Unit Roots in Heterogeneous Panels', *Journal of Econometrics,* forthcoming.

List, J. A. (1999), 'Have Air Pollutant Emissions Converged Amongst US Regions? Evidence from Unit-Root Tests', *Southern Economic Journal* 66, 144-155.

Mankiw, N. G., D. Romer and D. N. Wei1 (1992), 'A Contribution to the Empirics of Economic Growth', *Quarterly Journal of Economics* 107, 407-438.

Marland, G. et al. (1989), *Estimates of C02 Emissionsfrom Fossil Fuel Burning and Cement Manufacturing, Based on United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data.* ORNL, Oak Ridge, Tennessee.

Ng, S. and P. Perron (1995), 'Unit Root Tests in ARMA Models with Data-Dependent Methods for the Selection of the Truncation Lag', *Journal of the American Statistical Association 90,* 269-281.

Perron, P. (1989), 'The Great Crash, the Oil Price Shock, and the Unit Root Hypothesis', *Econometrica* 57, 1361-1401.

Quah, D. (1996), 'Empirics for Economic Growth and Convergence', *European Economic Review* 40, 1353-1375.

Solow, R. (1956), 'A Contribution to the Theory of Economic Growth', *Quarterly Journal of Economics* 70, 65-94.

World Bank (2001), *World Development Indicators.* Washington, D.C.