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Re-Examining the Empirical Evidence for Stochastic Convergence of Two Air Pollutants with a Pair-Wise Approach

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Abstract This paper examines the hypothesis of stochastic convergence for two air pollutants emissions (carbon dioxide [CO_2] and sulfur dioxide [SO_2]). The value-added of this paper lies in the use of a recent, alternative econometric method, a pair-wise approach that considers all the possible pairs of log per-capita pollutant emission gaps across all the countries in the sample. In this method, all emissions differences must be stationary around a constant mean. Empirical results support different conclusions on stochastic convergence in per capita CO_2 and SO_2 emissions depending on the choice of the unit root test. The use of specific critical values from the ADF-KPSS joint test overcomes these initial conflicting results and leads to small percentages of stationary pairs around a constant mean; which invalidate the hypothesis of stochastic convergence for per capita emissions of CO_2 and SO_2, even over the OECD sub-dataset.

Keywords Air pollution · Carbon dioxide · Joint confirmation Hypothesis · Stochastic convergence · Sulfur dioxide · Unit roots

JEL Classification C32 · C33 · Q53 · Q54

1 Introduction: Context and Purpose of the Paper

The question of convergence of pollutant emissions between countries has recently been investigated, essentially for carbon dioxide (CO_2) emissions (Nguyen Van 2005; Strazicich and List 2003; Stegman and Kibbin 2005; Aldy 2006, 2007; Ezcurra 2007; Romero-Avila 2008; Westerlund and Basher 2008; Barassi et al. 2008) but also some other pollutants (List 1999 and Bulte et al. 2007 for sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions). While the analysis of convergence in pollutant emissions is more empirical than

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theoretical, theoretical justifications have been developed and improved. Initially, the question of environmental convergence was related to income convergence and the environmental Kuznets curve. Since some empirical results support income conditional convergence and the existence of an inverted-U relation between income and pollution (Grossman and Krueger 1995), it seems possible that income convergence leads to pollutant emissions convergence. Bulte et al. (2007) analyse the notion of pollution convergence in an extended version of Andreoni and Levinson's model (2001). They found that pollutant emissions converged in the long term but, in the mid-term, pollution levels may diverge or converge, depending on the income difference between states. This result is graphically presented in Aldy (2006). The model of Bulte et al. (2007) provides a theoretical basis behind the empirical analyses of this paper. It is worth noting that, even if per capita distribution of pollutant emissions does not influence health and environmental effects, it may affect multilateral negotiations over environmental agreements (Aldy 2006). Convergence in emissions is also assumed in many climate change models. In this context, it is useful to examine in detail the reality of convergence in different pollutant emissions. The empirical study of convergence described in this article deals with two transboundary air pollutants, CO_2 and SO_2 emissions, selected as they could lead to differing results in terms of convergence or divergence : SO_2 emissions impair human health and are responsible for acid rain, while CO_2 emissions are responsible for 40% of global warning. Moreover, international environmental protocols have succeeded in decreasing SO_2 emissions, whereas policies against climate change have not yet resulted in CO_2 emissions reductions.

A widespread analysis of all convergence methods is beyond the scope of this paper which, instead, focuses on stochastic convergence. This examines the long-run behaviour of differences in pollutant emissions per capita across countries. In this context, two countries are converging in the stochastic sense if the limit of their expected emissions per capita gap tends to zero as the forecast horizon grows, implying the deviations are always transitory. In this approach, the difference in emissions per capita between two nations cannot contain a unit root or time trend. Bernard and Durlauf (1995, 1996) were the first to propose testing cross-country stochastic convergence with cointegration techniques. However, their empirical approach is limited since it cannot be applied to more than a small sample of countries. Thus, empirical studies of convergence in pollutant emissions have recently been based on the methodology of Carlino and Mills (1993, 1996). The idea is to examine the log of the ratio of emissions per capita in country i relative to the average emissions per capita for the whole sample and test for a unit root. In this approach, stochastic convergence implies that the effects of shocks on per capita emissions over average per capita emissions dissipate over time or, likewise that the time series does not possess a unit root. In this context, national per capita pollutant emissions "converge stochastically" after an exogenous shock. In contrast, if shocks on the ratio of per capita emissions to the mean are permanent, then time series are integrated and countries are diverging. To summarize, a unit root in the log relative series supports divergence and rejection of a unit root suggests convergence across countries.

Unfortunately, as underlined by Islam (2003), "the source of the rejection of the null of unit root", i.e. the case of convergence between countries, "is not always clear" in these models. Indeed, the existence of a unit root in the pollutant series of just one of the countries in the sample will cause the average series to contain a unit root. Relative emissions for all the economies, except the one that has a unit root, will thus be integrated. This means that previous empirical studies on pollution convergence based on this methodology provide weak and biased results. In this context, instead of implementing state-of-the-art unit root tests to check Carlino and Mills' notion of stochastic convergence, as in previous analyses, a recent alternative methodology to test stochastic convergence for two air pollutants is used.

To overcome the drawbacks of Carlino and Mills' approach, Islam (2003) suggests examining each country's deviation from all the others. This analysis is developed in this article using Pesaran's method (2007), which considers all $N(N-1)/2$ possible pairs of log per-capita emissions gaps across N economies. Note that this pair-wise approach has up to now only been used to test output, growth convergence and purchasing power parity (Pesaran 2007; Pesaran et al. 2007). To sum up, the value added of this paper lies in the use of a recent alternative methodology that will provide robust and precise empirical results on stochastic convergence for two air pollutants.

The remainder of this paper is divided in five sections. Section 2 briefly describes previous studies dealing with the issue of stochastic convergence in pollutant emissions. The econometric method, the pair-wise approach, is examined in Sect. 3. Section 4 presents the data and analyses empirical results. Since first results are conflicting, an extension of the study is described, both theoretically and empirically, in Sect. 5. Section 6 concludes.

2 Brief Literature Review

Table 1 shows the important features of empirical papers[1] on stochastic convergence in pollutant emissions. It is apparent that the majority of econometric analyses deals with CO_2 emissions per capita. Indeed, only two articles examine stochastic convergence in SO_2 and NO_x emissions per capita (List 1999; Bulte et al. 2007). Based on American data only, these papers result in contradictory conclusions concerning stochastic convergence in SO_2 and NO_x emissions per capita. In this context, my study of SO_2 stochastic convergence will differ from these two analyses in at least two aspects. Firstly, instead of using Carlino and Mills' methodology, Pesaran's pair-wise approach is implemented to examine the unit root properties of each emission pair. The second major difference is the formation of the dataset. In this article, the sample is composed of 81 (developed and developing) countries over the period 1950–1990 (cf. Sub-Sect. 4.1 and Table 3 in Appendix). Therefore, this paper provides the first analysis of SO_2 stochastic convergence on panel data.

Concerning econometric analyses on CO_2 emissions (Strazicich and List 2003; Aldy 2006; Romero-Avila 2008; Westerlund and Basher 2008; Barassi et al. 2008), note datasets are mainly composed of developed countries. Only Aldy (2006) includes developing countries in an analysis of stochastic convergence, in a sample of 88 industrialised and developing nations. For comparison, in this article, the panel dataset is for 127 countries between 1950 and 2003. Moreover, in previous studies, different unit root tests are applied to analyse unit-root properties of per capita emissions over average per capita emissions in accordance with Carlino and Mills' approach. There unit root tests include individual or panel unit root tests, tests allowing breaks in intercept and/or trend, and tests robust to cross-sectional dependence. However, the empirical results support different conclusions: Strazicich and List (2003); Romero-Avila (2008) and Westerlund and Basher (2008) support the hypothesis of stochastic convergence in CO_2 emissions per capita; whereas Aldy (2006) and Barassi et al. (2008) provide evidence in favour of divergence.

In this context, my analysis of stochastic convergence in CO_2 emissions per capita will contribute to the empirical debate since unit root properties of each emission pair in the sample using Pesaran's approach are examined, instead of analysing emissions relative to the average as in Carlino and Mills' methodology.

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[1] This table presents only parametric estimations. Note that the question of pollutant emission convergence has also been investigated with non-parametric methods (Stegman and Kibbin 2005; Nguyen Van 2005; Ezcurra 2007).

Table 1 Review of econometric literature on stochastic convergence

Author	Date	Sample		Definition of stochastic convergence	Econometric test	Results
		Number of countries	Temporal dataset			
SO_2 *and* NO_x *emissions per capita*						
List	1999	10 EPA Regions of USA	1929–1994	Carlino and Mills (1993)	Region by region ADF	Divergence
					ADF with a break in the trend	
Bulte et al.	2007	48 American states	1929–1994		State by State	Convergence
					Two breaks minimum LM unit root test	
CO_2 *emissions per capita*						
Strazicich and List	2003	21 Industrialised countries	1960–1997	Carlino and Mills (1993)	Panel: IPS	Convergence
Aldy	2006	88 Countries	1960–2000		Country by country ADF-GLS	Little evidence in favour of convergence
		A sub-sample of 23 OECD countries				
Romero-Avila	2008	23 OECD countries	1960–2002		Country by country: KPSS	Divergence
					Panel: Hadri	
					Panel and breaks in intercept and trend: CBL	Convergence

Table 1 continued

Author	Date	Sample		Definition of stochastic convergence	Econometric test	Results
		Number of countries	Temporal dataset			
Barassi et al.	2008	21 Developed countries	1950–2002	Carlino and Mills (1993)	Country by Country: KPSS, ADF Panel: Hadri, IPS Panel robust to cross sectional correlation: Harris et al. and Breitung and Das	Divergence
Westerlund and Basher	2008	28 Countries A sub-sample of 16 developed countries	1870–2002	Evans (1998)	Panel robust to cross sectional correlation: Phillips and Sul, Moon and Perron, Bai and Ng	Convergence
CO_2 *Consumption and production*						
Aldy	2007	American states	1960–1990	Carlino and Mills (1993)	Panel: IPS	Consumption: Convergence Production: Divergence

3 Pair-Wise Convergence Methodology

3.1 Definitions

Consider firstly that the log of per capita pollutant emissions of country i, for $i = 1, 2\ldots, N$, at time t, e_{it}, is represented by:

$$e_{it} = c_i + g_i t + \boldsymbol{\theta}_i' \boldsymbol{f}_t + \varepsilon_{it} + \eta_{it} \tag{1}$$

where $(c_i + g_i t)$ is the deterministic component (constant and trend), $(\boldsymbol{\theta}_i' \boldsymbol{f}_t + \varepsilon_{it})$ is a multi-factor model with $\boldsymbol{f}_t$ a (mx1) vector of common components, $\boldsymbol{\theta}_i$ the associated vector of loadings and ε_{it} the idiosyncratic component specific to country i, and η_{it} is a stationary process.

The analysis of convergence using a pair-wise approach is traditionally based on the definition of convergence for two countries provided by Bernard and Durlauf (1995). Countries i and j converge if

$$\lim_{k\to\infty} E\left(e_{i,t+k} - e_{j,t+k}\,| I_t\right) = 0, \forall t \tag{2}$$

where I_t is the information set at time t, which contains at least the current and past series $e_{i,t-s}$ for $i = 1,2\ldots N$ and $s = 0, 1, 2\ldots$. Replacing $e_{i,t}$ and $e_{j,t}$ by their formula (cf. Eq. 1) in Eq. (2), it can be seen that countries i and j converge in the sense of Bernard and Durlauf if $c_i = c_j$ and $g_i = g_j$, and also $\theta_i = \theta_j$ in the case where $\boldsymbol{\theta}_i' \boldsymbol{f_t}$ contains a unit root. Therefore, a necessary condition for convergence of countries i and j is that the series $e_{i,t}$ and $e_{j,t}$ are cointegrated with cointegrating vector $(1, -1)$.

Pesaran (2007) offers a less stringent definition. Countries i and j converge if for some positive constant C, and a tolerance probability measure $\pi \geq 0$,

$$\Pr\left\{\,\left|e_{i,t+s} - e_{j,t+s}\right| < C \mid I_t\right\} > \pi, \quad \text{at all horizons } s = 1, 2, \ldots, \infty \tag{3}$$

Using (1) to express $e_{i,t+s}$ and $e_{j,t+s}$ and replacing them in (3), countries i and j converge only if $g_i = g_j$ and $\theta_i = \theta_j$. In a cointegrating framework, those conditions are the cointegrating and cotrending restrictions respectively. Therefore, to confirm the pair-wise convergence hypothesis, both these conditions must be checked: firstly, unit root test on the gap, $e_{i,t} - e_{j,t}$, and secondly cotrending test for a stationary gap (Pesaran 2007). The advantage of this procedure is to avoid the pre-testing of unit root in individual series, an empirical step required by the cointegration approach. In a multi-country analysis, the definition of convergence is the following. Countries $i = 1, 2, \ldots, N$ are said to converge if for some positive constant C, and a tolerance probability measure $\pi \geq 0$,

$$\Pr\left\{\bigcap_{i=1,\ldots,N-1;\, j=i+1,\ldots,N} \left|e_{i,t+s} - e_{j,t+s}\right| < C \mid I_t\right\} > \pi, \quad \text{at all horizons } s = 1, 2, \ldots, \infty \tag{4}$$

Therefore, when there are more than two countries to consider, Pesaran's definition of pair-wise convergence given for a pair of countries should hold for all the $N(N-1)/2$ pairs of countries being considered. Hence, unit root and trending properties are examined for all the $N(N-1)/2$ possible pairs.

3.2 Econometric Tests

Consider any two countries i and j and denote their log per-capita pollutant emissions gap by $e_{it} - e_{jt}$. According to Pesaran's definition, two countries are (pollution) convergent if $e_{it} - e_{jt}$ is an $I(0)$ process with a constant mean. The first step is to test for a unit root in $d_{ijt} = e_{it} - e_{jt}$. In this context, I use the augmented Dickey-Fuller (ADF) regressions with an intercept and a linear trend:

$$\Delta d_{ijt} = a_{ji} + \beta_{ij}\left(g_i - g_j\right)t + \beta_{ij}\, d_{ij,t-1} + \sum_{s=1}^{p_{ij}} \delta_{ijs}\Delta d_{ij,t-s} + v_{it} \tag{5}$$

The hypotheses tested are then:

- Null hypothesis $H_0 : \beta_{ij} = 0$. There is a unit root and so emissions e_{it} and e_{jt} are divergent.
- Alternative hypothesis $H_a : \beta_{ij} < 0$. The presence of a unit root is rejected and hence emissions e_{it} and e_{jt} are convergent.

Note that in the empirical application, results for three augmentation orders, p_{ij}, are reported corresponding to the following information criteria:[2] the Akaike information criterion (AIC), the Schwarz criterion (SC) and the Hannan-Quinn criterion (HQ). It should be highlighted that for each series d_{ij}, three different unit-root test statistics are computed, namely the standard ADF(p) statistic, the ADF-GLS(p) statistic proposed by Elliot et al. (1996) and the ADF-WS(p) statistic proposed by Park and Fuller (1995). Since empirical results do not differ between the three ADF regressions, just results from the ADF-WS test[3] are presented.

In order to either confirm or invalidate the results based on the ADF regression, the KPSS test (Kwiatowski et al. 1992) is also implemented. In contrast to the ADF test, it is based on the null hypothesis of stationarity, i.e. convergence.

Both tests are applied to all pollutant emissions pairs, i.e. $N(N-1)/2$ tests are carried out. Even if results across the different gaps are dependent, Pesaran (2007) demonstrates that, assuming independently distributed country-specific shocks ($\varepsilon_{it} + \eta_{it}$ in Eq. 1), the estimated proportions of converging pairs are consistently estimated for N and T sufficiently large. Moreover, in the case of KPSS (ADF) tests, the proportion of diverging (converging) pairs is expected to be close to the significance level of the test under the (non-)convergence hypothesis. To see this, using Eq. (1) and the two conditions of convergence, the gap d_{ijt} satisfies, under the convergence hypothesis (H_c):

$$H_c : e_{it} - e_{jt} = c_i - c_j + \psi_{ijt} \quad \text{for all } i \neq j$$

where $\psi_{ijt} = \varepsilon_{it} - \varepsilon_{jt} + \eta_{it} - \eta_{jt}$ is a mean zero stationary process under H_c.

Under the alternative hypothesis of divergence ($\bar{H}_c$), the gap d_{ijt} will be defined by: $\bar{H}_c : e_{it} - e_{jt} = c_i - c_j + \left(\theta_i - \theta_j\right)' f_t + \psi_{ijt}$ for all $i \neq j$, with f_t and/or ψ_{ijt} containing unit roots.

Consider the ADF-WS(p) test applied to the emission gap, d_{ijt}, and note:

$$Z_{ij,T} = \begin{cases} 1 & \text{if } \mathrm{ADF}_{ijT}(p_{ij}) < K_{T,p,\alpha} \text{ (rejection of } \bar{H}_c) \\ 0 & \text{otherwise} \end{cases}$$

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[2] Note that the number of lagged first-difference variables, chosen by the information criteria, is between 0 and 4.

[3] Detailed tables of empirical results for the three ADF regressions are available upon request.

where $K_{T,p,\alpha}$ is the critical value of the ADF-WS test of size α, such that $\lim_{T\mapsto\infty} \Pr(\mathrm{ADF}_{ijT}(p_{ij}) < K_{T,p,\alpha} \left|\bar{\mathrm{H}}_{\mathrm{c}}\right.) = \alpha$ and $\mathrm{ADF}_{ijT}(\mathrm{p}_{ij})$ the empirical value. The proportion of the $N(N-1)/2$ pairs for which the convergence hypothesis is accepted is given by : $\bar{Z}_{NT} = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} Z_{ij,T}$. Hence, the mean of this proportion is:

$$\begin{aligned} E\left(\bar{Z}_{NT} \left|\bar{\mathrm{H}}_{\mathrm{c}}\right.\right) &= \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} E\left(Z_{ij,T} \left|\bar{\mathrm{H}}_{\mathrm{c}}\right.\right) \\ &= \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \Pr\left(\mathrm{ADF}_{ijT}(p_{ij}) < K_{T,p,\alpha} \left|\bar{\mathrm{H}}_{\mathrm{c}}\right.\right) \end{aligned}$$

and so $\lim_{T\mapsto\infty} E\left(\bar{Z}_{NT} \left|\bar{\mathrm{H}}_{\mathrm{c}}\right.\right) = \alpha$. Under the divergence hypothesis, i.e. ADF-WS regressions, we would expect $\bar{Z}_{NT}$, the proportion of stationary pairs, to be close to α, the size of the test.

A similar result appears for KPSS tests. $Z_{ij,T}$ is now defined by:

$$Z_{ij,T} = \begin{cases} 1 & \text{if } \mathrm{KPSS}_{ijT}(\ell) > K_{T,\alpha} \text{ (rejection of } \mathrm{H_c}) \\ 0 & \text{otherwise} \end{cases}$$

where $K_{T,\alpha}$ is the critical value of the KPSS test of size α, such that $\lim_{T\mapsto\infty} \Pr(\mathrm{KPSS}_{ijT}(\ell) > K_{T,\alpha} \left|\mathrm{H_c}\right.) = \alpha$ and $\mathrm{KPSS}_{ijT}(\ell)$ the empirical value. In this case, $\bar{Z}_{NT}$ estimates the percentage of pairs for which the stationary hypothesis is rejected. Under the null of convergence, i.e. KPSS tests, we expect $\bar{Z}_{NT}$ to be close to the size of the test.

After examining unit roots, the hypothesis of cotrending, i.e. d_{ijt} is not trending, is tested for stationary pairs only. Following Pesaran's definition of pair-wise convergence, only stationary pairs accepting the hypothesis of the absence of a linear trend are converging pairs.

4 Data and Empirical Results

4.1 Data Description

Data for SO_2 emissions are taken from a larger database constructed by ASL and Associates (1997; Lefohn et al. 1999) for the period 1850–1990. SO_2 emissions are estimated by a bottom-up method: they are based on the use of hard coal, brown coal and petroleum and the extent of mining and smelting activities, combined with estimated sulfur content and retention factor for each country or year, and each fuel/metal type. The interest of these data is to supply annual national SO_2 emissions over a century and a half computed using a uniform methodology.

Data for CO_2 emissions are taken from Marland et al. (2007). This database provides global, regional and national estimations of annual fossil-fuel CO_2 emissions for the period 1751–2003. Fossil-fuel CO_2 emissions includes gas, liquid and solid fuels, gas flaring and cement production. This database omits natural carbon emissions (eruptions, vegetal, animal and human respiration, organic matter decomposition), representing at most 30% of total CO_2 emissions. Like the ASL database, the Marland database is interesting since it provides emissions data for a relative large number of countries and years computed using consistent methodology.

Population data are extracted from the Penn World Table Version 6.2 (Heston et al. 2006).

To sum up, the samples for CO_2 and SO_2 emissions are composed respectively of 127 countries (8,001 pairs) between 1950 and 2003 and 81 countries (3,240 pairs) over the period 1950–1990[4] (cf. Table 3 in Appendix). I also examine stochastic convergence over the OECD sub-dataset.

4.2 Empirical Results

I begin by analysing the results of unit-root tests on all per capita CO_2 emissions gaps pairs in the total sample over 1950–2003. Table 4 (cf. Appendix) reports the percentage of pairs rejecting the unit root hypothesis at 5 and 10% significance levels, using the ADF-WS regression and three information criteria orders of augmentation. Note that proportions are substantially higher than the significance level of the unit root tests. In the case of ADF tests, the proportion of stationary pairs is expected to be close to the significance level of the tests under the non-convergence hypothesis. In this context, there is some evidence of per capita CO_2 convergence for both samples. After identifying the stationary pairs, their cotrending properties are examined. Note that the proportion of converging pairs ranges from 3.46 to 8.50% over 1950–2003 (cf. Table 5 in Appendix). Since the percentages of emission gap pairs that meet both criteria, stationarity around a constant mean, are very small; empirical evidence in favour of stochastic convergence in CO_2 emissions per capita seems limited. Moreover, the hypothesis of convergence is not supported by the KPSS test, which, on the contrary, supports the divergence hypothesis. Indeed, the proportion of pairs rejecting the null hypothesis of stationarity is higher than 80% (mean stationarity) and 75% (trend stationarity) (cf. Table 6). In the case of the KPSS test, the proportion of diverging pairs is expected to be close to the significance level of the test under the convergence hypothesis. Hence, the use of the pair-wise approach provides slightly contradictory empirical evidence on convergence in CO_2 emissions per capita.

Similar results are obtained on the OECD sub-sample.[5] Indeed, ADF-WS regression provides some evidence in favour of stochastic convergence since the proportions of stationary pairs are substantially higher than the significance level of the test. Note that the proportion of converging pairs, stationary pairs around a constant mean, over the OECD sample ranges from 1.72 to 3.45% over 1950–2003. As for KPSS tests, empirical results are against the hypothesis of stochastic convergence. The percentages of non-stationary pairs are higher than 90 and 85% in the mean and trend stationarity models respectively. In this context, the pair-wise method also leads to conflicting results on convergence in CO_2 emissions per capita over the OECD sample.

As for per capita SO_2 emissions, empirical results from the pair-wise estimation are also uncertain (see footnote 5). Indeed, both over the whole sample and the OECD sub-sample, ADF regressions provide some weak evidence of stochastic convergence while inferences from KPSS tests support the divergence hypothesis. To sum up, unfortunately, this first econometric analysis provides contradictory conclusions on stochastic convergence in per capita CO_2 and SO_2 emissions depending on the choice of the unit root test. At this point of the study, the use of the pair-wise approach, instead of Carlino and Mills' methodology, does not

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[4] To check the robustness of the results, the convergence test has been realised on two sub-periods, corresponding to different dynamics of economic growth, for each pollutant: 1950–1974 and 1975–2003 for CO_2 emissions, and 1950–1970 and 1971–1990 for SO_2 emissions. Since empirical results do not show any significant difference, they are not presented in this article but are available upon request.

[5] Detailed tables of empirical results on per capita CO_2 emissions over the OECD sample and on per capita SO_2 emissions (whole and OECD datasets) are not presented in the article for purpose of brevity but are available upon request.

give a clear-cut view of CO_2 and SO_2 stochastic convergence. In this context, an extension of the econometric analysis is needed to clarify these first findings. To understand it, it must be noted that standard marginal critical values have been used while testing the null hypotheses of unit root and stationarity and yet Carrion-i-Silvestre et al. (2001) show that simultaneous tests of stationarity and unit root must be carried out by using specific marginal critical values. In this context, it would be interesting to test the joint confirmation hypothesis of a unit root for all the $N(N-1)/2$ pairs by using critical values computed by Carrion-i-Silvestre et al. (2001) and Keblowski and Welfe (2004).

5 Extension of the Analysis with the ADF-KPSS Joint Test

5.1 The Joint Confirmation Hypothesis

This extension is based on the complementarity of the results of unit root and stationarity tests. Indeed, the main idea of the joint confirmation hypothesis is the simultaneous use of empirical results from unit root and stationarity tests, instead of separate analyses. Therefore, in this section, the pair-wise approach developed by Pesaran (2007), described in part 3, is combined with the analysis of the joint confirmation hypothesis. The latter tests the null joint hypothesis of a unit root, that is to say both rejection of the KPSS null hypothesis and acceptance of the ADF null hypothesis.[6] To do this, standard ADF and KPSS tests on each gap pair, $d_{ijt} = e_{it} - e_{jt}$, are applied. Their unit-root properties with both tests are examined using critical values from the joint confirmation hypothesis. Note that these specific critical values are taken from Carrion-i-Silvestre et al. (2001) and Keblowski and Welfe (2004) for small samples.

Based on Pesaran's expected results, under the divergence hypothesis, the proportion of converging pairs, i.e. rejecting the null of the ADF test and accepting the null of the KPSS test, is expected to be close to the significance level of the test. However, four different results can be observed, two showing an agreement and the two others a disagreement between the tests, as shown by Table 2. Therefore, during the interpretation of the empirical results, only non-ambiguous results are interesting: the proportion of stationary and integrated pairs with both tests using critical values from the joint confirmation hypothesis are computed and respectively compared to the significance level of the test and the probability of joint confirmation.

Table 2 Possible results from the joint ADF-KPSS test

		ADF test results	
		Unit root H_0^D accepted	*Stationarity* H_0^D rejected
KPSS test results	*Unit root* H_0^K rejected	Same conclusions	Ambiguous result
	Stationarity H_0^K accepted	Ambiguous result	Same conclusions

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[6] See Carrion-i-Silvestre et al. (2001) for a detailed presentation of the test.

5.2 Empirical Results

5.2.1 CO_2 Emissions Convergence

I begin by analysing the results of the joint confirmation hypothesis on all per capita CO_2 emissions gaps pairs in the sample over 1950–2003. Table 7 (cf. Appendix) reports the proportions of stationary and integrated pairs, with or without a trend, for both tests using critical values from the joint confirmation hypothesis. In other words, the percentage of stationary (integrated) pairs corresponds to the proportion of pairs rejecting (accepting) the null hypothesis of the ADF test and accepting (rejecting) the null of the KPSS. Note that proportions of (mean or trend) stationary pairs are small, even null in the case of the OECD sample, and not superior to 2.5%. Concerning integrated pairs, percentages are very high, varying according to the information criterion from 77.45 to 87.81% for the whole sample and from 84.73 to 91.13% for the OECD dataset. In this context, focusing on the proportion of mean-stationary (i.e. converging) pairs, the combination of the joint confirmation hypothesis with the pair-wise approach leads to empirical results against the hypothesis of stochastic convergence in CO_2 emissions per capita, both over the whole and OECD samples. Therefore, this extension overcomes initial conflicting results (cf. Sect. 4.2) and so supports the studies of Aldy (2006) and Barassi et al. (2008) concerning stochastic divergence in per capita CO_2 emissions.

5.2.2 SO_2 Emissions Convergence

Results of unit-root tests on all per capita SO_2 emissions gaps pairs over 1950–1990 are summarized in the Appendix (Table 8). Like estimations on per capita CO_2 emissions, the proportions of (mean or trend) stationary pairs are small, even null in the case of the OECD sample and not superior to 2%. Concerning integrated pairs, percentages are very high, and according to the information criterion, vary from 84.73 to 95.4% for the whole sample and from 92.89 to 96.84% for the OECD dataset. Focusing on the proportion of mean-stationary pairs (i.e. converging pairs), the combination of the joint confirmation hypothesis with the pair-wise approach leads to empirical results against the hypothesis of stochastic convergence in SO_2 emissions per capita, both over the whole and OECD samples. Therefore, this extension supports the study of List (1999) and invalidates the one of Bulte et al. (2007) on stochastic convergence in SO_2 emissions per capita.

6 Conclusion

This paper has re-examined the hypothesis of stochastic convergence for two air pollutants (CO_2 and SO_2) by applying a recent alternative econometric method, the pair-wise approach. Previous studies have implemented Carlino and Mill's methodology despite the fact it can give biased results. Hence, Pesaran's method (2007), based on the analysis of each emission gap pair, can provide some reliable and interesting findings in the context of mixed results supported by previous empirical studies.

Unfortunately, the pair-wise methodology leads to conflicting results concerning per capita CO_2 and SO_2 emissions convergence. Indeed, while inferences from the KPSS tests are clearly against the convergence hypothesis (both over the whole sample and the OECD subsample), ADF-WS regressions provide some evidence of convergence. In order to clarify these preliminary findings, the analysis of stochastic convergence was extended by applying specific critical values of the ADF-KPSS joint test to compute the proportion of stationary and integrated pairs. Empirical results show that this extension overcomes the conflicting initial results. Indeed, both on the CO_2 and SO_2 samples (total and OECD datasets), the percentage of stationary pairs are small, not superior respectively to 2.5 and 2%. As for integrated pairs, proportions are very high, the minimum being 78%. In this context, using Pesaran's definition of stochastic convergence, the small percentages of mean stationary-converging-pairs strongly invalidate the hypothesis of stochastic convergence both for CO_2 and SO_2 emissions per capita, even over the OECD sub-dataset.

Several policy implications of this result can be noted. Firstly, convergence in emissions is a key feature of many climate change models, such as the emissions scenarios published in 2000 by the Intergovernmental Panel on Climate Change. As my analysis invalidates the hypothesis of convergence in emissions, long-run projections of CO_2 stemming from these scenarios are based on an unrealistic assumption. Therefore, policymakers should be cautious when formulating emissions abatement strategies relying on those projection models. Moreover, even if per capita distribution of pollutant emissions does not affect environmental effects, divergence in emissions may make multilateral negotiations on environmental agreements harder (Aldy 2006). Indeed, in this context, it is likely to make it tough for developing countries to agree to emissions abatement obligations. In addition, the existence of emissions divergence implies that the establishment of a per capita emissions allocation scheme results in substantial resource transfers through international emissions trading or relocation of emissions-intensive economic activities. Therefore, as Barassi et al. (2008) points out, "imposing per capita convergence, when there is no natural tendency to such convergence, may impose a burden of significant adjustment costs due to the required re-distribution of emissions".

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Appendix

See Tables 3, 4, 5, 6, 7 and 8.

Table 3 List of countries in the samples

A. Dataset for CO_2 emissions

Total Sample (N = 127)

Albania, Algeria, Angola, Argentina, Australia, Austria, Bahamas, Bahrain, Barbados, Belgium, Belize, Bermuda, Bolivia, Brazil, Brunei, Bulgaria, Canada, Capa Verde, Chile, China, Colombia, Costa Rica, Cuba, Cyprus, Czechoslovakia, Korea Democracy, Denmark, Djibouti, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Faeroe Islands, Fiji, Finland, France, French Guinea, Gambia, Germany, Ghana, Gibraltar, Greece, Greenland, Grenada, Guadeloupe, Guam, Guatemala, Guyana, Haiti, Honduras, Hong-Kong, Hungary, Iceland, India, Indonesia, Iraq, Ireland, Iran, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Kuwait, Lebanon, Liberia, Libyan Arabia, Luxembourg, Madagascar, Malta, Martinique, Mauritius, Mexico, Mongolia, Morocco, Mozambique, Myanmar, The Netherlands, New-Caledonia, New-Zealand, Nicaragua, Nigeria, Norway, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Puerto Rico, Qatar, Republic of Cameroon, Republic of Korea, Reunion, Romania, Saint Lucia, Samoa, Saudi Arabia, Sierra Leone, South Africa, Spain, Sri Lanka, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Sudan, Suriname, Sweden, Switzerland, Syrian Arab Republic, Taiwan, Thailand, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkey, US Virgin Islands, Uganda, UK, USA, Uruguay, USSR, Venezuela, Zaire.

Table 3 continued

OECD sample ($N = 29$)

Australia, Austria, Belgium, Canada, Czechoslovakia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, The Netherlands, New-Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, UK, USA

B. Dataset for SO_2 emissions

Total sample ($N = 81$)

Afghanistan, Albania, Algeria, Argentina, Australia, Austria, Bahrain, Barbados, Belgium, Bolivia, Brazil, Bulgaria, Canada, Chile, China, Colombia, Cuba, Cyprus, Czechoslovakia, Denmark, Ecuador, Egypt, Finland, France, Ghana, Germany, Greece, Hong-Kong, Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Japan, Kenya, Kuwait, Lebanon, Luxembourg, Madagascar, Malaya-Malaysia, Mexico, Mongolia, Morocco, Mozambique, Namibia, The Netherlands, New-Zealand, Nigeria, North Korea, Norway, Peru, Philippines, Poland, Portugal, Puerto Rico, Romania, Saudi Arabia, South Africa, South Korea, Spain, Sri Lanka, Sweden, Switzerland, Syria, Taiwan, Thailand, Trinidad and Tobago, Tunisia, Turkey, UK, USA, Uruguay, U.S.S.R, Venezuela, Zaire, Zambia, Zimbabwe

OECD sample ($N = 23$)

Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, The Netherlands, New-Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK, USA

Table 4 Proportion of CO_2 emission gap pairs for which the unit-root hypothesis is rejected

Sample period	1950–2003 ($T = 54$)	
Number of countries	$N = 127$	
Number of pairs	8,001 pairs	
Tests (significance level) (%)	5	10
ADF-WS(p)		
p(AIC)	16.18	23.2
p(SC)	18.02	26.02
p(HQ)	17.03	24.47

The unit-root tests are based on augmented Dickey–Fuller (ADF) regressions with an intercept and a linear trend (cf. Eq. 5), and are carried out at the 5 and 10% level. ADF-WS(p) is due to Park and Fuller (1995). Critical values are taken from Pesaran (2007). The number in a cell is the percentage of pairs rejecting the hypothesis of a unit root

Table 5 Proportion of stationary CO_2 emission gap pairs with non-significant trend, i.e. converging pairs

Sample period	1950–2003 ($T = 54$)			
Number of countries	$N = 127$			
Number of pairs	8,001 pairs			
Tests of unit root (%)	5		10	
Tests (significance level) (%)	5	10	5	10
ADF-WS(p)				
p(AIC)	4.22	3.46	6.86	5.50
p(SC)	5.05	4.16	8.50	6.94
p(HQ)	4.56	3.77	7.47	6.05

The number in a cell represents the proportion of converging pairs in the whole sample. Tests of unit roots and cotrending are conducted at the 5 and 10% level. Critical values for the cotrending test are asymptotic standard normal values, i.e. 1.96 and 1.645 at the 5 and 10% level, respectively

Table 6 Proportion of CO_2 emission gap pairs for which the stationarity hypothesis is rejected (mean or trend stationarity)

Sample period	1950–2003 ($T = 54$)	
Number of countries	$N = 127$	
Number of pairs	8,001 pairs	
Test level (%)	5	10
Mean stationarity		
$\ell = 2$	80.05	88.14
Trend stationarity		
$\ell = 2$	77.43	86.21

Note that for the computation of the KPSS test statistics, the window lag ℓ is chosen approximately as the integer of $0.75T^{1/3}$. Hence, for $T = 54$, the window lags is 2 ($0.75T^{1/3} = 2.83$). The critical values obtained for the case with an intercept only and with an intercept and a trend are taken from Stephton (1995). The number in a cell is the proportion of pairs rejecting the stationarity hypothesis

Table 7 The joint confirmation hypothesis on CO_2 emission gap pairs (total and OECD samples)

Sample period	1950–2003							
Dataset	Total sample				OECD sub-sample			
Number of countries	$N = 127$				$N = 29$			
Number of pairs	8,001 pairs				406 pairs			
Test level (%)	5		10		5		10	
Proportion of pairs	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$
With trend								
p(AIC)	1.17	85.45	1.67	80.09	0.7	90.89	0.7	85.47
p(SC)	1.02	83.68	1.77	77.45	0.7	90.64	0.7	84.73
p(HQ)	1.11	84.28	1.71	78.57	0.7	90.89	0.7	85.22
Without trend (constant only)								
p(AIC)	0.52	87.81	2.22	82.83	0	91.13	0.49	86.45
p(SC)	0.56	86.49	2.11	80.55	0	90.64	0.49	85.47
p(HQ)	0.55	86.78	2.22	81.36	0	90.64	0.49	86.21

The unit-root tests are based on augmented Dickey–Fuller (ADF) regressions, either with an intercept and a linear trend or only with a constant, and are carried out at the 5 and 10% level. The ADF test statistic was computed using three different information criteria, with a maximum of five lag-differences. Note that for the computation of the KPSS test statistics, the window lags ℓ are chosen approximately as the integer of $0.75\mathrm{T}^{1/3}$. Critical values for ADF and KPSS tests, with a trend and without, are taken from Carrion-i-Silvestre et al. (2001) and Keblowski and Welfe (2004). For a $I(0)$ column, the number in a cell is the percentage of stationary pairs whereas for a $I(1)$ column, it is the percentage of integrated pairs according to the ADF-KPSS joint test

Table 8 The joint confirmation hypothesis on SO_2 emission gap pairs (Total and OECD samples)

Sample period	1950–1990							
Dataset	Total sample				OECD sub-sample			
Number of countries	$N = 81$				$N = 23$			
Number of pairs	3,240 pairs				253 pairs			
Test level (%)	5		10		5		10	
Proportion of pairs	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$
With trend								
p(AIC)	0.8	94.75	1.39	91.52	0	94.47	1.58	92.89
p(SC)	0.92	95.4	1.39	92.07	0	94.86	1.58	93.68
p(HQ)	0.89	94.91	1.39	91.64	0	94.07	1.58	92.89
Without trend (constant only)								
p(AIC)	0.18	93.39	0.59	89.38	0.79	96.44	0.79	94.47
p(SC)	0.15	93.67	0.46	89.04	0.40	96.84	0.40	93.68
p(HQ)	0.18	93.55	0.55	89.26	0.79	96.84	0.79	94.07

Same as Table 7

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