# A panel data heterogeneous Bayesian estimation of environmental Kuznets curves for CO2 emissions

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# A panel data heterogeneous Bayesian estimation of environmental Kuznets curves for $CO_2$ emissions

**Abstract**

This paper investigates the environmental Kuznets curves (EKC) for $CO_2$ emissions in a panel of 109 countries during the period 1959-2001. The length of the series makes the application of a heterogeneous estimator suitable from an econometric point of view. The results, based on the hierarchical Bayes estimator, show that different EKC dynamics are associated with the different sub-samples of countries considered. On average, more industrialized countries show evidence of EKC in quadratic specifications, which nevertheless are probably evolving into an N shape based on their cubic specification. Nevertheless, it is worth noting that the EU, and not the Umbrella group led by US, has been driving currently observed EKC-like shapes. The latter is associated to monotonic income-CO2 dynamics. The EU shows a clear EKC shape. Evidence for less developed countries consistently shows that $CO_2$ emissions rise positively with income, though there are some signs of an EKC. Analyses of future performance, nevertheless, favor quadratic specifications, thus supporting EKC evidence for wealthier countries and non-EKC shapes for industrializing regions.

*Keywords:* Environmental Kuznets Curve, $CO_2$ emissions, Bayesian approach, heterogeneous panels

JEL classification: C23, Q53

## 1. Introduction

Since the pioneering work of Grossman and Krueger (1995), Shafik (1994) and Holtz-Eakin and Selden (1992) interest in the so-called Environmental Kuznets Curve (EKC) has increased. The EKC hypothesis is that, for many pollutants, relationships between per capita income and pollution show inverted U-shapes, following the more famous original Kuznets hypothesis which has been considered over time in its original and revised forms (Tsakloglu, 1988). Most investigations have focused on major air emissions, though evidence for other externalities like local atmospheric and water emissions, and waste has begun to accumulate[1]. In this study we focus on $CO_2$ emissions, which have been recognized as a major source of environmental pollution. First, $CO_2$ emissions are directly linked to the production and consumption of energy and, thus, the shape of the relationship between $CO_2$ emissions and economic development has implications for the definition of an appropriate economic and environmental policy. Second, empirical evidence in support of an EKC dynamics, or delinking between emissions and income growth, has been shown to be more limited and fragile in the case of $CO_2$ emissions with respect to local air and water pollutants. A decoupling between income growth and $CO_2$ emissions is not (yet) apparent for many important economies in the world (Vollebergh and Kemfert, 2005); where it is observed, it is a relative rather than the

[1] Waste, which is a very different externality with respect to impacts and local dimension, is the only pollutant other than $CO_2$ where there is a lack of robust evidence in favour of absolute delinking (Mazzanti and Zoboli, 2005; Mazzanti, 2007; Wang et al., 1998). There is some recent evidence of EKC trends in waste generation (Mazzanti, Montini, Zoboli, 2008a,b).

absolute delinking assumed by the EKC hypothesis (Fischer-Kowalski and Amann, 2001).

Theoretically based works do not predominate in studies of EKC[2]

[2] A recent seminal paper by Copeland and Taylor (2004) surveys the literature and presents a model in which sources of growth, increasing returns to abatement, income and threshold effects are the main drivers of EKC.

though some contributions have aimed at establishing some foundations for the empirics of EKC. They generally try to explain EKC dynamics by a preference based technological externality type, and policy factors. Some of these works are worthy of further comment. Andreoni and Levison (2001) is a seminal work that suggests that EKC dynamics may be quite simply technologically micro founded, and not strictly related to growth and externalities issues. Kelly (2003) shows that the EKC shape depends on the dynamic interplay between the marginal costs and benefits of abatement.

**Comment [CL1]:** Sorry not sure if this is correct

At a more macroeconomic level, Brock and Taylor (2004) integrate the EKC framework with the Solow model of economic growth; they show that this revised model generates an EKC relationship between both flow of pollution emission and income per capita, and the stock of environmental quality and income per capita, with the resulting EKC being either an inverted U shape or strictly declining. Chimeli and Braden (2005) integrate the EKC into a model of total factor productivity. Low levels of income involve high values of discount rate, which are obstacles to the adoption of a pollution abatement policy. Only when the discount rate falls, as a consequence of growth, is it possible to implement measures for emissions reductions, leading to an inverse U-shaped income-pollution pattern.



Notwithstanding the increasing relevance of theoretical studies on EKC, it is the quantitative side of the analysis that has dominated, and nevertheless still provides scope for research improvements at the margins. In fact, with some exceptions which we comment on below, studies using macro-panel data generally assume slope homogeneity across countries, and employ the classic fixed or random effects estimators or the more recent panel cointegration approach.

With the increasing time dimension of panel data sets, however, a more heterogeneous estimator might be more suitable from an econometric point of view (Pesaran and Smith, 1995; Pesaran *et al.*, 1999; Hsiao *et al.*, 1999).

The paper is organized as follows. In section 2, we review recent developments in EKC analysis for $CO_2$, focusing on the heterogeneity of panel data estimators. Section 3 describes the econometric framework. Section 4 presents the results of the estimations and section 5 concludes. Data sources and definitions are provided in the appendix.

## 2. Recent developments in studies of EKC for $CO_2$

Although there are a large number of studies on $CO_2$ decoupling of income growth and $CO_2$ emissions is often not (yet) apparent from the data for many of the important world economies (Vollebergh and Kemfert, 2005); where delinking is observed, it is often of a relative and not an absolute kind, as assumed by the usual EKC hypothesis.

Recent works, on the basis of newly updated data and new techniques, have highlighted that some evidence, even if differentiated by geographical area and by estimation technique, is emerging of a delinking (Martinez-Zarzoso and Bengochea-Morancho, 2004; Vollebergh et al., 2005; Galeotti et al., 2006). Although this evidence is patchy, i.e. heterogeneous across various attempts (which use different data with respect to time span and countries), it can be claimed that, for the OECD countries, some EKC evidence for $CO_2$ is emerging. The picture is thus slightly more optimistic, counterbalancing to a degree less optimistic views (Harbaugh et al., 2002; Stern, 1998, 2004). However, overall the evidence is far from robust, and results should be interpreted with care. Though we do not here aim at completely surveying the literature, some recent contributions deserve specific attention.

Cole (2005) recently applied the heterogeneous Swamy random coefficients estimator and concluded that the income-pollution relationship varies widely across countries. This suggests that the assumption of constant coefficients across countries in a traditional fixed-effects specification is inappropriate. More fundamentally, it suggests that there is no income-pollution relationship that is common to all countries, which questions the existence of a general EKC shape.

Most of the existing empirical literature applies pooled panel data estimators to samples of heterogeneous countries. Recent developments in the literature test the robustness of the EKC hypothesis by applying flexible parametric specifications, by exploiting partially or fully non-parametric models, or by looking at the cointegration properties of $CO_2$ time series (Vollebergh et al., 2005; Galeotti, Lanza, Pauli, 2006), and producing mixed results that do not help to account for the intrinsic EKC empirical fragility. In a nutshell, the main criticisms in recent years have focused on the plausibility of a standard "homogenous" panel in cross country analyses where different income-$CO_2$ relationships may exist.

Dijkgraaf and Vollebergh (2005) and Vollebergh et al. (2005) allow for both heterogeneity across countries and flexible (non parametric) functional form, and show that traditional panel models with country specific, or country and time effects may present turning points within the observed income ranges; nevertheless, the null hypothesis of slope homogeneity is strongly rejected by the data, thus questioning the existence of an overall EKC and the assumption of homogeneity.

Dijkgraaf and Vollebergh's (2005) paper casts doubt on the EKC results based on homogenous panel estimation. They use the sample of the 24 OECD countries for

1960-1997 and challenge the existence of EKC dynamics for $CO_2$, at least for the OECD countries. They suggest a more in depth country-specific investigation. Traditional panel models that include country specific or country and time effects show turning points at around $14,000-15,000; nevertheless, the null hypothesis of slope homogeneity is strongly rejected by these data. A general model with slope heterogeneity shows a higher turning point ($20,600). However, all these levels are within the sample range. The most striking result is that time series analysis, compared to heterogeneous panel estimations, presents a different picture. Only five out of 13 countries that showed evidence of an EKC dynamics confirm this outcome. The authors conclude that more work should be done on time series data, assuming there is sufficient availability[3].

Vollebergh et al. (2005) explore various parametric and non parametric specifications of a $CO_2$ dataset of OECD countries and find that EKC shapes are quite sensitive to the degree of heterogeneity included in the panel estimations, indicating the need for further exploration not only using heterogeneous panel specifications, but also more flexible estimation tools. Parametric models generate EKC shapes with quite low turning points, while the evidence for semi parametric estimations is less robust. The non-parametric setting demonstrates the necessity to incorporate heterogeneity, which leads to the exploration of single, country specific time series, and to the suggestion of caution in relation to panel based EKC outcomes, especially if they do not address the heterogeneity issue in some way.

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[3] They also point out that for some pollutants, such as $CO_2$, the lack of homogeneity is not a surprising outcome given the trends in international specialization, differences in local features and absence of strongly coordinated policies at least at the international level.

These authors thus argue that the inverted U shaped curve is likely to exist for many countries (with higher incomes), but not all countries: homogeneity in EKC shapes, therefore, is a too restrictive hypothesis. The existence of an EKC curve, in cross country international framework such as OECD based analysis, may depend on the balance between high income countries showing an inverted U shape dynamics, and high income countries, which present a still positive elasticity for emissions with respect to income. Trying to consider together widely different countries may present difficulties and lead to not easily interpretable and not very useful outcomes for informing policy making, which needs to rely on the assumption of country heterogeneity in costs and performance in order to set efficient and effective allocations.

Galeotti, Lanza and Pauli (2006) are rather skeptical of the assumption of an EKC, and test the robustness of the EKC hypothesis by analysing $CO_2$ series. The paper provides mixed evidence, focusing on $CO_2$ and estimating different specifications based on varying sets of emissions data and the parametric structure of the model, but is optimistic in its conclusions. Robustness is tested on the basis of data typology and on the basis of alternative specification hypothesis. Results show that data sources seem not to affect EKC evidence. By exploiting a flexible parametric model, an inverted U shape curve is found for the OECD countries, regardless of the data source used; for the non-OECD countries the EKC is basically increasingly, but results are more dependent on the data source. Turning points for the OECD countries occur around €16,000 and for the non-OECD countries at between €16,000 and €20,000, which, as expected, demonstrates the less stable relationship between $CO_2$ and GDP, with respect to the data source.

The papers referred to highlight the role of semi-parametric and fully non-parametric EKC estimations. Taskin and Zaim (2000) use non-parametric production frontier techniques, establishing an EKC relationship using kernel estimation methodology. Both kernel and parametric estimations show an N shape from the data: non-parametric estimations give robustness to the choice of a cubic specification. Turning points for the N shape curve are found at $5,000 and $12,000 per capita.

Another interesting recent study is by Azoumahou et al. (2006), who use $CO_2$ data for 1960-1996 for 100 countries, exploiting non-parametric and parametric specifications for comparison. The paper discusses recent evidence from the semi- and non-parametric literature, arguing that functional issues are of more concern than heterogeneity issues. The authors compare various models, finding that EKC shapes emerge from a parametric panel model (signs positive for linear and squared terms, and negative for cubic terms), and that a monotonous relationship emerges from non-parametric settings and first difference regressions.

In light of these recent developments, we argue that, by increasing the time dimension of panel data sets, the choice of a more heterogeneous estimator may be preferred. In this paper, we use heterogeneous panel data estimators, derived from the Bayesian approach. In particular, we apply the "hierarchical Bayes estimator" proposed by Hsiao et al. (1999), which has been shown to be preferable to other heterogeneous panel data estimators (Hsiao et al., 1999; Baltagi et al., 2004).

We note that we do not control for possible determinants of $CO_2$ emissions, such as energy prices or technological change. This is scope for further research. In addition, as pointed out by Azoumahou et al. (2006) there are reasons for this kind of econometric specification. The two basic ones are related to data availability over long time series and many countries in terms of additional covariates, and comparability with existing studies. The third is more econometrically-based: although a specification that excludes the determinants of $CO_2$ emissions is not appropriate ceteris paribus for measuring the impact of GDP on $CO_2$ emissions, this kind of econometric specification is very useful for capturing the global effect of GDP on $CO_2$ including the indirect effects linked to the omitted variables which are correlated with GDP.

The specific incremental value added of this paper is twofold. First, we present evidence on $CO_2$, exploiting a new method aimed at dealing with country heterogeneity. This is a methodological advancement. $CO_2$ is the only emission for which currently there is sufficient data availability to implement this kind of quantitative methodology at the international level. Second, in order to provide more economic and policy meaningful results, we test the EKC hypothesis on sub-samples of countries (G7, OECD, $EU_{15}$, non-OECD, poorest countries[4]), and compare EKC trends with the total sample trend. We share the view that the EKC hypothesis is not applicable as a general concept, as it was present an overall cross country dynamic development of the emission-income relationship: many EKC shapes are possible, depending on the country, the area and th he period defined.

**Comment [CL2]:** Do you mean as it would, because it would, because it presents??

### 3. Econometric framework

[4] We argue that this sub-division is useful for deriving policy conclusion in the $CO_2$ policy arena, where the reasoning mainly revolves around the role played by different areas according to their environmental and development path.

### 3.1 Estimation issues

The fact that the time dimension is allowed to increase to infinity in macro panel data generates two sets of ideas. The first is related to time series procedures applied to panel data to deal with non-stationarity, spurious regressions and cointegration (Kao and Chiang, 2000; Phillips and Moon, 1999). The second rejects the homogeneity of the parameters implicit in the use of a pooled estimator in favour of heterogeneous regressions.

Within this strand of literature and treating the parameters as fixed, it is possible to estimate separate ARDL (Auto-Regressive Distributed Lags) equations for each group and examine the mean of the estimated coefficients – the so-called Mean Group (MG) estimator (Pesaran and Smith, 1995). The MG, however, does not take into account the fact that certain parameters may be the same across groups. Pesaran et al. (1999), therefore, proposed an intermediate estimator, the Pooled Mean Group (PMG) estimator which allows the intercepts, short-run coefficients and error variance to differ across groups, while the long run coefficients are identified by an equality constraint.

Another way of building heterogeneous panel data estimators derives from the Bayesian approach, which treats the parameters as random, and as drawn from some distribution with a finite number of them[5]. Recently, Hsiao and Tahmiscioglu

[5] Although within the slightly different framework of policy evaluation, we note the work by Brock et al. (2003), who propose model averaging methods as a statistical procedure to tackle model uncertainty. Within this reasoning, based on averaging models using a formalized statistical procedure rather than informal methods, the Bayesian paradigm and statistics (versus Waldean and frequentist) plays a crucial role. Since EKC issues are within the broader realm of empirical macro economics and are to some extent linked to policy evaluation studies, this type of reasoning has

(1997) and Hsiao et al. (1999) proposed the use of Bayes and hierarchical Bayes estimators, building on early work by Lindley and Smith (1972) and Swamy (1970): in fact the Swamy (1970) random coefficients model, motivated by the classical generalized least squares arguments, can also be considered a Bayes estimator.

However, making the choice between fixed and random coefficients formulations, despite the extensive discussion in the literature, is difficult in practice (Hsiao *et al.*, 1995).

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In the following, we apply Hsiao et al.'s (1999) hierarchical Bayes approach to the estimation of an ECK for $CO_2$ emissions. Our choice is motivated by the fact that using both Monte Carlo experiments and an empirical example of a q investment model, Hsiao et al. (1999) find that this estimator is preferable to the other consistent estimators. Moreover, reconsidering the q-investment model and contrasting the performance of 9 homogeneous estimators and 11 heterogeneous and shrinkage Bayes estimators, Baltagi et al. (2004) find that the Hsiao et al. (1999) hierarchical Bayes estimator gives the best performance.

### 3.2 Econometric model and estimation methodology

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relevancy even within this framework. First, model uncertainty, which is discussed at length, is a key pillar of this literature. With or without a formalized theoretical model, the spectrum of empirical models is wide. Within the EKC framework, following the authors' taxonomy of uncertainty, theory uncertainty (e.g. which empirical model, which non-linear assumption), specification uncertainty (e.g. non linearity, number and content of covariates) and heterogeneity uncertainty (data sources, time span, statistical units) as interrelated and overlapping concepts, are relevant. Secondly, more and more studies are analysing the extent to which policies modify the endogenous EKC dynamic (reducing the turning point income level and/or the environmental indicator peak).

We are interested in the estimation of the mean coefficients of a standard EKC function in the presence of slope heterogeneity across cross-sectional units for our sample of 109 countries for the period 1959-2001. Let us consider the following random coefficients specification:

(1) $$y_i = X_i \theta_i + u_i, \quad i = 1,\ldots,N$$

where $y_i = \left(y_{i1}, y_{i2},\ldots, y_{iT}\right)'$ is the $(T \times 1)$ vector of observations for the dependent variable $\left(y_i = \ln\left(co_{2i}\right)\right)$, namely the logarithm of $CO_2$ emissions per capita, and $X_i = \left(x_{i1},\ldots, x_{iT}\right)'$ is a matrix of dimensions $(T \times k)$ of the explanatory variables for the *i*'th cross-sectional unit. If we are interested in the estimation of a cubic formulation for the ECK, we obviously obtain a $(T \times 3)$ matrix of explanatory variables, given by: $X_i = \left(\ln y_i, (\ln y_i)^2, (\ln y_i)^3\right)$ where y is GDP per capita.

The central assumption of the random coefficients formulation is that $\theta_i = \overline{\theta} + \varepsilon_i$ where the $\varepsilon_i$ are independently normally distributed with mean 0 and covariance $\Delta$, i.e. $\theta_i \sim IN(0,\Delta)$ and $Cov\left(\theta_i, \theta_j\right) = 0$ if $i \neq j$. Each regression coefficient can thus be considered a random variable with a probability distribution. The random coefficients formulation reduces the number of parameters to be estimated, while still allowing the coefficients to differ across countries.

Additional assumptions are that: i) the disturbances are heteroskedastic and uncorrelated across different cross-sectional units, i.e. $u_i \sim iid\left(0, \sigma_i^2\right)$ and

$Cov(u_i, u_j) = 0$ if $i \neq j$; ii) the explicative variables are strictly exogenous, i.e. $X_{it}$ and $u_{is}$ are independent for all *t* and *s*.

From a Bayesian point of view, Hsiao et al. (1999) focus on the inference of the mean coefficient vector, $\bar{\theta}$ conditional on *y*, and the underlying model *M*, summarized in the posterior density $p(\bar{\theta}|y, M)$. The observations in *y* define a mapping from the prior $p(\bar{\theta})$ into $p(\bar{\theta}|y, M)$. When there is reliable prior information on $\Delta$ and $\sigma_i^2$, the posterior distribution of $\bar{\theta}$ can be derived by expressing the likelihood function conditional on the initial values $y_0$ and combining it with the prior distribution of $\bar{\theta}$:

(2) $$p(\bar{\theta}|y, y_0) \propto p(y|\bar{\theta})\, p(\bar{\theta}).$$

Lindley and Smith (1972) discuss the derivation of the Bayes estimator of $\bar{\theta}$: they propose a three-stage hierarchical method. The first stage of the hierarchy corresponds to the joint density function of $y_i$. Following the previous assumptions we can write:

(3) $$p(y_i|X_i, \theta_i) \sim N(X_i\theta_i, \Omega_i)$$

where $\Omega_i$ is a block diagonal matrix given by $\Omega_i = \sigma_i^2 \mathbf{I}_T$. The second stage is defined as the density function of the vector of parameters $\theta_i$:

(4) $p(\theta_i) \sim N(\bar{\theta}, \Delta)$,

and the third stage corresponds to the prior distribution of $\bar{\theta}$ :

(5) $\bar{\theta} \sim N(\varphi, \Psi)$.

These three stages allow us to derive the posterior distributions of the unknown parameters. Prior distributions for nuisance parameters, however, lead to integrals that cannot be expressed in closed form. Consequently, Lindley and Smith (1972) propose a naïve approximation, based on using the posterior distribution mode rather than the mean. However, as a result of recent advances in sampling-based approaches to calculating marginal densities, a full Bayesian implementation of this model is now feasible. In particular, Hsiao et al. use the Gibbs sampling approach proposed by Gelfand and Smith (1990) which is an iterative Markov chain Monte Carlo method that only requires knowledge about the full conditional densities of the parameter vector.

**Comment [CL5]:** Not in refs list

## 4. Empirical evidence

### 4.1 Preliminary tests

We first consider the issue of slope homogeneity across countries. For this, we focus on Swamy's (1970) random coefficients model and apply the $\chi^2$ test statistic suggested by Swamy (1971) to test the null hypothesis of coefficients constancy across countries. This test is based on the differences between the OLS estimates, equation by equation, and the weighted average of the OLS estimates. The results strongly support the hypothesis of slope heterogeneity across cross-sectional units. Thus, while the aggregation on sub-areas is inspired by heterogeneity in institutional and policy related factors, the econometric analysis points strongly to the need to apply heterogeneous estimators in the panel setting.

Assuming slope heterogeneity we apply the hierarchical Bayes estimator. Table 1 summarizes our estimates of $\overline{\theta}$ obtained from the estimation of equation (1), highlighting the average shape of the income-carbon dioxide relationship and the eventual turning point, taking into account both a non-limited income range and the observed income range. In line with the literature, we consider both a quadratic and a cubic specification.

The hierarchical Bayes estimator requires prior information on the distribution of the coefficients. For this, we use the results obtained from the Swamy (1970) random coefficients regression estimator, which is a weighted average of the individual least squares estimates where the weights are inversely proportional to their variance-covariance matrices.

### 4.2 Main outcomes

#### 4.2.1 Quadratic specifications

The results are as follows. First, regarding the quadratic specifications, the inverted U shape is validated for the full sample of countries, but not within the observed income domain, while for three of the five sub-samples (G7, EU15, OECD) the EKC hypothesis is robust. Turning points are found for more developed areas in the range \$14.688and \$18.607 per capita (Table 1 shows observed income ranges).

The non-OECD and poorest countries, consistent with *a priori* expectations, show the reverse EKC picture. A monotonic increase in emissions with respect to GDP is robustly assessed by estimates without signs of a reversal trend.

It should be especially noted that the group of countries known in the climate change political arena as the Umbrella Group, currently led (in order of relevance) by the US, Australia, Japan and Norway, is associated with a monotonic path resembling that of the full sample[6]. This is plausible given the large weight of such countries in global emissions, and contradicts the evidence we find for "pro-Kyoto" regions, such as the EU, which are in favour of stringent, faster, and more nationally based climate change policies. The Umbrella Group instead supports less stringent (actions shifted to later in the future) and less costly policies (through the abatement of emissions in developing countries). The latter is certainly relevant, but out aim here is not to discuss which strategy is preferable, which is beyond the scope of this paper and for which evidence, though mounting, is still ambiguous. Nevertheless, we can say that our evidence confirms what has been emerging in the political arena: the Umbrella Group claims that climate change should be addressed by following an endogenous Kuznets path: economic growth, sooner or later, will bring an inversion in the trend, with no or limited need for policy action. The monotonic shape, which is an inverted U only in the complete range, confirms that the underlying structure is coherent with the climate change actions supported. The most stringent policy actions in the EU, which have has led to a position favourable



[6] The inverted U is shown only for the range of values not constrained to the current observed GDP values. It is just a possibility for a future time.

to the Kyoto protocol[7], which has been ratified by the EU countries, but not by US, could in part explain the observed EKC path. We note only that this structure might claim for a relatively more important role, in terms of CO2 abatement, of the Umbrella Group countries and the less developed areas. From an economic efficiency perspective, the weight could be shifted to countries where the marginal cost is relatively lower: although other complementary evidence is needed to evaluate marginal costs, it is likely that these are lower when a Kuznets path is still not visible.

To sum up, the full-sample analysis is thus a very approximate approach to investigating the presence of EKC. It hides regional and sub-sample differences, which is an indication of its questionable meaningfulness for economic and policy implications, although it provides some interesting insights.

Comment [CL6]: Is this what you wanted to say?

**4.2.3 Cubic specifications**

We conducted further analyses exploiting cubic specifications,[8] which provides a slightly changed picture, which demonstrates their relevance here. The full sample presents an inverted N shape, but, as before, this analysis is less meaningful than specific geographical sub sample investigations.

For the $EU_{15}$ and OECD countries, a mixed picture emerges. An N shape can be identified for the non-limited income range. However, we note that, within the incomes observed, the emerging shape is a typical Kuznets inverted U, with turning

[7] Among others, see de Brauw (2006), Lindholt (2005) and Bohringer abd Loschel (2003) for for policy-oriented empirical analyses on Kyoto Protocl issues recently published in this journal.

[8] See fig.1 for fitted and real values of the cubic specifications.

points at levels not very different from the above. This means that more industrialized countries have experienced an inversion in the emissions/GDP relationship; on average, the path of economic growth seems to provide a further boost to emissions, which is more than proportional, at least for regional aggregates,. The N shape evidence is stronger for the EU than the OECD countries. In terms of the turning point, while the higher peak of N is well within the income range, the second, lower peak is higher than the observed incomes (our levels are above $30.000 per capita at 1990 constant prices). In the near future then, emissions could be characterized by a positive elasticity with respect to GDP per capita. In any case, the G7 group actually presents a monotonous inverse of emissions, even without signs of EKC reversal. The monotonic shape for the Umbrella Group is confirmed at this stage of the analysis.

**Comment [CL7]:** Aggregate figures? Ranges? Levels?

This evidence is plausible. Vollebergh and Kemfert (2005) underline that, on the one hand, technological change effects, complementarities between local and global emissions reduction efforts and policies recently implemented by some of the wealthier areas, may favour the re-shaping of the income- $CO_2$ relationship towards an EKC curve, or absolute delinking, while on the other hand, the long term nature of $CO_2$ abatement benefits and the global dimension of agreements still act as counter-balancing forces. EKC shapes with different ("high" and "low" as in an N-shaped curve) turning points over time, may be compatible with the dynamics of industrialized countries. Scale effects are mitigated and somewhat reversed by supply side and demand side effects as well as by emerging policies, but nevertheless along a non-linear path.

Finally, evidence for the non-OECD and poorest countries highlights signs of the three income terms: negative, positive and negative. This implies an "inverted N shape" dynamics, which would imply a potential EKC dynamics for less developed countries. In any case both non-OECD countries and the 40 poorest countries (consistently) present monotonic relationships within the income range, confirming the quadratic specifications outcomes. The only turning point observed for non-OECD countries is largely outside the income range.

**Comment [CL8]:** Or do you mean 40 (consistently) ... st countries

#### 4.2.3 Summing up the evidence

We can see that in both the quadratic and the cubic specifications, and as suggested by various authors, the full sample analysis hides some more interesting and critical dynamics[9]. Both specifications lead to an EKC dynamic for the more developed countries while, as expected, monotonously-rising emissions with respect to GDP, are observed for the less developed countries.

**Comment [CL9]:** Do you mean monotonically

However, the cubic specifications provide some additional evidence. The more industrialized countries may be experiencing a new dynamic where the elasticity of emission with respect to GDP returns to a positive value, after a phase of decrease. The turning points at which both inversions occur are below $20,000 per capita,



[9] Even preliminary analysis from scatter plots clearly shows that heterogeneity concerning EKC trends is a key issue. We also argue that the scatter plots show that a high value added may derive from analyses based on country level data, possibly exploiting geographic/economic within-country heterogeneity. See, as rare examples, List and Gallet (1999), Managi (2006) for EKC frameworks, and Kim (2004) in the original Kuznets curves literature. The simple but useful scatter plot investigation highlights that, at least in panels with long time series, the cross country heterogeneity is an even more crucial issue. Dynamic trends could differ sharply from country to country, leading to the (here) often stressed necessity of using either heterogeneous estimators, or country specific time series/panel datasets.

and above $30,000. Stocking to observed income ranges, the EKC hypothesis is valid for more industrialized countries.

**Comment [CL10]:** Do you mean the more industrialized or more countries (a greater number)

Developing countries, on the other hand, and according to the cubic regressions, experience a monotonic increase in $CO_2$, with weak signals favouring EKC shapes, but with a turning point well outside the income range[10]. Overall, the cubic specifications tend to support the evidence for EKC trends in the industrialized countries[11].

Aggregate evidence, in terms of average slope coefficients, is still against EKC dynamics; further research could be carried out on specific countries, both industrialized and industrializing. In any case, our evidence provides specific tests on sub-samples of countries, showing the added value of these estimates compared to those for the full sample[12].



### 4.3 Forecast performances

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[10] EKC trends in the non-OECD countries have been, and will be more and more in the future, driven by fast growing and high energy consuming countries, such as India and China. Meuniè (2004) exploits data for the 30 Chinese regions for 1990-1999, and for $CO_2$ finds some initial evidence in favour of an EKC. The peaks are quite sensitive to the specification used, ranging from Yuan 2,900 to Yuan 8,500 per capita in 1995.

[11] We decided to present both the quadratic and cubic specifications (although the robustness of the latter may make any comments on the former irrelevant) to show the consequential estimation procedures related to testing the usual EKC hypothesis against the relatively new N shape modified hypothesis.

[12] For a recent example of (mixed) EKC evidence on $CO_2$ for a sample of 84 countries and 40 years, see Kahuthu (2006).

In order to test the relative performance of the quadratic and cubic specifications more formally, we carried out some procedures to assess what, at least in terms of forecast properties, is the preferred specification for our data. In this section we use criteria of performance of the prediction in order to inform the choice between quadratic and cubic specifications. We re-estimated the model using observations from 1949 to 1996, reserving the last five years (1997-2001) for forecasts. The choice of a time span of less than five years is consistent with the need to test forecasting, and allows comparison of both specifications. In fact, it is intuitive that longer spans may by default omit the cubic shapes obtained from fitting the data, since N shapes are eventually characterized by final more recent trends towards an EKC dynamics.

Table 2 enables a comparison of different specifications using the root mean square errors (RMSE) criterion. As pointed out by Baltagi et al. (2004), the ability of an estimator depends on both short-run and long-run forecast performance. Consequently, the average RMSE is calculated across countries at different forecasting horizons. We report the RMSE after one year, five years and the average of 5 years.

The estimated parameters (not reported here) are very similar to those obtained for the entire time period (Table 1). Overall, we can conclude that the forecast performance of the quadratic specifications is better than that of their cubic counterparts for the one year and five year forecast horizons. The only exception is when the 5 year horizon is considered for the full sample of countries[13].

We can see that [illegible]n we analyze the quadratic specification the one year forecast performance is very good for all sub samples while the quality of the five year counterparts depends on the sub-sample analyzed[14].

**Comment [CL11]:** Or do you mean we can say

It should also be mentioned that overall the forecast performance of the hierarchical Bayes estimator increases as the size of the sample analyzed increases. This may simply be due to the relative weight of each country, which decreases when the simple size increases, and thus the presence of outlier countries should have less effect for a large sample of countries.

## 5. Conclusions

This paper provides evidence of EKC-like dynamics for $CO_2$ emissions. This evidence confirms other recent results by exploiting a hierarchical Bayes estimator consistent with long time series panel data. We provide evidence of an EKC relationship between per capita emissions and income per capita, which, as

[13] Although these less than clear cut results have many possible interpretations, we argue that they may be evidence that the sub-sample analyses are more relevant. For these, the quadratic specification is always preferred.

[14] Even this outcome is open to interpretation; given that the literature does not indicate an "optional" rule for defining a proper forecast length, this result may mean that the loss of 5 years in the estimation process is relevant for achieving a good forecast. The 1 year forecast is the proper framework of assessment in this case. Scatter plots (fig. 2 depicts plots for the EU) nevertheless exclude the fact that the underlying reason for high values in the 5-year case may be due to a preference for a linear specification rather than a quadratic or cubic specification.

expected, is limited to the OECD, G7, and $EU_{15}$ groups. A monotonic relationship between income and emissions characterizes the less developed countries. The results of the cubic specifications point to the possible emergence of an N shape in the $CO_2$ emission paths in industrialized countries, and signal potential EKC dynamics for less developed countries. However, cubic specifications are not the preferred specifications for forecasting, for which quadratic specifications are more appropriate, and especially for informing policy makers. Within quadratic specifications, we note the interesting Kyoto-relevant evidence regarding EU and the so called Umbrella group: the former shows EKC dynamics while the latter a clear monotonic shape. This may be food for thought to policy making and post Kyoto negotiations.

The existence of EKCs does not imply that sustainability is a necessary outcome of economic growth. From a policy perspective, it is important that EKC evidence should not be interpreted as that rapid growth to high levels of GDP per capita automatically drives an 'absolute' or 'relative' delinking between $CO_2$ emissions and income; if this were the case, then growth would be the best 'policy strategy' to reduce environmental impacts. In fact, GDP growth has a direct 'scale effect' on emissions and, if it is not sufficiently innovative leading to emission efficiency (per capita and/or per unit of GDP) the 'scale effect' of income growth on emissions may prevail. The possible emergence of N-shaped EKCs as well as other complex configurations of the growth-emissions relationships, and the country/region specificity of EKCs resulting from our analysis, are an indication of the non-deterministic nature of the relationship between growth and the environment. Even in the presence of sustained growth, policy must not take a passive attitude towards the control of emissions.

The main added value of exercises aimed at refining the identification and measure of EKC relationships by employing new techniques, such as the one in this paper, is in enabling this complexity and differentiation to emerge. We argue that the proposed method is a valuable tool for cross country EKC analyses. Provided the problems posed by heterogeneity in examining and interpreting cross country focused datasets, research alternatives are time series or panel analysis at country level that exploit regional/provincial heterogeneity

These exercises, however, cannot substitute for explicit analyses of the economic and technological factors possibly leading to EKC-like dynamics, such as complex endogenous dynamics of economic systems, energy/emission innovations, and the effects of policies.

**Appendix. Data sources and definitions**

Data on emissions are from the database on global, regional, and national fossil fuel $CO_2$ emissions prepared by Marland et al. (2005) for CDIAC - Carbon Dioxide Information Analysis Center, US Department of Energy (available at cdiac.esd.ornl.gov). The database includes data on emissions dating back to 1751 for some countries, and for the world, and for 1950-2002 for the majority of countries. The latter set of data is derived from energy statistics published by the United Nations in 2005 using Marland and Rotty's (1984) methods. In this paper, we used the subset of emission data matching with the available time series on GDP per capita on the basis of joint availability, series continuity, and country definitions. This resulted in a sample of 109 countries for the period 1959-2001.

Data on GDP per capita for all 109 countries are from the database on the historical statistics of the world economy based on Maddison (2002), and managed by the OECD (www.theworldeconomy.org). Data on GDP per capita for all countries are in 1990 International 'Geary-Khamis' dollars, as used in the International Comparison Program (see unstats.un.org/unsd/methods.htm for details).

For country groups/aggregations, we adopted the current official composition of the G7, EU15 and OECD. The non-OECD group includes all 109 countries excluding OECD countries. The group of 40 poorest countries includes the 40 countries in our sample with the lowest per capita GDP.

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Table 1. Hierarchical Bayes Estimations (dependent variable: ln($CO_2$))

| Specification | Quadratic specification | | | | | | | Cubic specification | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Full sample | G7 | EU15 | OECD | NON-OECD | 40Poorest countries | Umbrella | Full sample | G7 | EU15 | OECD | NON-OECD | 40Poorest countries | Umbrella |
| Constant term | -9.98*** (0.15) | -50.9*** (0.08) | -50.9*** (0.06) | -42.4*** (0.08) | 0.42*** (0.05) | 0.30*** (0.06) | -18.88*** (0.98) | 6.61*** (0.03) | -482*** (0.05) | -395*** (0.02) | -132*** (0.01) | 11.11*** (0.05) | -6.39*** (0.07) | 16.18*** (0.05) |
| ln(y) | 1.96*** (0.04) | 10.91*** (0.09) | 10.76*** (0.08) | 8.91*** (0.08) | -0.29*** (0.03) | -0.16*** (0.03) | 3.84*** (0.23) | -2.74*** (0.03) | 145*** (0.07) | 118.9*** (0.02) | 31.7*** (0.01) | -4.53*** (0.03) | 3.09*** (0.06) | -7.40*** (0.15) |
| $(\ln(y))^2$ | -0.08*** (0.004) | -0.56*** (0.02) | -0.56*** (0.01) | -0.45*** (0.01) | 0.04*** (0.004) | 0.02*** (0.005) | -0.176*** (0.012) | 0.35*** (0.007) | -14.6*** (0.09) | -11.8*** (0.03) | -2.24*** (0.03) | 0.59*** (0.01) | -0.50*** (0.015) | 1.03*** (0.04) |
| $(\ln(y))^3$ | | | | | | | | -0.01*** (0.002) | 0.49*** (0.09) | 0.39*** (0.03) | 0.04* 0.024 | -0.02*** (0.002) | 0.03*** (0.005) | -0.04* (0.025) |
| Shape1 | Inverted U | Inverted U | Inverted U | Inverted U | U | U | Inverted U | Inverted N | monotonic | N | N | Inverted N | monotonic | Inverted N |
| Shape 2 | monotonic | Inverted U | Inverted U | Inverted U | monotonic | monotonic | monotonic | Inverted N | monotonic | Inverted U | Inverted U | monotonic | monotonic | Monotonic |
| Per capita GDP range | 201-43806 | 3553-28129 | 2794-23201 | 1105-28129 | 201-43806 | 201-2991 | 1843-28129 | 201-43806 | 3553-28129 | 2794-23201 | 1105-28129 | 201-43806 | 201-2991 | 1843-28129 |
| Turnings points | Out $1.045\times10^5$ | 14688 | 16105 | 18607 | Out 62 | Out 71 | Out 53852 | 535; 32338 | | 17693; Out 32533 | 13179; Out $1.23\times10^{12}$ | Out; Out 186 $1.86\times10^6$ | | Out, Out 254 30760 |
| $\chi^2$ test of coefficients constancy | 1.3e+05*** | 14023*** | 18173*** | 50713*** | 59213*** | 16989*** | 11283*** | 1.7e+04*** | 1965*** | 10862*** | 14143*** | 21422*** | 14632*** | 860*** |

Notes.
Standard errors in brackets.
*: significant at 10% level; **: significant at 5% level; ***: significant at 1% level.
Shape 1 indicates the shape of the relationship considered in the domain interval $\infty < y < \infty$.
Shape 2 indicates the shape of the relationship considered in the domain interval defined in the range of the observed values.
Per capita GDP range and turnings points are expressed in 1990 dollars.
Out indicates that the turning points are located outside the domain interval of per capita GDP.

Table 2. Comparison of forecast performances

| Specification | 1 st year RMSE | 5th year RMSE | 5-year average RMSE |
|---|---|---|---|
| QUADRATIC | | | |
| Full sample | 0.077 | 10486 | 2318 |
| G7 | 0.040 | 242676 | 51769 |
| EU15 | 0.034 | 1652550 | 340523 |
| OECD | 0.053 | 1021910 | 210967 |
| Non OECD | 0.092 | 1.77 | 1.43 |
| 40 poorest countries | 0.050 | 0.75 | 0.59 |
| Umbrella Group | 0.083 | 46834 | 10104 |
| CUBIC | | | |
| Full sample | 8.88 | 92.42 | 31.91 |
| G7 | 416 | 5.87E10 | 1.18E10 |
| EU15 | 311 | 4.13E10 | 8.33E9 |
| OECD | 162 | 1.30E9 | 2.64E8 |
| Non OECD | 14.92 | 2706 | 681 |
| 40 poorest countries | 9.07 | 1052 | 320 |
| Umbrella Group | 36 | 34324 | 8093 |

Low values indicate good forecast performance. We refer to Baltagi et al (2004).

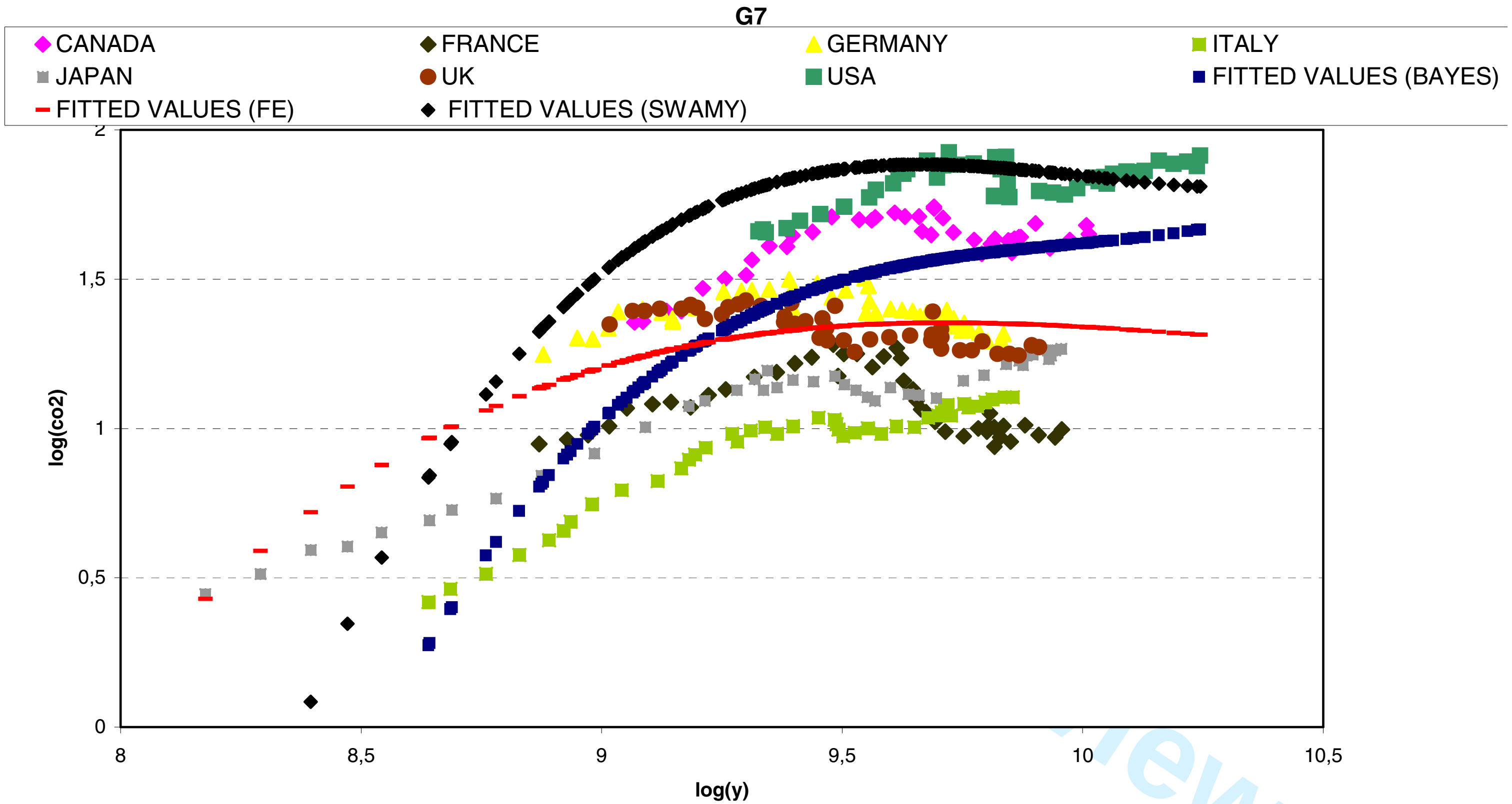


Figure 1. Real and fitted values – Cubic ECK specification

Fig. 2 Scatter plots for $EU_{15}$

(attached as separate wmf file)