Journal of Environmental Economics and Management **41,** 162–178 (2001)
doi:10.1006/jeem.2000.1132, available online at http://www.idealibrary.com on IDEAL®

Is There an Environmental Kuznets Curve for Sulfur?[1]

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Received August 18, 1998; revised May 5, 1999; published online December 7, 2000

Most existing estimates of the environmental Kuznets curve (EKC) for sulfur, which use samples of mainly high-income countries, indicate a maximum emissions turning point at middle to lower high-income levels of GDP per capita. We use a larger and more globally representative sample than previous sulfur EKC studies. We find that sulfur emissions per capita are a monotonic function of income per capita when we use a global sample and an inverted-U shape function of income when we use a sample of high-income countries. A model estimated in first differences results in a monotonic EKC when estimated with both high-income and global samples. Reductions in emissions are time-related rather than income-related.

1. INTRODUCTION

The environmental Kuznets curve (EKC) hypothesis proposes that there is an inverted U-shape relation between various indicators of environmental degradation and income per capita. A number of theoretical explanations for this relationship have been put forward (e.g., [20, 30]) but not empirically tested. Recently, a number of empirical studies have examined whether particular additional variables are responsible for the EKC relationship [33]. These researchers either argue that income and income squared are merely proxies for the true underlying variables or that additional explanatory power is contributed by the additional variables. However, there has been little systematic effort to test whether the basic EKC model is adequately specified. The finding that a specific variable helps explain the pattern of emissions or concentrations is potentially subject to omitted variables bias. The number of diagnostic statistics used in EKC studies has increased over time [33]. However, the results of these tests have only been used to select estimators and not to question whether the basic EKC model is correctly specified.

[1] Kali Sanyal provided research assistance. David Stern thanks AERE for providing a travel scholarship to attend the World Congress of Environmental Economics in Venice in order to present a version of this paper. We thank participants at the World Congress and at a seminar at the Department of Economics at the Research School of the Social Sciences at the Australian National University, Muhammad Akmal, Tony Auld, Adrian Pagan, and two anonymous referees for useful comments.
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0095-0696/00 $35.00

The work of Dijkgraaf and Vollebergh [7] represents a departure from this tendency. They estimate EKCs for carbon emissions for a panel data set of OECD countries and individual time-series regressions for each of the countries in the panel. The authors find that the coefficients in the individual time-series regressions vary widely. They found linear, inverted-U shaped, U shaped, and cubic EKCs in the individual countries versus an inverted-U in the sample as a whole. They also found that while the panel estimate has serially correlated residuals only some individual countries do. They conclude that while there is not a meaningful global EKC for carbon emissions there may be some meaningful relations between income and emissions in individual countries.

The majority of EKC studies, with the exception of carbon emissions studies, have been estimated using emissions data for mostly OECD countries or concentrations data for a variety of cities, mainly in developed countries.[3] These regressions typically show turning points—i.e., the level of income above which pollution declines—well within the sample. Estimated turning points for carbon EKCs are usually far above the maximum GDP in the sample. The usual explanation for this is that carbon does not have local pollution impacts and therefore has not been regulated, while pollutants such as sulfur have obvious and more localized impacts and have been subject to regulation [31]. However, the Dijkgraaf and Vollebergh [7] carbon EKC (estimated with fixed time and country effects), which is limited to OECD countries, has a turning point at 54% of maximal GDP in the sample. A study by Schmalensee *et al.* [29] also finds a within sample turning point for carbon. In this case, a 10-piece spline was fitted to the data such that the coefficient estimates for high-income countries are allowed to vary from those for low-income countries. List and Gallet [19] found a very high turning point for sulfur for US states. They use a long time period from 1929 to 1994 so that income per capita ranges from $1162 to $22,462 in 1987 US dollars. This suggests that including more low-income data points in the sample might yield a higher turning point for sulfur too. All these studies suggest that the differences in turning points that have been found for different pollutants may be due, at least partly, to the different samples used.

If there is an EKC relationship of some sort, it is possible that, due to omitted variables, turning point estimates from regressions using only developed country data may be biased downward. Though, in the absence of other statistical problems, fixed effects estimators can be used to provide consistent estimates of the parameters, these estimates are conditional on the effects in the sample and cannot be used to extrapolate to other samples. Therefore, fixed effects estimates from high-income samples are not necessarily informative about the future development of emissions in less developed countries. If the omitted variables are integrated variables then the fixed effects estimator will not even be consistent. The regression will be spurious.

Sulfur emissions and concentrations are one variable for which there is evidence that there is an inverted U-shape EKC (e.g., [10, 26, 30, 31]). It is of particular interest, therefore, to examine this variable in a study of the possible downward bias of existing estimates. In addition, simultaneity issues [35] should be less

[3] Panayotou [25] uses data for a large number of countries to estimate a sulfur EKC. However, this turning point estimate is biased downward because he uses ordinary exchange rates in place of PPP data and a cross-section data set in place of a panel data set.

important than they might be for energy, CO_2, or deforestation EKCs [33]. In principle, sulfur can be removed using "end of pipe" technologies and substitution away from coal or high-sulfur coal is far easier than substitution away from fossil fuels in general. Changes in sulfur emissions are less likely to drive GDP growth than are changes in energy use, CO_2 emissions, etc.

In this paper, we make use of a new data set on sulfur emissions [1] which allows us to create a much larger sample of countries over a longer period of time than that used in previous sulfur EKC studies. The sample consists of 31 annual observations on each of 73 countries. Two-thirds of the countries are middle- or low-income countries. We estimate regressions for a global sample and for OECD and non-OECD subsamples of the data and for both levels and first differences models. The results indicate that sample selection has important effects on levels estimates and that models in first differences have much better statistical properties than levels models. The first difference model indicates a monotonic EKC when estimated on both high- and low-income samples. However, technical change has substantially reduced emissions in OECD countries over the entire period and since the mid 1970s in non-OECD countries.

Section 2 of the paper reviews the literature on sulfur EKCs with particular attention to estimated turning points. Section 3 discusses our data and section 4 our econometric methods. Section 5 presents our results. In Section 6, we discuss the results and offer our conclusions.

2. LITERATURE REVIEW OF SULFUR EKCs

A number of authors have estimated environmental Kuznets curves for sulfur (Cole *et al.* [3], de Bruyn [4], de Bruyn *et al.* [5], Carson *et al.* [2], Grossman and Krueger [9], Kaufmann *et al.* [18], List and Gallet [19], Panayotou [25, 26], Selden and Song [30], Shafik [31], Shukla and Parikh [32], Torras and Boyce [38]). In this section, we review the various estimates, summarizing some of the results in terms of turning points converted to 1990 US dollars (Table I) using the U.S. GDP implicit price deflator. Stern *et al.* [35] argued that higher turning points are found for regressions using purchasing power parity exchange rates and emissions relative to regressions using market exchange rates and ambient concentrations. We need to control for these factors when we examine the impact on the estimated turning point of different temporal and geographical samples and additional explanatory variables. Therefore, we pay particular attention to the countries and time periods in each sample, whether sulfur is measured in terms of emissions or in terms of ambient concentrations, whether GDP is measured in ordinary exchange rates or in purchasing power parity terms, and which additional explanatory variables (besides GDP and GDP squared) are included in the model. Only one study [25] uses cross-sectional data and it has the lowest estimated turning point. Those studies using both random and fixed effects estimators generally find that, according to the Hausman test, the random effects model cannot be estimated consistently.

It is not possible to calculate relevant turning points for all the studies listed above. Some of the studies do not use a conventional quadratic or cubic specification (e.g., [2, 5]). The majority of the remaining studies use concentrations data, usually from the GEMS database. This database comprises ambient measurements

TABLE I
Sulfur EKC Studies

Authors	Turning point 1990 USD	Emis. or concs.	PPP	Additional variables	Data source for sulfur	Time period	Estimation technique	Countries/ cities
Cole *et al.*, 1997	$8232	Emis.	Yes	Country dummy, technology level	OECD	1970–92	RE, FE, OLS	11 OECD countries
Grossman and Krueger, 1991	$4772–5965	Concs.	No	Locational dummies population density, trend	GEMS	1977, '82, '88	RE	Up to 52 cities in up to 32 countries
Kaufmann *et al.*, 1998	$14,730	Concs.	Yes	GDP/area, steel exports/GDP	UN	1974–89	RE, FE, OLS	13 developed and 10 developing countries
List and Gallet, 1999	$22,675	Emis.	N/A	—	US EPA	1929–94	RE, FE	US states
Panayotou, 1993	$3137	Emis.	No	—	Own estimates from fuel use data	1987–88	OLS	55 developed and developing countries
Panayotou, 1997	$5965	Concs.	No	Population density, policy variables	GEMS	1982–84	RE, FE	Cities in 30 developed and developing countries
Selden and Song 1994	$10,391–10,620	Emis.	Yes	Population density	WRI—primarily OECD source	1979–87	RE, FE, OLS	22 OECD and 8 developing countries
Shafik, 1994	$4379	Concs.	Yes	Time trend, locational dummies	GEMS	1972–88	FE	47 Cities in 31 countries
Torras and Boyce, 1996	$4641	Concs.	Yes	Income inequality, literacy, political and civil rights, urbanization, locational dummies	GEMS	1977–91	OLS	Unknown number of cities in 41 countries
This study	$101,166	Emis.	Yes	Time and country effects	ASL	1960–90	RE, FE	73 developed and developing countries

from a variety of sites in various cities in many countries during different periods of time. The majority of observations are for developed country cities. With the exception of the Kaufmann *et al.* [18] estimate, all turning point estimates using concentration data are less than \$6000. Kaufmann *et al.* [18] used an unusual specification which includes GDP per area and GDP per area squared variables. Panayotou [25] estimates the lowest turning point among the emissions based estimates—\$3137. His single cross-section of data is based on consumption of the various fuels under the assumption that emissions coefficients for each fuel are the same in all countries. In addition, he measured income using market exchange rates. Both Selden and Song [30] and Cole *et al.* [3] use databases that are dominated by, or consist solely of, emissions from OECD countries. Their estimated turning points are \$10,391 and \$8232, respectively. List and Gallet use data for a long time period for the 50 US states. Their estimated turning point is the highest reported to date. They use data from 1929 to 1994 so that income per capita ranges from \$1162 to \$22,462 in 1987 US dollars. This suggests that including more low-income data points in the sample might yield a higher turning point. However, this turning point is still lower than our estimate for the global EKC in levels reported in the last row of Table I.

3. DATA

We use a new sulfur emissions data set [1] which includes emissions of sulfur from burning hard coal, brown coal, and petroleum, and sulfur emissions from mining and smelting activities for most of the countries of the world from 1850 to 1990. Estimated emissions are based on the use of these fuels and the level of smelting activity, estimated sulfur content, and estimated sulfur retention or removal from waste streams. These data have been compiled due to the strong interest in the role of sulfur emissions in global climate change, primarily in the northern hemisphere, in the last century and a half [13, 17, 28]. Previous sulfur emissions time series were global, but had either low temporal or low spatial resolution (e.g., [6, 11, 16, 36]) or were confined to certain countries and regions (e.g., [22, 39]). Previous EKC analyses of sulfur have used either ambient concentrations (e.g., [10, 31]), cross-sectional emissions estimates [25], or emissions data from mainly OECD countries in the 1970s and 1980s [30].[4]

We use GDP per capita data from the Penn World Table [37]. These data are in real 1990 international dollars. Any missing income figures are extrapolated using growth rates of GDP in constant domestic prices from *International Financial Statistics* [15] and other sources. Population data for computing sulfur emissions per capita are also taken from these sources.

Our global EKC estimates use data for all countries that have a full set of sulfur and purchasing power parity GDP per capita for 1960–90 with the exception of Kuwait. Kuwait was omitted because of its very high per capita income levels in the 1960s. Including Kuwait did not affect our results in any important way. There are 73 countries in our sample (see the Appendix for a list). The countries include around 81% of the world population in 1990. The complete data set of 2263

[4]Selden and Song [30] used data for 23 OECD countries plus China, Hungary, India, Israel, Kuwait, and Yugoslavia.

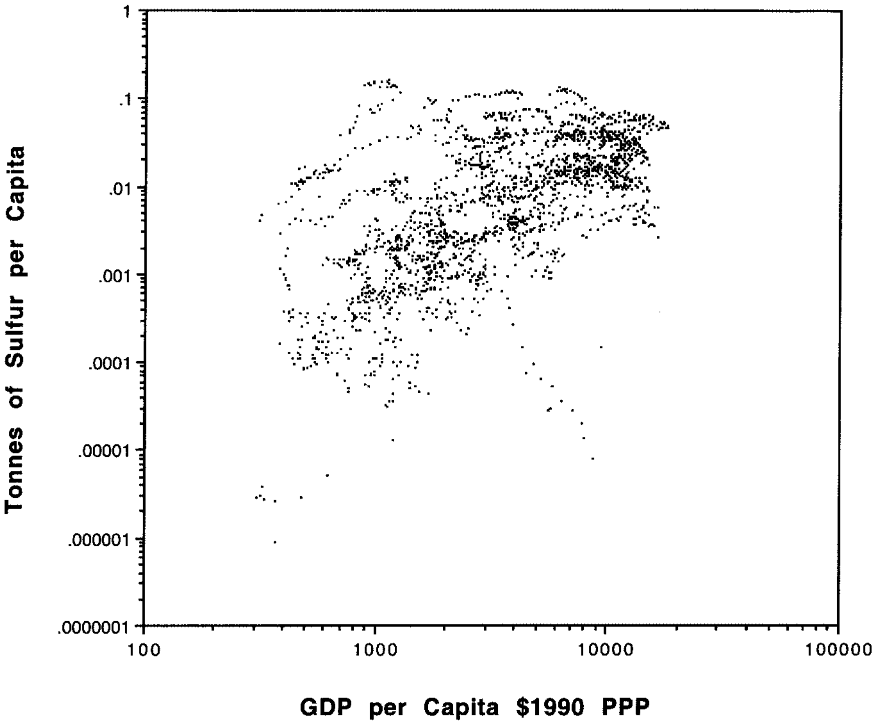

FIG. 1. Complete data set.

observations is presented in Fig. 1. Generally, emissions rise with income though there is some sign of a decline at high-income levels. The full data set is divided into OECD and non-OECD subsets, which are specified in the Appendix.

We also use a close replica of the Selden and Song sample of countries and time periods (see the Appendix for details) using data from our database. Hungary and Iceland were included in Selden and Song's full sample but are omitted from our sample due to incomplete data. We also omit Kuwait. Selden and Song did not use all their listed countries for all pollutants or for all sample periods and appear to have omitted Kuwait from their estimates of the sulfur EKC. Including Kuwait in this data set gave very different results with a U-shape EKC. The Selden and Song sample is not a conventional panel data set. Rather, data points are three-year averages for each country for the periods 1973−1975, 1979−1981, and 1982−1984. The purpose of using the Selden and Song sample is to check whether the differences between our estimates and previous estimates are due to our sample or due to our source of data.

It is interesting that ASL's estimated emissions for many developed countries, such as West Germany, Canada, Sweden, and Japan, differ substantially from the better-known OECD estimates. UK and US data are similar in both databases. OECD estimates for the former group of countries tend to overestimate emissions in the early 1970s and underestimate emissions in the late 1980s and the 1990s relative to the ASL data. The ASL data show much smaller reductions in emissions over time for these countries. In the case of Sweden, emissions rise over time instead of declining. In addition, Vincent [41] shows a steep decline in Malaysian emissions between 1988 and 1989 due to a switch to gas-fired electricity generation. The ASL data show a big increase in emissions due to increased coal burning at exactly the same point in time. *A priori* it is not clear whether the OECD or the ASL data are of higher quality. OECD data are submitted by member governments and may vary widely in quality. The ASL data use a uniform methodology but could be poorer than the best individual country estimates in the OECD database.

4. ECONOMETRIC METHODS

We estimate a logarithmic quadratic EKC for World, OECD, and non-OECD samples. We use both fixed effects and random effects models with both country and time effects. Both dependent (emissions per capita) and independent (PPP GDP per capita) variables are in natural logarithms. The model is given by

$$\ln(S/P)_{it} = \alpha_i + \gamma_t + \beta_1 \ln(\mathrm{GDP}/P)_{it} + \beta_2(\ln(\mathrm{GDP}/P))^2_{it} + \varepsilon_{it}, \qquad (1)$$

where S is sulfur emissions in tonnes of sulfur, P is population, ε is a random error term, the α_i's are country specific intercepts, the γ_t's are time specific intercepts, and the countries are indexed by i and the time periods by t. The time specific intercepts are intended to account for time varying omitted variables and stochastic shocks that are common to all countries.

The fixed effects model treats the α_i and γ_t as regression parameters. In practice, the means of each variable for each country are subtracted from the data for that country and the mean for all countries in the sample in each individual time period is also deducted from the observations for that period. Then OLS is used to estimate the regression with the transformed data. The random effects model treats the α_i and γ_t as components of the random disturbance. The residuals from an OLS estimate of the model with a single intercept are used to construct variances utilized in a GLS estimate. More details are provided by Hsiao [14].

If there is correlation between the effects α_i and γ_t and the explanatory variables then the random effects model cannot be estimated consistently [14, 23]. Only the fixed effects model can be estimated consistently. A Hausman [12] test can be used to test for inconsistency in the random effects estimate. This test compares the slope parameters estimated for fixed effects and random effects models. A significant difference indicates that the random effects model is estimated inconsistently, due to correlation between the explanatory variables and the error components. Assuming that there are no other statistical problems, the fixed effects model can be estimated consistently, but the estimated parameters are conditional on the country and time effects in the selected sample of data [14]. Therefore, they cannot be used to extrapolate to other samples of data. This means that an EKC estimated with fixed effects using only developed country data might say little about the future behavior of developing countries.

The turning point level of income is calculated by

$$\tau = \exp(-\beta_1/(2\beta_2)). \qquad (2)$$

We also test for serial correlation in the regression residuals. We regress the residuals on one lag of the residual and calculate a t-statistic for the autocorrelation coefficient. The sample omits the first observation in each country so that we do not regress the first residual of each country on the last residual of the previous country. The Chow F-test tests whether pooling the data in the World model instead of estimating separate OECD and non-OECD regressions significantly reduces the goodness of fit.

GDP may be an integrated variable [24]. Tests for integration and cointegration in panel data are currently under development. Perman and Stern [27] employ some of these tests and find that the variables in our data set may all be integrated. Stern [34] finds evidence of integration in the case of the Western European countries in our sample. If the EKC regressions do not cointegrate then the estimates may be spurious. The fixed and random effects transformations remove stochastic trends from the data that are variable specific but common to all countries, but they cannot remove country specific stochastic trends. In the presence of such country specific stochastic trends, neither random effects nor fixed effects estimators will be consistent. Differencing the data will eliminate potential stochastic trends in the series. A first differences model could be inappropriate if there is in fact cointegration in each country. But it is unlikely that there is in fact a single global cointegrating vector as imposed by the panel regression model [27].

We, therefore, also estimate the three regional models in first differences. First differencing also eliminates the country effects and so we estimate this model using OLS:

$$\Delta \ln(S/P)_{it} = \gamma + \beta_1 \Delta \ln(\mathrm{GDP}/P)_{it} + \beta_2 \Delta\left[(\ln(\mathrm{GDP}/P))^2\right]_{it} + \varepsilon_{it}. \quad (3)$$

The constant represents the mean rate of technical progress, which is assumed to be a deterministic linear trend in the levels model. We can also estimate a model with a common stochastic technical change process

$$\Delta \ln(S/P)_{it} = \gamma_t + \beta_1 \Delta \ln(\mathrm{GDP}/P)_{it} + \beta_2 \Delta\left[(\ln(\mathrm{GDP}/P))^2\right]_{it} + \varepsilon_{it}, \quad (4)$$

which we estimate with a fixed effects transformation for time effects only. The α_t's are then period specific rates of technical change. The time effects may capture other common time related effects besides technical change in the neoclassical sense.

5. RESULTS

The results for the levels model for the full data set are presented in Table II for World, OECD, and non-OECD samples and in Table III for the Selden and Song sample. The adjusted R^2 statistics for the fixed effects models may seem low in comparison with some previous results. This is because we calculate the statistic in a regression of data transformed to remove the country and time effects. Some previous EKC studies use dummy variables instead of transforming the variables and include the contribution of the dummy variables in the explained sum of squares. The adjusted R^2's for fixed effects and random effects models are not

TABLE II

Regression Results

Region	World $n = 2263$		OECD $n = 713$		Non-OECD $n = 1550$	
Model	Fixed effects	Random effects	Fixed effects	Random effects	Fixed effects	Random effects
Constant		−24.2750		−59.3599		−19.7937
		(−13.6096)		(−18.2329)		(−7.8174)
ln GDP/P	3.7091	3.8040	12.1102	12.1660	2.7918	2.6668
	(8.6340)	(8.7734)	(15.5903)	(16.4930)	(4.4050)	(4.1693)
(ln GDP/P)^2	−0.1609	−0.1745	−0.6631	−0.6666	−0.1017	−0.1046
	(−6.0056)	(−6.4747)	(−14.2225)	(−15.9407)	(−2.5345)	(−2.5676)
Adjusted R^2	0.1371	0.1459	0.3033	0.3221	0.1353	0.1402
ρ	0.8569	0.8624	0.9109	0.9070	0.8507	0.8574
AR(1)	86.8212	89.1724	56.3466	54.9303	70.8924	72.9760
Turning point	101166	54199	9239	9181	908178	343689
Chow F-test	10.6587	4.0256				
	(0.0156)	(0.0399)				
Hausman test		10.7873		0.3146		14.1904
		(0.0045)		(0.8545)		(0.0008)

Note. Figures in parentheses are t statistics for regression coefficients and significance levels for the Hausman test statistic. Turning points are in real 1990 purchasing power parity US dollars. AR(1) is a t-test on the residual autocorrelation coefficient ρ.

TABLE III

Regression Results—Selden and Song Sample

Model	Fixed effects	Random effects
Constant		−4.1068
		(−0.4975)
GDP/P	0.01100	0.006603
	(3.2560)	(3.4677)
(GDP/P)^2	−0.000000592	−0.000000340
	(−4.2990)	(−3.1234)
Period effect	1.4379	0.9156
(1979−1981 = 1)	(0.9764)	(0.6392)
Period effect	−0.8917	−1.6635
(1982−1984 = 1)	(−0.5239)	(−1.0810)
Adjusted R^2	0.2821	0.1412
Turning point	9265	9702
Hausman test		19.7370
		(0.0005628)

Note. Figures in parentheses are t statistics for regression coefficients and significance levels for the Hausman test statistic. Turning points are in real 1990 purchasing power parity US dollars. $n = 81$.

directly comparable as the dependent variable is transformed differently in the two cases. The other statistics are explained in Section 4 above.

For the World as a whole, the EKC has an inverted-U shape for both random and fixed effects formulations (Table II). The Hausman test indicates that the effects are correlated with the explanatory variables so that the random effects model cannot be estimated consistently. The implied turning point is very high by the standards of the existing literature: \$101,166. The EKC is effectively monotonic for the global sample.

The time effects from the three fixed effects models in Table II are presented in Fig. 2. These time effects are equivalent to the regression coefficients for dummy variables that are one in the year given and zero otherwise. They measure the logarithmic difference between sulfur emissions in the year given relative to the sample mean. For the global sample, the time effects show a decline in emissions *ceteris paribus*. The average rate of decline is 1.5% per annum. These time effects do not point to sudden declines associated with events such as the oil price shocks and the LRTAP (Long Range Transportation of Air Pollution) protocols of the 1980s in Europe, but instead to more subtle variations imposed on a long run

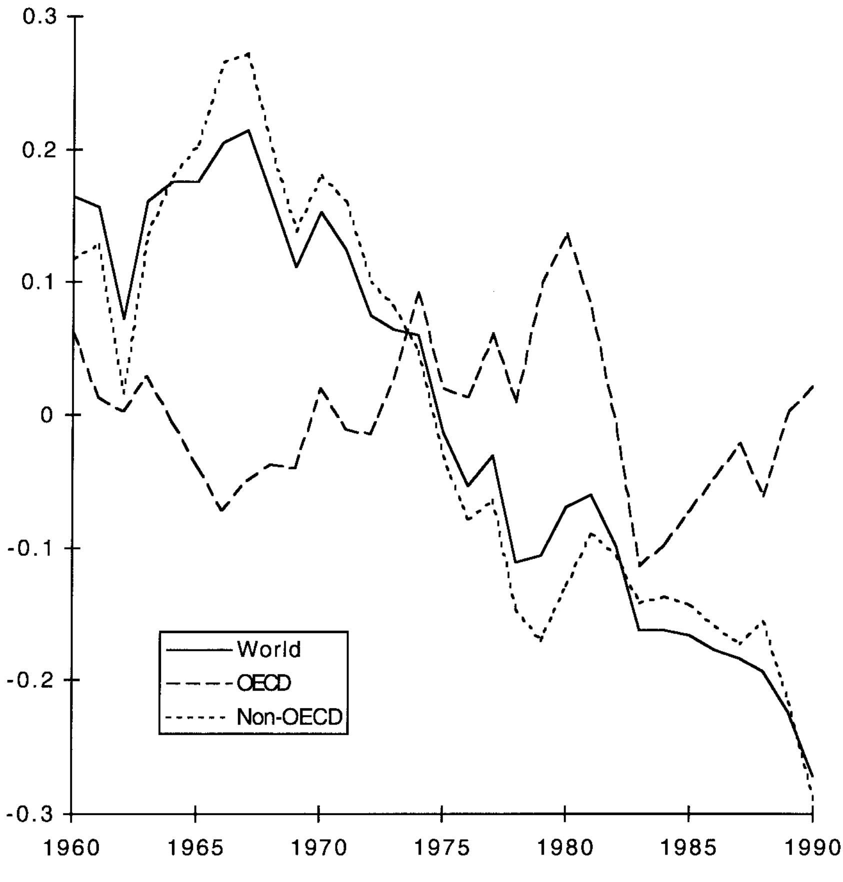

FIG. 2. Fixed time effects for World, OECD, and non-OECD EKCs for the levels model. The effects are expressed in logarithmic differences in per capita sulfur emissions relative to the mean.

decline. Despite removing these common time effects, the residuals for all three models are highly autocorrelated. This suggests that there are highly serially correlated variables that differ between countries that are omitted from this basic EKC model.

In the case of the 23 OECD countries the random effects estimator is consistent —the country and time effects are not correlated with the explanatory variables. There is, however, still severe serial correlation. The insignificance of the Hausman statistic in this case is very sample sensitive. If, for example, Turkey and Portugal are dropped from the sample the statistic for the remaining 21 countries is highly significant. The time effects (Fig. 2) do show a sharp decline in the mid-1980s (around the time of the LRTAP protocol) but emissions have tended to increase again, *ceteris paribus*. The overall rate of decline is very low. Again, the EKC has the inverted-U shape. The turning point is very much lower than for the global model: $9239. This turning point is well within the sample. This result is in line with previous studies such as Selden and Song [29] and suggests that differences between our data and data published by the OECD are not the reason for our very high estimate of the global turning point.

As in the case of the World model, the random effects model for the non-OECD sample cannot be estimated consistently. The estimated turning point is extremely high—$908,178. The EKC for this subsample is monotonic. The estimated time effects (Fig. 2) are very similar to those estimated for the global sample. Emissions decline strongly over time though emissions increase strongly with rising income levels.

As the random effects model is not consistently estimated for World and non-OECD samples, the Chow test for the fixed effects model is most relevant. The null hypothesis that there is a single world EKC model can be easily rejected at the 5% or 2% levels of significance but not at the 1% level.

Table III presents results for the Selden and Song sample. This model is estimated in levels instead of logarithms using the fixed effects and random effects estimators for country effects with the time effects consisting of two explicit dummy variables. In contrast to our OECD sample, the Hausman statistic is highly significant. The estimated turning points are almost exactly the same as those for our OECD only sample and Selden and Song's own fixed effects estimates. As expected, parameter variances are higher than in our OECD sample as the Selden and Song sample is much smaller. The major difference between these estimates and Selden and Song's own estimates is the time effects. Neither of the period effects is significantly different from zero in our estimate while Selden and Song found that they were highly significant and both effects were negative. Their other parameter estimates are also apparently far more precise. The estimated turning point of $9265 (Table III) is about $1000 lower than Selden and Song's estimate converted to 1990 dollars (Table I).

Perman and Stern [27] and Stern [34] show that the time series used here are integrated series. The Hausman tests above show that there may be omitted variables that are correlated with GDP. The very high reported autocorrelation coefficients also point toward this conclusion. It is possible, therefore, that there are omitted integrated variables so that the regression results reported above may be spurious. Therefore, we estimate the first differences models described in Section 4.

The results for the first differences models are presented in Table IV. The R^2 statistics for these models are, as expected, far lower than for the levels models but are all still highly significant. The OECD OLS model may suffer from multicollinearity as the income regression coefficients are not individually very significant but the F-test for excluding both income terms is highly significant. The degree of residual autocorrelation is low though not zero for either the non-OECD or the global models estimated with either OLS or fixed effects. The Breusch–Pagan test shows no evidence of heteroskedasticity in the OLS models. The Chow test does not reject pooling the data in the global model for the OLS models but does reject pooling the fixed effects estimates at a 5% significance level.

The EKC is monotonic in each case. In fact, the estimated OECD turning point is higher than the non-OECD turning point. The fixed effects estimates of the turning point are somewhat more moderate than the OLS estimates. Using the fixed effects estimates and sample means the income elasticity of sulfur emissions is 0.67 in the OECD and 0.50 in non-OECD countries. In 1990 the mean OECD income elasticity was 0.55 and the non-OECD elasticity 0.43. So, though the explanatory power of the model is low, the income effects are quite large as well as statistically significant.

The rates of technical change in the first difference OLS results and the mean rate for the fixed effects models are the opposite of those for the levels models reported above. The rate of technical change is high in the OECD and almost zero in the non-OECD model. Figure 3 presents the technical progress trends for the

TABLE IV
First Differences Regression Results

Region	World $n = 2190$		OECD $n = 690$		Non-OECD $n = 1500$	
Model	OLS	Fixed effects	OLS	Fixed effects	OLS	Fixed effects
Constant or mean time effect	−0.002739 (−0.4206)	−0.000899	−0.01973 (−3.1981)	−0.01430	−0.000542 (−0.0616	0.000501
$\Delta \ln \mathrm{GDP}/P$	2.3057 (2.6751)	2.3164 (2.6820)	2.8404 (1.6146)	4.0524 (2.2528)	2.7209 (2.3846)	2.6702 (2.3397)
$\Delta((\ln \mathrm{GDP}/P)^2)$	−0.1059 (−1.9166)	−0.1112 (−2.0080)	−0.1069 (−1.0637)	−0.1855 (−1.8018)	−0.1363 (−1.8344)	−0.1362 (−1.8338)
Adjusted R^2	0.01807	0.01449	0.05856	0.04078	0.01693	0.01402
F-test on income terms	21.1460 (0.0000)	33.1748 (0.0000)	22.4277 (0.0000)	30.2907 (0.0000)	13.4260 (0.0000)	22.3226 (0.0000)
ρ	0.1249	0.1300	0.06011	0.07863	0.1284	0.1311
AR(1)	5.8557	6.1022	1.5679	2.0537	4.9861	5.0972
Breusch–Pagan heteroskedasticity test	4.8665 (0.0878)		0.3980 (0.8196)		1.3904 (0.4990)	
Turning point	53,590	33,290	586,965	55,481	21,545	18,039
Chow F-test	0.42762 (0.9704)	6.3824 (0.0400)				

Note. Figures in parentheses are t statistics for regression coefficients and significance levels for test statistics. AR(1) is a t-test on the residual autocorrelation coefficient ρ. The F-test on income terms restricts the coefficients for both income variables to zero. Turning points are in real 1990 purchasing power parity US dollars.

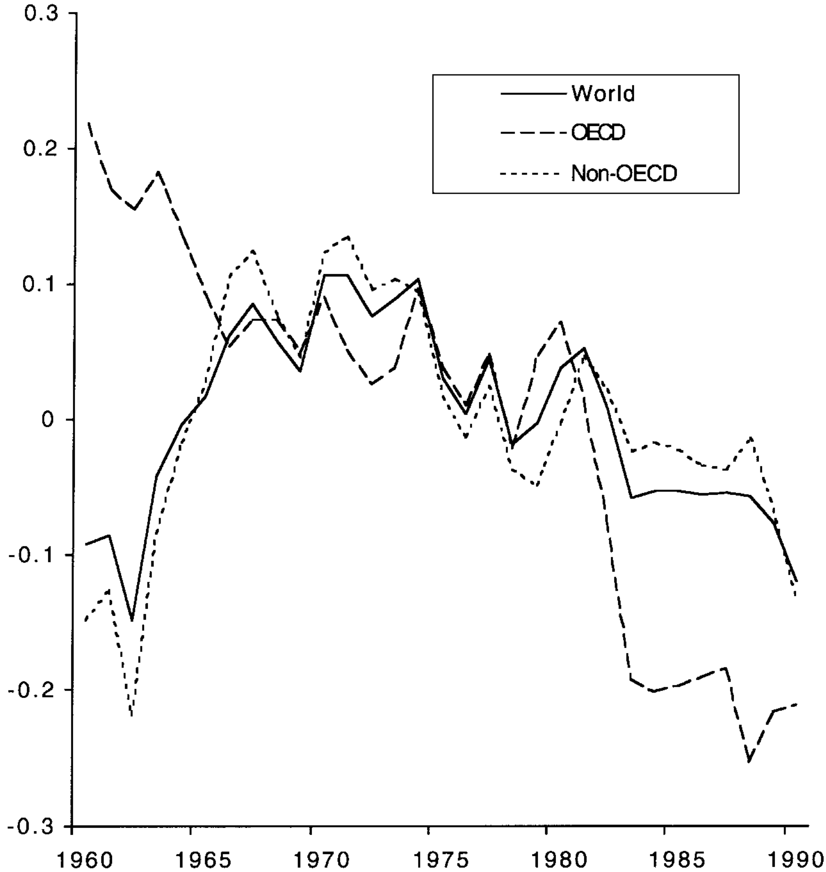

FIG. 3. Integrated trends of fixed time effects for World, OECD, and non-OECD EKCs for the first differences model. The effects are expressed in logarithmic differences in per capita sulfur emissions relative to the mean.

fixed effects models. These are calculated by integrating the time effects α_t. In the OECD, emissions reducing technical progress continues throughout the sample period. There is a big technical improvement in 1981–1983 around the time of the LRTAP protocol. The pattern of change in non-OECD countries is very different. Technical change is emissions producing until the mid-1970s. After this time, there is a slow decline in emissions. This may provide support for the hypothesis that the energy crisis in 1973 had some effect on sulfur emissions, but ironically not for the developed countries studied by Moomaw and Unruh [21] and Unruh and Moomaw [40].

6. DISCUSSION AND CONCLUSIONS

Our results show that estimating an EKC using data for only the OECD countries yields a lower estimated turning point than when the EKC is estimated using data for the world as a whole. The global emissions–income relation is essentially monotonic, as the estimated turning point is far above all countries' income levels. Our estimates using OECD-only data and our estimate using the Selden and Song sample from our data confirm that this is not because of our new data source. List and Gallet [19] found a high turning point for sulfur for U.S. states. Because of the long time period they use (1929–1994) income per capita ranged from \$1162 to \$22,462 in 1987 US dollars. Their finding of a high turning point for US-only data does not, therefore, contradict our results.

Until recently, it was understood that carbon EKCs had high turning points and sulfur and other EKCs low turning points. This was thought to be because sulfur emission externalities are local and immediate while carbon emission externalities are global and mainly in the future [31]. But now both carbon and sulfur EKC turning point estimates appear to depend on whether the sample is globally representative or not. These results call these economic arguments into question and suggest that the effect of sample choice should be examined for other pollutants too.

The Hausman test for the global and non-OECD estimates indicates that there may be omitted variables correlated with GDP. The test statistic is not significant for the OECD-only estimate but is very sensitive to the exact sample chosen. Dropping a couple of countries from the OECD sample yields a very significant Hausman statistic. The non-OECD estimate is either inconsistent in the case of the random effects estimator or conditional on the data in the subsample in the case of the fixed effects estimator. But all the levels models suffer from severe serial correlation. It is likely that there are omitted integrated variables so that these regressions are spurious.

Estimates in first differences are much better specified. Differencing reduces the serial correlation and removes the country effects that are related to the specification problems in the levels model. If there are omitted integrated variables the first differences estimator is consistent. Therefore, we regard these results as the most reliable for determining the marginal effect of income on emissions. We find that the income–emissions relation is monotonically increasing in income in both OECD and non-OECD subsamples. Income primarily has a scale effect on emissions with a 1990 mean income elasticity of emissions of 0.43 in developing countries and 0.55 in the OECD. Non-OECD countries show negligible technical change in reducing emissions over the period as a whole, while the mean rate of emissions reducing technical change in OECD countries is high, averaging 1.4% per annum. Policy changes such as the signing of the LRTAP protocol in Europe can induce large amounts of technical change. There is a slower decline in emissions in developing countries since the mid-1970s. The time effects may capture other common time related effects besides technical change in the neoclassical sense. For example, the response to the LRTAP protocol could be a common substitution of other fuels or capital for coal using existing technologies.

We emphasize that the solution to the problems raised in this paper is not just the use of more widely representative databases such as the ASL database. Our results show that, for the case of sulfur, a single global EKC model is a misspecification. Similarly, List and Gallet [19] have found that a single EKC for sulfur for all US states is a misspecification. Estimating the model in first differences results in more reliable estimates, but is an incomplete model of emissions change and our fixed effects estimate shows that again the single global model is a misspecification. In any case, it is clear that with our current state of knowledge it is unwise to use

EKC relationships estimated from data sets dominated by OECD countries to predict future emissions as global per capita incomes and population grow.

APPENDIX

List of Countries—Full Sample

Data are each year 1960–1990.

OECD

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

Non-OECD

Algeria, Argentina, Barbados, Bolivia, Brazil, Chile, China, Colombia, Cyprus, Czechoslovakia, Egypt, Ghana, Guatemala, Honduras, Hong Kong, India, Indonesia, Iran, Israel, Kenya, Korea, Madagascar, Malaysia, Mexico, Morocco, Mozambique, Myanmar, Namibia, Nicaragua, Nigeria, Peru, Philippines, Romania, South Africa, Saudi Arabia, Singapore, Sri Lanka, Syria, Taiwan, Tanzania, Thailand, Trinidad & Tobago, Tunisia, Uruguay, USSR, Venezuela, Yugoslavia, Zaire, Zambia, Zimbabwe

List of Countries—Selden and Song Sample

Data are averages for 1973–1975, 1979–1981, and 1982–1984.
Austria, Belgium, Canada, China, Denmark, Finland, France, Greece, India, Ireland, Israel, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Thailand, Turkey, UK, USA, West Germany, Yugoslavia

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