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Per Capita Carbon Dioxide Emissions

Convergence or Divergence?

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Abstract

Understanding and considering the distribution of per capita carbon dioxide (CO_2) emissions is important in designing international climate change proposals and incentives for participation. I evaluate historic international emissions distributions and forecast future distributions to assess whether per capita emissions have been converging or will converge. I find evidence of convergence among 23 member countries of the Organisation for Economic Co-operation and Development (OECD), whereas emissions appear to be diverging for an 88-country global sample over 1960–2000. Forecasts based on a Markov chain transition matrix provide little evidence of future emissions convergence and indicate that emissions may diverge in the near term. I also review the shortcomings of environmental Kuznets curve regressions and structural models in characterizing future emissions distributions.

Key Words: emissions distributions, environmental Kuznets curve, Markov chain transition matrix

JEL Classification Numbers: O40, Q54, Q56

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Introduction

Long-term forecasts of carbon dioxide (CO_2) emissions are critical inputs to both assessing the potential impacts of climate change and evaluating the cost of emissions abatement. They have been made with structural models (e.g., through the Intergovernmental Panel on Climate Change and the Stanford Energy Modeling Forum) and reduced-form models (e.g., Schmalensee et al. 1998). Such forecasts focus on the time path of global emissions, with little attention paid to the geographic distribution of CO_2 emissions. To address this issue, I focus on two questions: Have per capita emissions been converging in the past, and should we expect per capita emissions to converge in the future?

Although the geographic distribution of greenhouse gas emissions does not influence the climatic impact of those emissions, the per capita distribution may affect the political economy of negotiating multilateral climate change agreements in two ways. First, countries with lower per capita emissions (i.e., developing countries) may expect countries with higher per capita emissions (i.e., industrialized countries) to make more effort toward mitigating climate change. For example, the Framework Convention on Climate Change and the Kyoto Protocol established emissions goals and commitments for industrialized countries but not for developing countries. This discrepancy in effort allocation may reflect industrialized countries' larger contribution to climate change (a "responsibility" notion of equity) or greater resources (an "ability to pay" notion). Given the correlation between development and emissions, a country's per capita emissions may serve as a proxy for either.[1] China's response to a proposed process for

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[1] The correlation between the natural logarithm of per capita income and the natural logarithm of per capita CO_2 emissions is 0.87 for a sample of 88 countries over the 1960–2000 period. This sample is described in the next section, **Evaluation of Historical Convergence**. All analyses in this paper focus on fossil fuel–based CO_2 emissions.

developing-country emissions obligations at the 1997 Kyoto Conference summarizes many developing countries' views on this issue: "In the developed world only two people ride in a car, and yet you want us to give up riding on a bus" (quoted in Climate Action Network 1997).

Second, in lieu of periodically renegotiating ad hoc emissions obligations (as is the status quo), some policymakers have suggested explicit rules to the assignment of emissions rights or obligations that would encourage the participation of developing countries. In a per capita emissions allocation scheme, for example, an aggregate quantity of greenhouse gas emissions would be set, then allocated among all (participating) countries according to population. Professor Saifuddin Soz, union minister for environment and forests of India, advocated for such an approach at the 1997 Kyoto Conference: "Per capita basis is the most important criteria [sic] for deciding the rights to environmental space. This is a direct measure of human welfare" (Soz 1997). Such an approach has gained the support of some nongovernmental organizations and academics; more than one-quarter of the 40+ climate policy proposals reviewed by Bodansky (2004) included a per capita emissions allocation.

A per capita scheme would allocate emissions rights in a vastly different way than the current emissions distribution, which reflects variations in economic development; climate; and policies for land use, energy, and the environment. Given current emissions, the distribution of rents implicit in a per capita scheme would not likely elicit the support of developed countries. If emissions converged over time, then this concern might become less important. If per capita emissions did not converge, then a per capita emissions allocation would result in substantial resource transfers through international emissions trading or the relocation of emissions-intensive economic activity.

To illustrate the potential impacts of a per capita emissions allocation, suppose that the Kyoto Protocol allocated per capita emissions commitments to Annex B countries in lieu of the fraction of historical emissions approach currently used. I compared the actual allocations of greenhouse gas emissions under the Kyoto Protocol to a hypothetical allocation of the aggregate emissions target for Annex B countries on the basis of each country's share of 1997 total population of those countries. These two allocation schemes would differ significantly; under the per capita scheme, the average allocation to an Annex B country would differ by 46 percent from its Kyoto Protocol allocation. For example, under the per capita allocation, the U.S. emissions commitment would be 29 percent lower than its 1990 Kyoto target of –7 percent, whereas that of France would be more than 70 percent higher than its 1990 Kyoto target of –8 percent. More than 800 million tons of carbon equivalent would change hands annually if the Annex B targets were reallocated on a per capita basis. Because the prices of tradable emissions permits could range up to hundreds of dollars per ton of carbon, tens to hundreds of billions of dollars in annual rents would be at stake with the allocation decision.

The lack of emissions convergence may make developing countries less likely to agree to emissions abatement obligations. Efforts to increase the participation of developing countries through a per capita allocation rule may not garner the support of developed countries in the absence of emissions convergence. Informing the policy debate on these issues requires a more detailed examination of the distributional dynamics of greenhouse gas emissions.

My research findings indicate that CO_2 emissions are converging among 23 member countries of the Organisation for Economic Co-operation and Development (OECD) but diverging for an 88-country global data set. This combination of a converging club of developed countries within a diverging world context is also evident in forecasts of future distributions based on nonparametric transition matrix analysis. The long-run steady-state world distributions have thick tails and are less compact than current distributions. Forecasts of future dispersion measures reveal little convergence relative to the current world distribution. I discuss the shortcomings of current reduced-form parametric analysis—environmental Kuznets curves—and structural models later [see **Forecasting Future Emissions Distributions** and the **appendix**].

Next, I introduce the data used in this paper, followed by historical analyses. Then, I present the forecasting of future emissions distributions and present my analyses of the environmental Kuznets curves and structural models. The appendix complements the graphical analysis of the environmental Kuznets curve. Finally, the last section provides my overall conclusions.

International Emissions Data

The data on fossil fuel–based CO_2 emissions are from Marland et al. (2003). All statistical analyses were conducted with a balanced panel of 88 countries (referred to as the World sample[2]) over 1960–2000 and a balanced panel of 23 OECD countries over the same

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[2] The 88 countries are Algeria, Angola, Argentina, Australia, Austria, Bahrain, Belgium, Bolivia, Brazil, Bulgaria, Cameroon, Canada, Chile, China, Colombia, Costa Rica, Côte d'Ivoire, Cuba, Cyprus, Czechoslovakia, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Ethiopia, Finland, France, Germany, Ghana, Greece, Guatemala, Honduras, Hong Kong, Hungary, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Kuwait, Lebanon, Luxembourg, Mexico, Mongolia, Morocco, Myanmar, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Panama, Peru, Philippines, Poland, Portugal, Puerto Rico, Qatar, Romania, Saudi Arabia, Singapore, South Africa, South Korea, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syria, Taiwan, Thailand,

period (referred to as the OECD sample[3]). All countries with CO_2 emissions less than 1 million tons of carbon equivalent in 2000 and all countries with any missing observations during 1960–2000 were excluded from analysis. If countries had changed borders over time, country aggregates were constructed: For the 1990s, USSR observations were constructed from data for the 15 former Soviet republics, and Czechoslovakia observations from data for the Czech Republic and Slovakia; and for 1960–1990, Germany observations were constructed from data for East and West Germany. Total emissions analysis indicates that the 88 countries in the World sample are responsible for 92 percent of global fossil fuel CO_2 emissions.

Evaluation of Historical Convergence

To determine whether per capita CO_2 emissions have been converging, I used two common concepts of convergence. First, I evaluated the emissions data to discern whether countries that have low per capita emissions "catch up" to countries that have high per capita emissions. This cross-sectional convergence could manifest through a reduction in the cross-sectional dispersion and compression in the distribution of emissions. Second, I investigated whether disparities in per capita emissions are persistent, thereby reflecting the permanence of shocks to per capita emissions. This stochastic convergence lends itself to examination via time series tests for unit roots. My primary analysis focuses on the 88-country World dataset. To complement this analysis and to build on the research by Strazicich and List (2003), I also analyze a 23-country set of OECD countries.

Methods

I undertook three types of analysis to assess cross-sectional convergence. First, drawing from the economic growth literature on σ-convergence, I estimate the annual standard deviation

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Trinidad and Tobago, Tunisia, Turkey, United Arab Emirates, United Kingdom, United States of America, United Soviet Socialist Republics, Uruguay, Venezuela, and Yugoslavia.

[3] The 23-country OECD set includes Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, and United States of America. I excluded member countries that joined the OECD during the 1990s.

of the natural logarithm of per capita CO_2 emissions. If this measure of dispersion declines over time, then per capita emissions are converging in a σ-sense (Barro and Sala-i-Martin 1992).[4]

Second, I present distributions of per capita emissions over time to illustrate emissions trends. Understanding the change in the complete distributions over time can further illuminate the intradistributional dynamics that may not be captured by a single parameter that characterizes the variance of the cross section (σ-convergence). For these illustrations, a country's per capita emissions are expressed as the ratio of its emissions per capita to the world average for that year (i.e., relative emissions per capita [RE_{it}]). Normalizing a country's emissions against the global average allows us to discern country-specific movements from global growth or trends in emissions. This presentation of the estimated distributions also sets the stage for the nonparametric distributional forecasting presented later (see **Forecasting Future Emissions Distributions**).

Third, I estimate various percentiles in the emissions distributions over time and test whether the spread in a given interpercentile range differs statistically over various periods. Previous analyses of cross-sectional convergence in the economic growth literature do not characterize whether convergence—evidenced by a reduction in dispersion or compression in the distribution—is statistically meaningful. As a way to address this gap in the literature, I estimate the 25th and 75th percentiles and associated 75–25 interquartile ranges (IQRs) for the emissions per capita relative to the world average for the turn of each decade in my data: 1960, 1970, 1980, 1990, and 2000.[5] I also present results based on 3-year samples (1960–1962, 1969–1971, 1979–1981, 1989–1991, and 1998–2000), which yield very similar point estimates but smaller estimated standard errors.

I used least absolute deviations estimators to construct these percentiles and IQRs, and the estimated variance–covariance matrices were based on bootstrapping with 1,000 replications. These estimates allow for an explicit evaluation of whether the spread in distribution changes

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[4] I have not undertaken β-convergence regressions in this paper. The typical test for β-convergence would be based on regressing average growth rates for per capita emissions (e.g., averaged over 1960–2000 in my dataset) on per capita emissions for the initial period (e.g., 1960). This approach suffers from a regression toward the mean problem identified in the literature (Friedman 1992; Quah 1993a, 1993b; Evans and Karras 1996; Lee et al. 1997; Strazicich and List 2003, endnote 7). As Quah (1993b) shows, such a β-convergence regression can yield a negative sign on the initial per capita level, implying convergence, even as the cross-section distribution diverges.

[5] I have also estimated the 80–20 interquantile and the 90–10 inderdecile ranges, and these results are available from the author upon request.

over time in a statistically meaningful way through tests comparing the estimated magnitudes of the IQRs. I examine the null hypotheses that the 75–25 IQRs for 1970, 1980, 1990, and 2000 are no different from that for 1960:

$$H_0^i : \mathrm{IQR}_{1960} = \mathrm{IQR}_i \text{ for } i = 1970, 1980, 1990, 2000 \qquad (1)$$

A decrease in IQRs since 1960 and a rejection of the null suggests that the tails of the emissions distribution have moved closer over time, indicating emissions convergence; an increase in IQRs over time and a rejection of the null suggests emissions divergence.[6]

To assess stochastic convergence, I tested for whether time series of relative emissions per capita were characterized by a unit root. If per capita emissions are converging in a stochastic sense, then shocks to emissions are temporary and the data are stationary over time. If a unit root characterizes the emissions time series, however, then shocks are permanent and emissions are not converging. Carlino and Mills (1993) used these tests for unit roots to evaluate income convergence among the U.S. states, List (1999) conducted such tests for assessing regional convergence in per capita emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2), and Strazicich and List (2003) applied a panel-based unit root test to OECD countries for per capita CO_2 emissions.

Following the preceding literature (and using List's notation), I analyze the log of the ratio of per capita emissions for one country to the world average. Specifically, I model the log of a country's RE_{it} as a function of a time-invariant equilibrium differential (RE_i^{eq}) and time- and economy-specific deviations from that differential (u_{it}):

$$\mathrm{RE}_{it} = \mathrm{RE}_i^{eq} + \mathrm{u}_{it} \qquad (2)$$

The stochastic process u_{it} is represented by

$$u_{it} = c_{i0} + \varepsilon_{it} \qquad (3)$$

where c_{i0} represents the initial deviation from the equilibrium differential.[7] Like Carlino and Mills (1993) and List (1999), I substitute Eq. 3 into Eq. 2 to yield the stochastic convergence equation

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[6] To evaluate these hypotheses, I jointly estimate the IQRs for each pair under consideration and compare estimates with the use of a Wald test.

$$\mathrm{RE}_{it} = \mu_i + \varepsilon_{it} \tag{4}$$

where $\mu_i = \mathrm{RE}_i^{eq} + c_{i0}$. If the deviations from the long-run equilibrium differential, ε_{it}, are temporary, then the economies are converging in a stochastic sense.

To test for whether these disturbances were temporary, I expanded Eq. 4 to include a linear time trend and conducted country-specific tests for unit roots with a generalized least squares version of the augmented Dickey–Fuller test developed by Elliott et al. (1996). This DF–GLS test is more powerful than the augmented Dickey-Fuller test of the null hypothesis that the time series of a country's emissions is characterized by a unit root. In selecting the optimal lag length for each country-specific DF–GLS test, I followed Ng and Perron (2001), whose Modified Information Criteria method can further improve the power of the DF–GLS test.

My approach to testing for unit roots differs from the panel-based approach used by Strazicich and List (2003). Although we both are motivated by concerns regarding the low power of the augmented Dickey-Fuller test, Strazicich and List used a panel-based test developed by Im et al. (2003) to assess stochastic convergence in per capita CO_2 emissions among OECD countries. With the Im et al. method, Strazicich and List tested the null hypothesis that all country-specific time series in the panel have unit roots. Rejecting the null hypothesis as they do does not imply that all time series are stationary; one can infer from such a test result only that at least some of the time series are stationary.

My approach can complement their results by testing for unit roots on a country-by-country basis to better understand whether their findings reflect stochastic convergence among all or only a subset of OECD countries. Furthermore, analyzing the broader World sample can expand on their findings to determine whether stochastic convergence is evident among developing countries.

Historical Results

Figure 1 depicts the dispersion in the log of per capita CO_2 emissions for the World and OECD samples for 1960–2000. For the World sample, this dispersion has remained fairly

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[7] We should expect not complete emissions convergence but an equilibrium differential among any set of economies because of variations in climates, in associated energy demand, and in the composition of economic activity. See Aldy 2005 for evidence that per capita emissions vary with heating and cooling demand and historic energy endowments to U.S. states.

constant over the past 40 years or so but is slightly higher in 2000 than in 1960. This lack of emissions convergence may reflect the absence of income convergence for this sample of countries. In contrast, the OECD sample reveals a substantial decline in dispersion over the entire period.

I estimated distributions of per capita emissions by first constructing the ratio of per capita CO_2 emissions for each country in the World sample to the world average. I then placed each country into one of five categories: less than one-quarter of the world average, one-quarter to one-half of the world average, between one-half of and the world average, between the world average and twice the world average, and more than twice the world average (Quah 1993a, Kremer et al. 2001). The same categorization was applied to the OECD sample, relative to the OECD average.

Figure 2 displays histograms based on these five categories for 1960, 1980, and 2000 in the World sample. Two phenomena are very clear. First, the tails are thick. The per capita emissions of most countries are a factor of 2 away (i.e., less than one-half of or greater than twice the world average) from the world average. In 1960, 70 percent of all countries in the sample were a factor of 2 away from the world average, with modest improvement to 62 percent in 1980 but up to 66 percent in 2000. Second, the emissions data suggest a twin peaks phenomenon that may parallel some evidence of twin peaks in income per capita (Quah 1993a; cf. Jones 1997, Kremer et al. 2001). In 1960, the density of the distribution was monotonically decreasing in relative per capita emissions. The densest category—less than one-quarter of the world average—had more than double the number of countries in the category of one to two times the world average in 1960. By 2000, these two categories had almost the same number of countries.

The OECD histograms in Figure 3 reveal more compressed distributions of emissions over time than the results for the World sample. In 1960, seven of 23 OECD countries were more than a factor of 2 away from the OECD average; by 2000, only two countries were so far away from the average. The increasing mass of the distribution around the OECD mean over time suggests that the twin peaks phenomenon in the World sample does not apply to this group of advanced economies.

Estimates of the 25th and 75th percentiles of the distribution of per capita emissions relative to the world average also show emissions divergence (Table 1). While the per capita emissions of a country at the 25th percentile increased from 12 percent of the world average in 1960 to nearly 40 percent of the world average in 2000, the per capita emissions of a country at the 75th percentile increased even more relative to the world average, from 1.17 times the world average in 1960 to 2.1 times the world average in 2000. The 75–25 IQR increased substantially between 1960 and 2000, from 1.05 to 1.75. These larger spreads between the 25th and 75th percentiles of the relative distributions of per capita emissions in 1990 and 2000 are statistically different from the 1960 75–25 IQR at the 10 percent and 5 percent levels, respectively. The results using the 3-year samples yield virtually identical point estimates and further evidence of the statistical difference between the 1960s distribution and the distribution for the periods around 1980, 1990, and 2000. The 50 percent of countries at the ends of the distribution of relative per capita emissions are farther apart now than they were in 1960.

The OECD results again contrast with the World sample results. The estimated 25th percentile of the OECD emissions distribution has steadily increased over time, whereas the estimated 75th percentile of the distribution has shown a modest decline (Table 2). The 75–25 IQR decreased substantially between 1960 and 2000, from 0.78 (0.70 in the 3-year sample) to 0.33 (0.32). The smaller spreads between the 25th and 75th percentiles of the relative distributions of per capita emissions in 1990 and 2000 for the 3-year samples are statistically different from the 1960 75–25 range at the 10 percent and 5 percent levels, respectively. In the OECD sample, countries that have low per capita emissions made substantial progress toward closing the gap with countries that have high per capita emissions over the 1960–2000 period.

The tests for stochastic convergence also provide little evidence that countries' per capita CO_2 emissions are converging. Table 3 shows that for only 13 of 88 countries in the World sample do the DF–GLS test statistics commend rejecting the null hypothesis of a unit root at the 10 percent critical level. Of these 13 countries with stationary time series, only 3 are OECD countries. Although these results indicate that many countries have time series for CO_2 emissions that appear to suffer from permanent shocks which may preclude convergence, they are not necessarily inconsistent with the findings of Strazicich and List (2003), who used a panel-based test that "allows for some (but not all) of the individual series to have unit roots under the alternative hypothesis" (Im et al. 2003 p. 55). The results presented here, based on a test with superior power than the augmented Dickey–Fuller test, suggest that stochastic convergence has been limited.

Forecasting Future Emissions Distributions

I consider three approaches to estimating future emissions distributions. First, I present results from a Markov chain transition matrix analysis, a nonparametric method used in the economic growth literature to evaluate income distributions. Second, I discuss reduced-form parametric environmental Kuznets curve (EKC) regressions and note the shortcomings in using a fitted EKC to characterize future emissions distributions. Third, I review the results from structural models used to forecast emissions for the *Special Report on Emissions Scenarios* (IPCC 2000) and characterize the implicit emissions distributions in these forecasts.

Markov Chain Transition Matrices

Methods

Quah (1993a) applied the transition matrix framework to evaluate the distribution of per capita incomes. Following Quah, my framework effectively maps today's distribution (F_t) of per capita CO_2 emissions into tomorrow's distribution (F_{t+1}):

$$F_{t+1} = M \cdot F_t \tag{5}$$

The mapping operator *M* can be assumed to follow any process, but like Quah (1993a) and Kremer et al. (2001), I assume a first-order Markov process with time-invariant transition probabilities. Iterating this expression *T* times yields

$$F_{t+T} = M^T \cdot F_t \tag{6}$$

As *T* becomes large and if $F_{t+T} = F_{t+T-1}$, this expression illustrates the long-run steady-state (ergodic) distribution of per capita CO_2 emissions.

Like Quah (1993a) and Kremer et al., I discretized the World sample data according to the five categories of per capita emissions relative to the world average described earlier (see **Evaluation of Historical Convergence**). I then calculated the 1-year transitions from one category to another to construct the transition matrix presented in Table 4. The transition probabilities in Table 4 represent the mapping operator that is applied to the distribution in the last year of the data set to estimate the future distribution for the data set. I also did this with OECD sample data, and the corresponding transition probabilities are presented in Table 5.

The benefit of this approach is that it imposes little structure on the data (other than in the construction of the five discrete categories and the first-order Markov assumption), so the data can reveal their evolution over time without substantial constraint. This approach has several downsides. First, while it may characterize future distributions, further analysis is necessary to understand why the emissions distribution evolves as it does. Second, the drivers of distributional dynamics in 2000 may be different from those in the 1960s or 1970s. Although this issue has not been explored in the economic growth literature, I address it by comparing ergodic distributions derived from transition probabilities based on various periods (1960–2000, 1970–

2000, 1980–2000, and 1990–2000). Finally, by using information on historical distributional dynamics to forecast future distributions, significant changes from past experience in policies or technologies (e.g., new CO_2 regulations, breakthroughs in renewable energy) may not be well represented by this approach.

Transition Matrices Results

Table 4 presents the transition matrix based on the 1960–2000 World sample and its ergodic distribution. As in the findings of Quah (1993a) and Kremer et al. on the dynamics of income distributions, considerable persistence is evident in the high probabilities along the diagonal. For example, a country in the lowest category (per capita emissions less than one-quarter of the world average) has a 97.5 percent probability of remaining in that category next year and a 2.5 percent probability of moving up one category. If that country does move up to the next category, then in the following year, it will have a 9.0 percent probability of moving up to the third category, a 7.2 percent probability of returning to the lowest category, and an 83.8 percent probability of remaining in the second category. The triple-diagonal condition noted in the literature on income distributions effectively holds here: Transition probabilities off of the three main diagonals are zero, implying that countries do not experience more than a doubling or less than a halving of per capita emissions from 1 year to the next.

The long-run steady-state (ergodic) distribution of per capita emissions shows that nearly 60 percent of all countries would be expected to have less than half of the world's average per capita emissions. Fewer than one out of three countries would have per capita emissions within a factor of 2 of the world average. The bottom of the ergodic distribution is thicker than in historical distributions (Figure 2), suggesting further emissions divergence.[8]

Table 5 shows the transition matrix for the OECD sample. Like Table 4, it shows persistence, with high probabilities along the main diagonal. The ergodic distribution provides some evidence of twin peaks in OECD emissions; per capita emissions are less than one-quarter of the OECD average in 25 percent of countries and between one-half of and the OECD average in more than 30 percent of countries.

The period of the observations chosen to construct the transition matrix appears to influence the estimated ergodic distribution. Table 6 shows the ergodic distributions for

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[8] To explore the sensitivity of using 1-year data, I also constructed 5-year averages. The estimated ergodic distribution is even thicker in the lowest two categories with the 5-year average transition matrix.

transition matrices based on periods starting in 1960, 1970, 1980, and 1990 (all ending in 2000) for the World sample. For 1960–2000, the transition matrix framework treats a transition in 1961 the same as one in 1999 for forecasting future distributions, even though it is reasonable that the underlying economic, technological, and institutional factors influencing transitions change over time. Estimating ergodic distributions with shorter panels weights the early observations in our sample with a zero and maintains equal unit weights on observations remaining in the shorter panels. The bottom of the emissions distribution appears to be thinner in the ergodic distributions after the 1970s, and in the one-decade 1990s sample, the ergodic distribution reveals the twin peaks characteristic evident of 2000 in Figure 2. While this sensitivity analysis raises questions about the appropriate length of a panel to construct transition matrices, none of the World sample ergodic distributions display meaningful emissions convergence.[9] In contrast, the OECD sample exhibits more compressed ergodic distributions over shorter periods (Table 7).

While the estimated ergodic distributions characterize the long-run steady-state emissions distribution, the near-term transition may be of more interest. Figure 4 illustrates the estimated dispersion measure over the next 100 years based on the transitions underlying the World sample ergodic distributions summarized in Table 6. Although the 1960–2000 and 1970–2000 transition matrices suggest some convergence over the next 100 years, the shorter, more recent panels show continued divergence over the next 50 or so years, followed by modest convergence back to current levels of dispersion.

EKC Analysis

The EKC attempts to characterize pollution (in this case, per capita CO_2 emissions) as an inverted-U function of per capita income. Some researchers have suggested that finding an inverted-U EKC is a test of cross-sectional convergence (e.g., List 1999). While this may be the case in the long term (assuming convergence in incomes), the EKC income–emissions

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[9] To test the sensitivity of constructing these five categories relative to the world average, I also conducted these transition matrix analyses with five categories of per capita emissions relative to the U.S. average: less than one-sixteenth, one-sixteenth to one-eighth, one-eighth to one-quarter, one-quarter to one-half, and greater than one-half of U.S. per capita emissions (see Jones 1997 for incomes per capita relative to the U.S. average). I find even more pronounced evidence of the twin peaks phenomenon in per capita CO_2, especially in the shorter panels-based ergodic distributions.

relationship cannot unambiguously support emissions convergence or divergence during the transition to a long-term steady state.[10]

Graphical analysis indicates that the EKC yields ambiguous conclusions about convergence during the transition to the steady state. Consider a scenario in which incomes converge, with four cases representing different levels of initial per capita emissions and shapes for the EKC.[11] In Figure 5, A corresponds to a representative developing country and B to a representative developed country. Times *t* and *T* represent the beginning and ending of the period under consideration. A determination of emissions σ-convergence would reflect the relative within–time frame differences among the countries: ($|CO2_{At} – CO2_{Bt}|$ versus $|CO2_{AT} – CO2_{BT}|$).

In Case I, at the beginning of the period, developing and developed countries have identical per capita emissions but different income levels (Figure 5a). With an inverted-U EKC, income convergence implies emissions divergence. Per capita emissions for developing countries would increase initially but then decrease by the end of the period ($A_t \rightarrow A_T$), whereas developed countries' emissions would decrease throughout the period ($B_t \rightarrow B_T$) and fall to a greater extent than the net effect of developing countries' emissions. Per capita emissions dispersion increases over the period: ($|CO2_{At} – CO2_{Bt}| < |CO2_{AT} – CO2_{BT}|$).

In Case II, developing countries' per capita emissions are greater than developed countries' emissions (Figure 5b). With the EKC relationship and these starting points, income convergence could imply emissions convergence or divergence, depending on the length of the period under consideration. For the longer period (*t* to *T*), developing countries' per capita emissions decline to a greater extent over the period than do developed countries' emissions, resulting in a decline in emissions dispersion over the period: ($|CO2_{At} – CO2_{Bt}| > |CO2_{AT} – CO2_{BT}|$). For the shorter period of *t* to *t*+1, the countries with higher per capita emissions would

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[10] An empirical EKC may even fail to yield long-term emissions convergence if the estimated shape of the curve reflects only transitory phenomena. For example, the inverted-U shape may reflect changes in production associated with a country's stage of development. A decrease in pollution in one economy may represent a shift in polluting production activity to another economy that then experiences an increase in pollution. Such a change could follow the development path from agriculture (low income) to heavy industry (middle income) to services (high income). Because agriculture tends to be less energy intensive (carbon intensive) than heavy industry—which is also more energy intensive (carbon intensive) than services—this development path could result in an EKC for CO_2. Note, however, that the inverted U would only be temporary because every economy cannot specialize in services and export its heavy industry to other economies. Refer to Aldy 2005 for evidence supporting this hypothesis.

[11] See the Appendix for a graphical analysis of these four cases assuming income divergence. In all four cases with income divergence, emissions may diverge over at least some portion of the transition path.

experience positive growth in emissions ($A_t \rightarrow A_{t+1}$), whereas those with lower per capita emissions would experience negative growth ($B_t \rightarrow B_{t+1}$), thereby increasing the dispersion of per capita emissions over time.

Case III most resembles the current state of the world, with developed countries' per capita CO_2 emissions levels exceeding those of developing countries (Figure 5c). Income convergence and the EKC again can imply emissions convergence or divergence. Emissions convergence could occur in the short or the long run, but divergence could characterize the medium term. In the emissions convergence subcases (periods t to t+1 and t to T), emissions dispersion decreases over time: ($|CO2_{At} - CO2_{Bt}| > |CO2_{AT} - CO2_{BT}|$ and $|CO2_{At} - CO2_{Bt}| > |CO2_{At+1} - CO2_{Bt+1}|$). Note, however, that although emissions dispersion is lower at the end of period T than at the beginning, it is higher than at the end of the short period t+1: $|CO2_{AT} - CO2_{BT}| > |CO2_{At+1} - CO2_{Bt+1}|$. These findings indicate that dispersion increases in the medium term as developing countries experience a substantial increase in per capita emissions ($A_{t+1} \rightarrow A_{t+2}$) and developed countries experience a modest decrease in per capita emissions ($B_{t+1} \rightarrow B_{t+2}$).

Case IV with income convergence uses a concave monotonic income–emissions relationship (Figure 5d). In this case, emissions are assumed to always grow with income, but at a declining rate. However, per capita emissions never fall with rising incomes in this case. Like Case III, Case IV best reflects the current state of the world with developed countries' per capita emissions exceeding developing countries' emissions. With this income–emissions relationship, income convergence unambiguously implies emissions convergence.

The results of Cases I–III illustrate the ambiguous implications of the EKC on emissions convergence, even with income convergence. They suggest the difficulty in extrapolating the implications of emissions convergence from EKC analyses. The combination of emissions divergence and convergence in some cases should raise questions about the appropriate timing for implementing any policies for the allocation of per capita emissions. Case IV illustrates a relationship between income convergence and emissions convergence, although at the expense of the inverted-U income–emissions relationship.

Structural Model Emissions Forecasts from IPCC 2000

The Intergovernmental Panel on Climate Change (IPCC) published long-term emissions forecasts (Leggett et al. 1992 IPCC 2000) that have been widely used and evaluated in the policymaking and academic communities. They likely provide the basis for decisionmakers' expectations about future emissions levels because they have served as inputs to global circulation models (e.g., Houghton et al. 2001) and long-term energy–economy models (e.g., the Stanford Energy Modeling Forum's EMF-14 exercise). The 1992 and 2000 emissions forecasts present emissions and population data in terms of four aggregated regions: OECD member countries as of 1990, the Soviet Union and Eastern Europe, Asia, and the rest of the world. IPCC does not report any statistics or figures characterizing the distribution of emissions but does provide the information necessary to construct measures of dispersion for these four regions.

The IPCC forecast in the central emissions scenario of its 1992 report (IS92a) revealed that the dispersion of per capita CO_2 emissions would decline by about 20 percent between 1990 and 2025 and by nearly 45 percent between 1990 and 2100 (Leggett, Pepper, and Swart 1992). Building on this earlier work, six long-term models were used to develop 40 long-term emissions scenarios for the IPCC 2000 report. In IPCC's A1 scenario (a "central" marker scenario), per capita CO_2 emissions converge among the four regions in all six models (Figure 6). In several models of this scenario, the dispersion coefficient falls by at least a factor of 3 over 1990–2100.

This convergence in the structural models may be a result of regional aggregation of the data. Figure 6 illustrates the historical dispersion in CO_2 per capita for countries (like in Figure 1) and for these four regions. The convergence among regions is evident in the historical data, but this masks the lack of convergence with the country-level data. While more disaggregated structural models exist (including those involved in the IPCC), they may not have sufficient geographic detail to adequately characterize historical or future emissions distributions.

Conclusions

As decisionmakers continue to debate policies to mitigate climate change, they will benefit from forecasts of future CO_2 emissions distributions. Understanding future levels of emissions (and associated climate impacts) can help decisionmakers determine the appropriate magnitude of emissions abatement effort, and understanding the future distributions of those emissions can help decisionmakers allocate abatement obligations. The lack of focus on emissions distributions in the existing literature and the continued interests in designing policies to increase participation by key developed and developing countries suggests that an analysis of past emissions distributions and forecasts of future distributions is merited. I have made an initial effort to describe past and future distributions of per capita CO_2 emissions.

My analysis of 88 countries for the 1960–2000 period shows no evidence of convergence and even some divergence in per capita CO_2 emissions based on a measure of dispersion, the distribution of emissions over time, and tests for stochastic convergence. In contrast, a sample of 23 OECD member countries appears to show convergence over this period, although the evidence for stochastic convergence is mixed.

Forecasts of long-run emissions distributions using a transition matrix framework provide little evidence of future emissions convergence for the World sample. Estimated steady-state (ergodic) distributions appear to be sensitive to choice of period when constructing transition probabilities, especially for the OECD sample. The estimated transitions to the steady-state show some further divergence among the World sample over the next 50 years or more.

Other means of forecasting future emissions may not adequately characterize emissions distributions. Empirical EKC regressions may not appropriately estimate long-run emissions distributions, especially if factors such as trade in energy-intensive goods are important, as appears to be the case in work on the U.S. states. Moreover, simply estimating an inverted-U emissions–income relationship does not unambiguously imply emissions convergence or divergence, at least during the transition to the steady state. By focusing on aggregated regions, structural models may not have sufficient geographic detail to adequately represent the international emissions distribution.

References

Aldy, J.E. 2005. An Environmental Kuznets Curve Analysis of U.S. State-Level Carbon Dioxide Emissions. *Journal of Environment and Development* (EPA special issue) 14(1): 48–72.

Barro, R.J., and X. Sala-i-Martin. 1992. Convergence. *Journal of Political Economy* 100(2): 223–251.

Bodansky, D. 2004. *International Climate Efforts Beyond 2012: A Survey of Approaches*. Arlington, VA: Pew Center on Global Climate Change.

Carlino, G.A., and L.O. Mills. 1993. Are U.S. Regional Incomes Converging? A Time Series Analysis. *Journal of Monetary Economics* 32: 335–346.

Climate Action Network. 1997. Diversionary Tactics. *Eco* 98(6). Dec. 6. http://www.climatenetwork.org/eco/eco6_cop3.html#contents, accessed Nov. 3, 2005.

Elliott, G., T.J. Rothenberg, and J.H. Stock. 1996. Efficient Tests for an Autoregressive Unit Root. *Econometrica* 64(4): 813–836.

Evans, P., and G. Karras. 1996. Convergence Revisited. *Journal of Monetary Economics* 37: 249–265.

Friedman, Milton. 1992. Do Old Fallacies Ever Die? *Journal of Economic Literature* 30: 2129–2231.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Eds.). 2001. *Climate Change 2001: The Scientific Basis*. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK: Cambridge University Press, for IPCC.

Im, K.S., M.H. Pesaran, and Y. Shin. 2003. Testing for Unit Roots in Heterogeneous Panels. *Journal of Econometrics* 115: 53–74.

IPCC (Intergovernmental Panel on Climate Change). 2000. *Special Report on Emissions Scenarios*. Cambridge, UK: Cambridge University Press.

Jones, C.I. 1997. On the Evolution of the World Income Distribution. *Journal of Economic Perspectives* 11(3): 19–36.

Kremer, M., A. Onatski, and J. Stock. 2001. Searching for Prosperity. *Carnegie–Rochester Conference Series on Public Policy* 55: 275–303.

Lee, K., M.H. Pesaran, and R. Smith. 1997. Growth and Convergence in a Multi-Country Empirical Stochastic Solow Model. *Journal of Applied Econometrics* 12(4): 357–392.

Leggett, J., W.J. Pepper, and R.J. Swart. 1992. Emissions Scenarios for IPCC: An Update. In *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Edited by J.T. Houghton, B.A. Callander, and S.K. Varney. Cambridge, U.K.: Cambridge University Press.

List, J.A. 1999. Have Air Pollutant Emissions Converged among U.S. Regions? Evidence from Unit Root Tests. *Southern Economic Journal* 66(1): 144–155.

Marland, G., T.A. Boden, and R.J. Andres. 2003. Global, Regional, and National CO_2 Emissions. In *Trends: A Compendium of Data on Global Change*. Oak Ridge, TN: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center.

Ng, S. and P. Perron. 2001. Lag Length Selection and the Construction of Unit Root Tests with Good Size and Power. *Econometrica* 69(6): 1519–1554.

Quah, D. 1993a. Empirical Cross-Section Dynamics in Economic Growth. *European Economic Review* 37: 426–434.

Quah, D. 1993b. Galton’s Fallacy and Tests of the Convergence Hypothesis. *Scandinavian Journal of Economics* 95(4): 427–443.

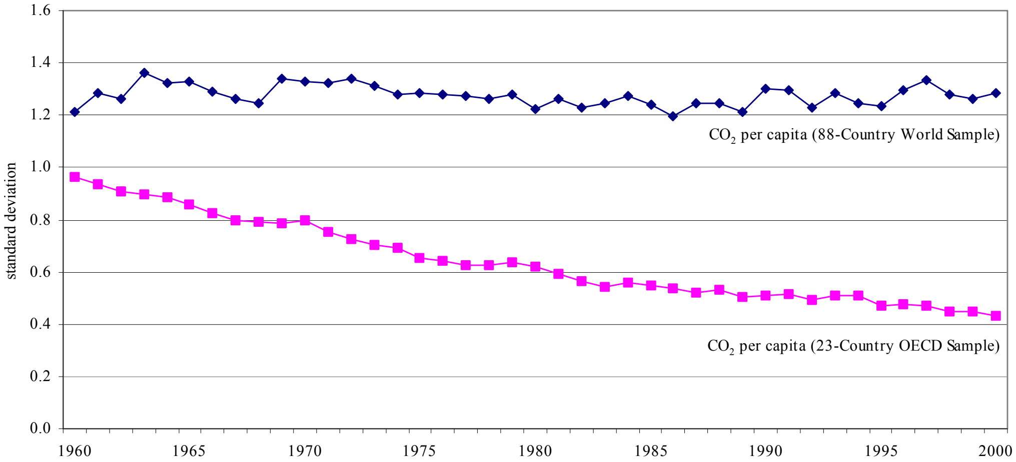
Schmalensee, R., T.M. Stoker, and R.A. Judson. 1998. World Carbon Dioxide Emissions: 1950–2050. *Review of Economics and Statistics* 80(1): 15–27.

Soz, S. 1997. *India Rejects Incorporation of New Environmental Commitments for Developing Countries* (transcript of speech). Presented at the 3rd Session of the Conference of the Parties to the Framework Convention on Climate Change, Kyoto, Japan, Dec. 8. http://www.indianembassy.org/policy/Environment/soz.htm

Strazicich, M.C., and J.A. List. 2003. Are CO_2 Emission Levels Converging among Industrial Countries? *Environmental and Resource Economics* 24: 263–271.

Figures

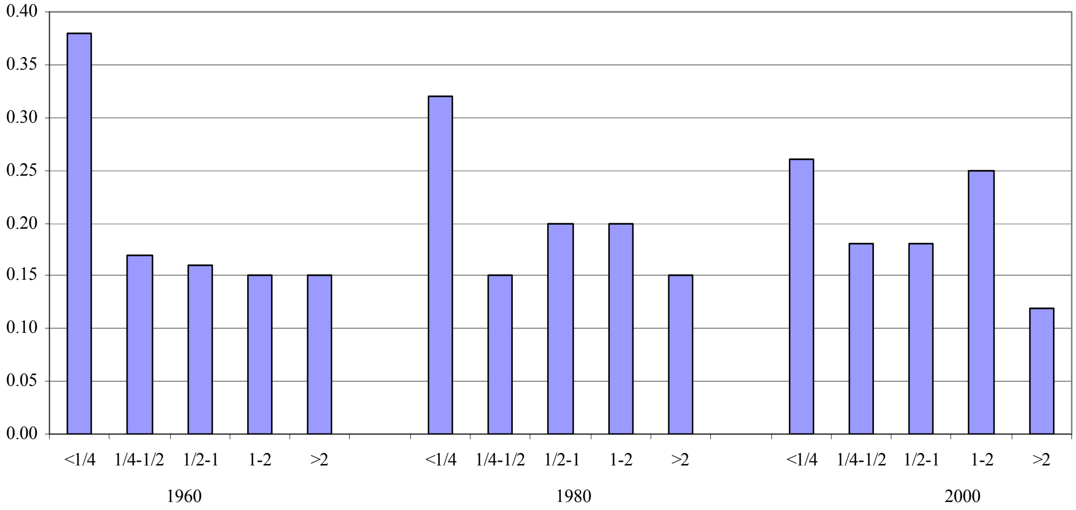
Figure 1. Dispersion in Per Capita CO_2 Emissions, World and OECD Samples, 1960–2000



Note: Data are standard deviations of the natural logarithm of per capita CO_2 emissions.

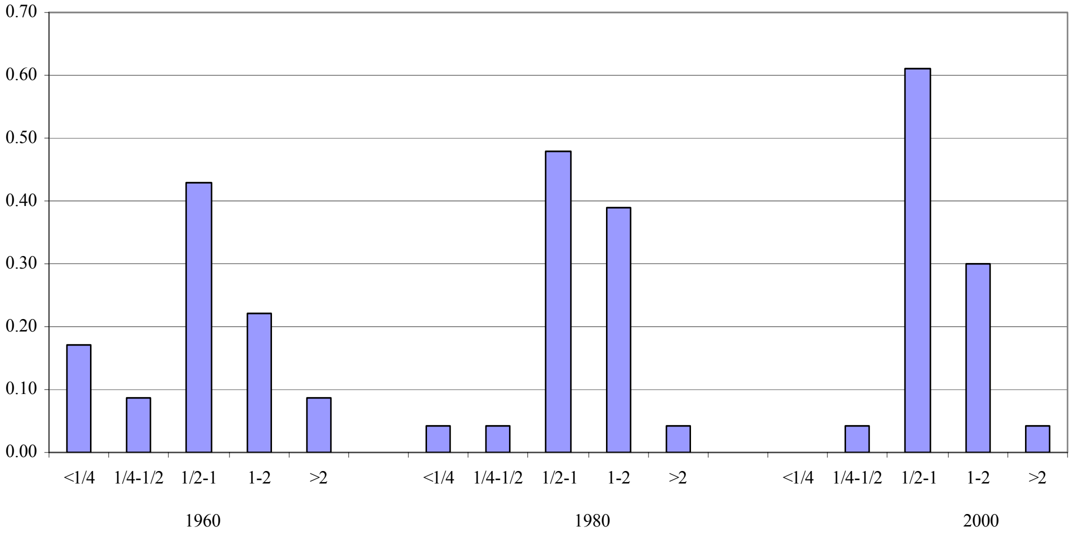
Source: CO_2 emissions data are from Marland et al. 2003.

Figure 2. Estimated Annual Distribution of Per Capita CO_2 Emissions, World Sample (Relative to World Average)



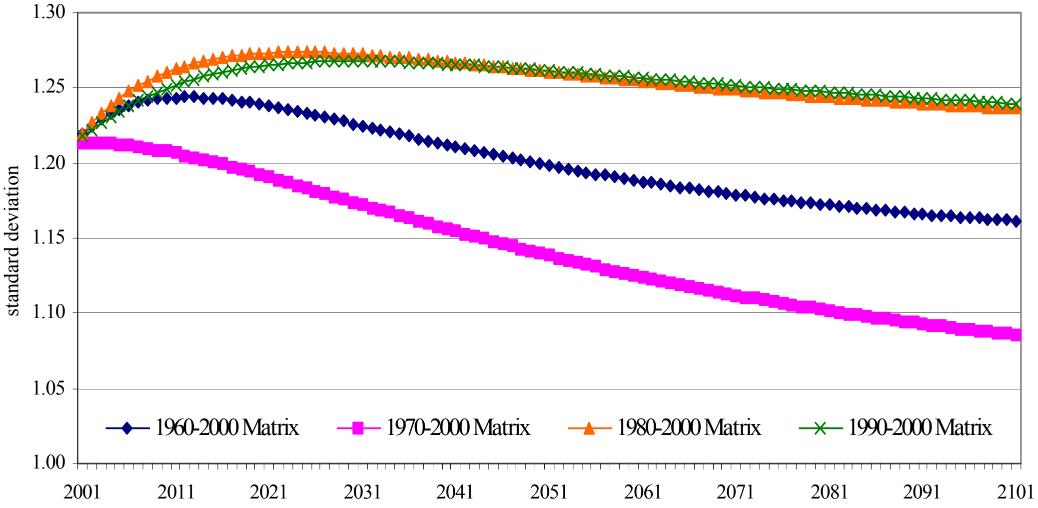
Source: CO_2 emissions data are from Marland et al. 2003.

Figure 3. Estimated Annual Distribution of Per Capita CO_2 Emissions, OECD Sample (Relative to OECD Average)



Source: CO_2 emissions data are from Marland et al. 2003.

Figure 4. Transition Path for Per Capita CO_2 Emissions Dispersion, Based on Various Markov Transition Matrices, World Sample, 2001–2101



Note: Data are standard deviations of the natural logarithm of per capita CO_2 emissions forecasts.

Source: CO_2 emissions data are from Marland et al. 2003.

Figure 5a. EKC Case I with Income Convergence: Initial Per Capita Emissions of Developing and Developed Countries Are Identical

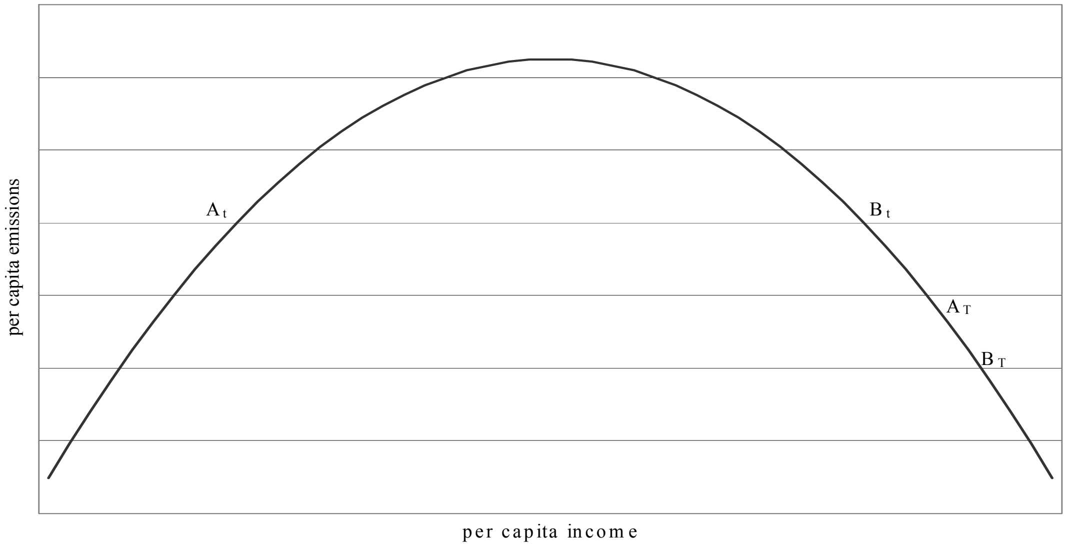


Figure 5b. EKC Case II with Income Convergence: Initial Per Capita Emissions Are Greater in Developing Countries than in Developed Countries

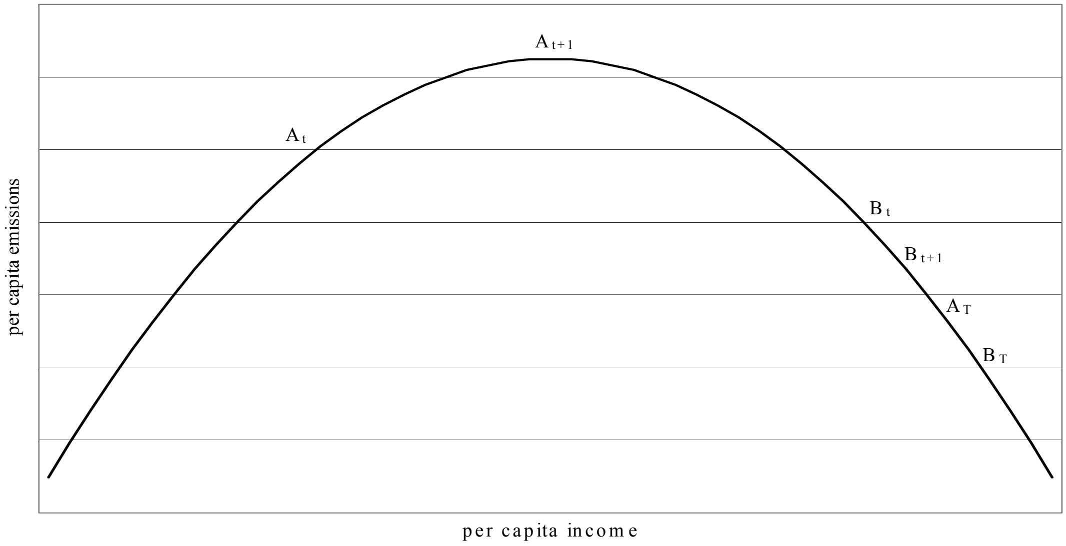


Figure 5c. EKC Case III with Income Convergence: Initial Per Capita CO_2 Emissions of Developed Countries Exceed Those of Developing Countries

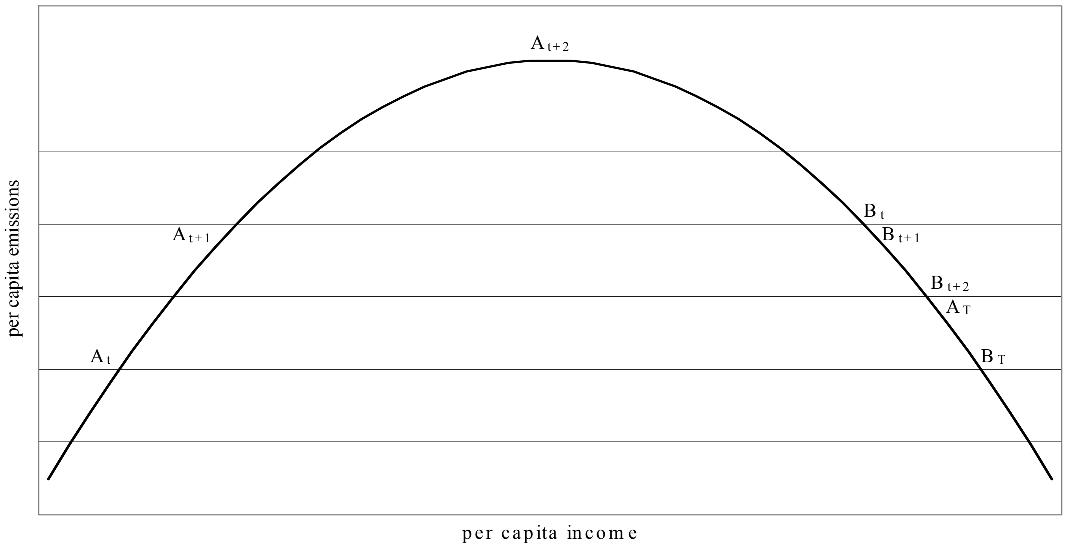


Figure 5d. EKC Case IV with Income Convergence: Initial Per Capita Emissions of Developed Countries Exceed Those of Developing Countries, Concave Monotonic Relationship

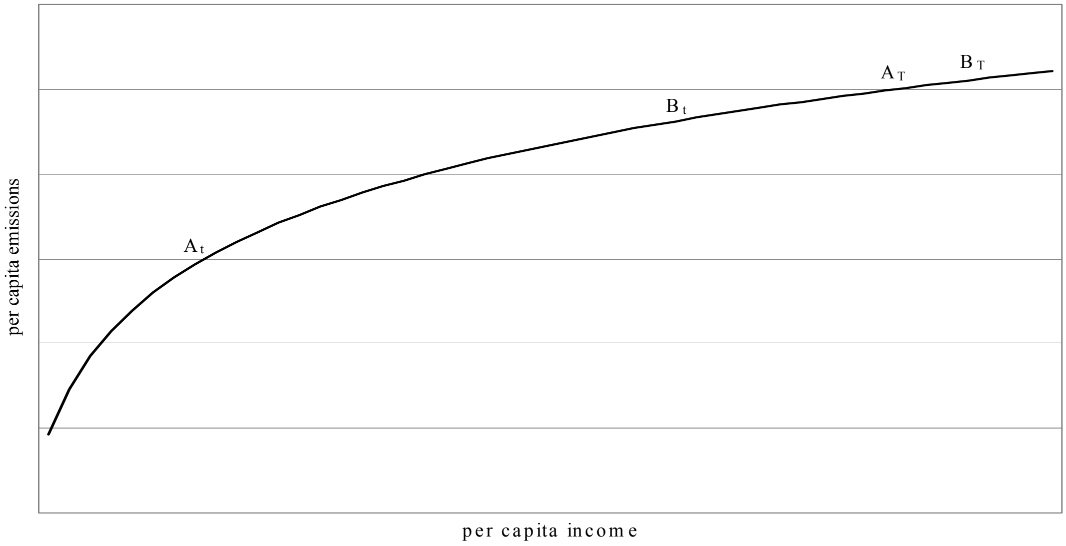
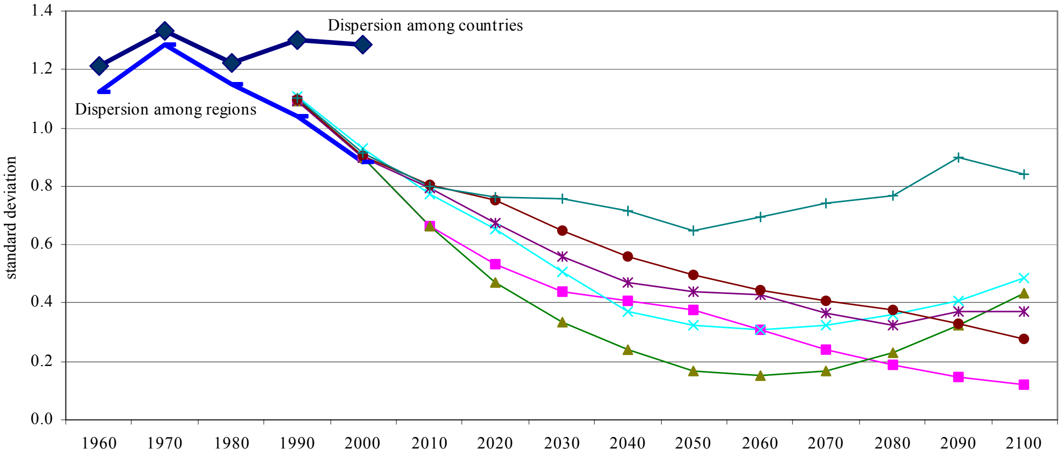


Figure 6. Historical Dispersion in Per Capita CO_2 Emissions, World Sample, and Forecast Dispersion by Six IPCC Models under IPCC's A1 Scenario (IPCC 2000) for Four IPCC Regions



Notes: Data are standard deviations of the natural logarithm of per capita CO_2 emissions. The four IPCC regions are OECD member countries as of 1990, Soviet Union and Eastern Europe, Asia, and the rest of the world.

Tables

Table 1a. Estimated 25th and 75th Percentiles and 75–25 IQR, World Relative Distribution of Per Capita CO$_2$ Emissions, 1960–2000: 1-Year Samples

	1960		*1970*		*1980*		*1990*		*2000*	
Percentile of distribution	25th	75th	25th	75th	25th	75th	25th	75th	25th	75th
CO$_2$ emissions per capita	0.12	1.17	0.17	1.70	0.24	1.93	0.29	1.93	0.38	2.13
(relative to world average)	(0.028)	(0.28)	(0.040)	(0.28)	(0.054)	(0.33)	(0.10)	(0.31)	(0.11)	(0.20)
CO$_2$ emissions per capita	1.05		1.54		1.68		1.64		1.75	
IQR	(0.25)		(0.25)		(0.32)		(0.21)*		(0.17)**	

Table 1b. Estimated 25th and 75th Percentiles and 75–25 IQR, World Relative Distribution of Per Capita CO$_2$ Emissions, 1960–2000: 3-Year Samples

	1960–1962		*1969–1971*		*1979–1981*		*1989–1991*		*1998–2000*	
Percentile of distribution	25th	75th	25th	75th	25th	75th	25th	75th	25th	75th
CO$_2$ emissions per capita	0.11	1.33	0.16	1.70	0.25	1.94	0.29	1.93	0.38	2.12
(relative to world average)	(0.019)	(0.18)	(0.019)	(0.14)	(0.035)	(0.19)	(0.038)	(0.15)	(0.061)	(0.11)
CO$_2$ emissions per capita	1.21		1.54		1.69		1.64		1.74	
IQR	(0.15)		(0.14)		(0.17)**		(0.14)*		(0.10)***	

Notes: Tests are based on estimating IQRs for pairs of periods. Bootstrapped standard errors based on 1,000 replications presented in parentheses.

*, **, *** indicate that *F*-tests comparing the estimated IQRs for the 1960 period and other periods reject the null that ranges of per capita CO$_2$ emissions are identical at the 10 percent, 5 percent, and 1 percent levels, respectively.

Table 2a. Estimated 25th and 75th Percentiles and 75–25 IQR, OECD Relative Distribution of Per Capita CO_2 Emissions, 1960–2000: Results Based on 1-Year Samples

	1960		*1970*		*1980*		*1990*		*2000*	
Percentile of distribution	25th	75th	25th	75th	25th	75th	25th	75th	25th	75th
CO_2 emissions per capita (relative to OECD average)	0.30 (0.10)	1.08 (0.82)	0.45 (0.12)	1.07 (0.61)	0.53 (0.13)	1.10 (0.37)	0.55 (0.12)	1.08 (0.33)	0.59 (0.10)	0.92 (0.20)
CO_2 emissions per capita IQR	0.78 (0.21)		0.62 (0.17)		0.57 (0.13)		0.54 (0.19)		0.33 (0.19)	

Table 2b. Estimated 25th and 75th Percentiles and 75–25 IQR, OECD Relative Distribution of Per Capita CO_2 Emissions, 1960–2000: Results Based on 3-Year Samples

	1960–1962		*1969–1971*		*1979–1981*		*1989–1991*		*1998–2000*	
Percentile of distribution	25th	75th	25th	75th	25th	75th	25th	75th	25th	75th
CO_2 emissions per capita (relative to OECD average)	0.36 (0.069)	1.07 (0.12)	0.47 (0.069)	1.03 (0.080)	0.53 (0.048)	1.06 (0.11)	0.56 (0.031)	0.96 (0.11)	0.59 (0.048)	0.91 (0.15)
CO_2 emissions per capita IQR	0.70 (0.13)		0.56 (0.067)		0.53 (0.077)		0.40 (0.11)*		0.32 (0.12)**	

Notes: Tests are based on estimating IQRs for pairs of periods. Bootstrapped standard errors based on 1,000 replications presented in parentheses.

*, **, *** indicate that *F*-tests comparing the estimated IQRs for the 1960 period and other periods reject the null that ranges of per capita CO_2 emissions are identical at the 10 percent, 5 percent, and 1 percent levels, respectively.

Table 3. Results of Unit Root Tests for Stochastic Convergence

Test	*Share of Sample Rejected Null Hypothesis of Unit Root* *World*	 *OECD*
Elliott et al. (1996) DF–GLS	13/88	3/23

Notes: Lag structures varying from one to nine lags were considered, and the optimal lag was selected using Ng and Perron's (2001) Modified Information Criteria. All tests include a linear time trend. The null hypothesis of a unit root was rejected if the DF–GLS statistic was larger (in absolute value) than the 10 percent critical value for the corresponding sample and lag structure.

Source: Data from Marland et al. 2003 were used in country-specific DF–GLS tests.

Table 4. Estimates of Transition Matrix and Ergodic Distribution, Per Capita CO_2 Emissions, World Sample, 1960–2000

Upper Endpoint	*Upper Endpoint (Ratio of National to World Per Capita CO_2 Emissions)* *0.25*	 *0.50*	 *1.00*	 *2.00*	 ∞
0.25	0.975	0.025	0	0	0
0.50	0.072	0.838	0.090	0	0[1]
1.00	0[1]	0.090	0.843	0.067	0[1]
2.00	0[1]	0	0.062	0.891	0.042
∞	0	0	0[1]	0.070	0.930
Ergodic	0.44	0.15	0.15	0.16	0.10

Source: Constructed by author with data from Marland et al. 2003.

[1] These five cells have non-zero transition probabilities representing a total of six observations but reflect atypical emissions shocks in energy-producing countries in the 1960s, with the exception of Kuwait following the 1990–1991 Gulf War. Non-zero probabilities were used in estimating the ergodic distribution presented in the last row.

Table 5. Estimates of Transition Matrix and Ergodic Distribution, Per Capita CO_2 Emissions, OECD Sample, 1960–2000

Upper Endpoint	*Upper Endpoint (Ratio of National to OECD Per Capita CO_2 Emissions)*				
	0.25	*0.50*	*1.00*	*2.00*	∞
0.25	0.944	0.055	0	0	0
0.50	0.103	0.853	0.044	0	0
1.00	0	0.018	0.945	0.036	0
2.00	0	0	0.059	0.924	0.017
∞	0	0	0	0.058	0.942
Ergodic	0.26	0.14	0.34	0.21	0.06

Source: Constructed by author with data from Marland et al. 2003.

Table 6. Estimated Ergodic Distributions Based on Various Periods, Per Capita CO_2 Emissions, World Sample

Period	*Upper Endpoint (Ratio of National to World Per Capita CO_2 Emissions)*				
	0.25	*0.50*	*1.00*	*2.00*	∞
1960–2000	0.44	0.15	0.15	0.16	0.10
1970–2000	0.52	0.14	0.14	0.13	0.07
1980–2000	0.38	0.14	0.18	0.18	0.12
1990–2000	0.39	0.13	0.17	0.19	0.12

Source: Constructed by author with data from Marland et al. 2003.

Table 7. Estimated Ergodic Distributions Based on Various Periods, Per Capita CO_2 Emissions, OECD Sample

Period	*Upper Endpoint (Ratio of National to OECD Per Capita CO_2 Emissions)*				
	0.25	*0.50*	*1.00*	*2.00*	∞
1960–2000	0.26	0.14	0.34	0.21	0.06
1970–2000	0.12	0.11	0.41	0.28	0.08
1980–2000	0.03	0.09	0.47	0.34	0.07
1990–2000	0.01	0.12	0.52	0.32	0.04

Source: Constructed by author with data from Marland et al. 2003.

Appendix: Environmental Kuznets Curve Analysis with Income Divergence

In the graphical analysis of the environmental Kuznets curve (EKC) in the main text of this paper (see **Forecasting Future Emissions Distributions** and Figure 5), I assume income convergence. That analysis yields ambiguous conclusions regarding the convergence of per capita emissions as per capita incomes converge. To complement that analysis, this Appendix presents a graphical analysis assuming divergence of per capita incomes. Per capita emissions divergence could occur under all four cases with income divergence, at least for part of the transition to the steady state.

Each graph in Figure A-1 has the same EKC shape and initial (i.e., at time *t*) emissions–income points for the representative developing (A) and developed (B) countries as the corresponding graph in Figure 5; only the emissions–income points for periods *t*+1, *t*+2, and *T* differ, reflecting the income divergence assumption. Although these figures are not exhaustive of the outcomes under income divergence, they do illustrate that emissions divergence is possible under all four cases.

In Case A-I, at the beginning of the period, developing and developed countries have identical per capita emissions but different income levels (Figure A-1a). With an inverted-U EKC, income divergence implies emissions divergence. Per capita emissions for developing countries would increase ($A_t \rightarrow A_T$), whereas developed countries' emissions would decrease ($B_t \rightarrow B_T$). Per capita emissions dispersion increases over the period: $|CO2_{At} - CO2_{Bt}| < |CO2_{AT} - CO2_{BT}|$.

In Case A-II, developing countries' per capita emissions are greater than developed countries' emissions (Figure A-1b). With the EKC relationship and these starting points, income divergence could imply emissions divergence. For both the shorter (*t* to *t*+1) and the longer (*t* to *T*) periods, the per capita emissions of developing countries increase while those of developed countries decline, thereby increasing emissions dispersion over time: $|CO2_{AT} - CO2_{BT}| > |CO2_{At+1} - CO2_{Bt+1}| > |CO2_{At} - CO2_{Bt}|$.

Case A-III most resembles the current state of the world, with developed countries' per capita CO_2 emissions levels exceeding the levels of developing countries (Figure A-1c). Income divergence and the EKC could imply emissions convergence or divergence. Emissions convergence could occur in the short term, but divergence could characterize the medium and long terms. In the emissions convergence subcase (*t* to *t*+1), emissions dispersion decreases over time: ($|CO2_{\mathrm{A}t} - CO2_{\mathrm{B}t}| > |CO2_{\mathrm{A}t+1} - CO2_{\mathrm{B}t+1}|$). After this initial convergence, per capita emissions diverge through the end of period T: $|CO2_{\mathrm{A}T} - CO2_{\mathrm{B}T}| > |CO2_{\mathrm{A}t+2} - CO2_{\mathrm{B}t+2}| > |CO2_{\mathrm{A}t+1} - CO2_{\mathrm{B}t+1}|$.

Case A-IV uses a concave monotonic income–emissions relationship (Figure A-1d). Like Case A-III, this case best reflects the current state of the world, with developed countries' per capita emissions exceeding developing countries' emissions. With this income–emissions relationship, income divergence could imply emissions convergence or divergence, depending on the extent of the income divergence and the relative slopes of the income–emissions function. As illustrated, per capita emissions diverge with the income divergence.

All four cases illustrate the ambiguous implications of the EKC on emissions convergence with income divergence. In all cases, emissions divergence is possible over at least some of the transition path. Whether per capita incomes converge or diverge, the EKC does not appear to provide much guidance on emissions convergence.

Appendix Figures

Figure A-1a. EKC Case A-I with Income Divergence: Initial Per Capita Emissions of Developing and Developed Countries Are Identical

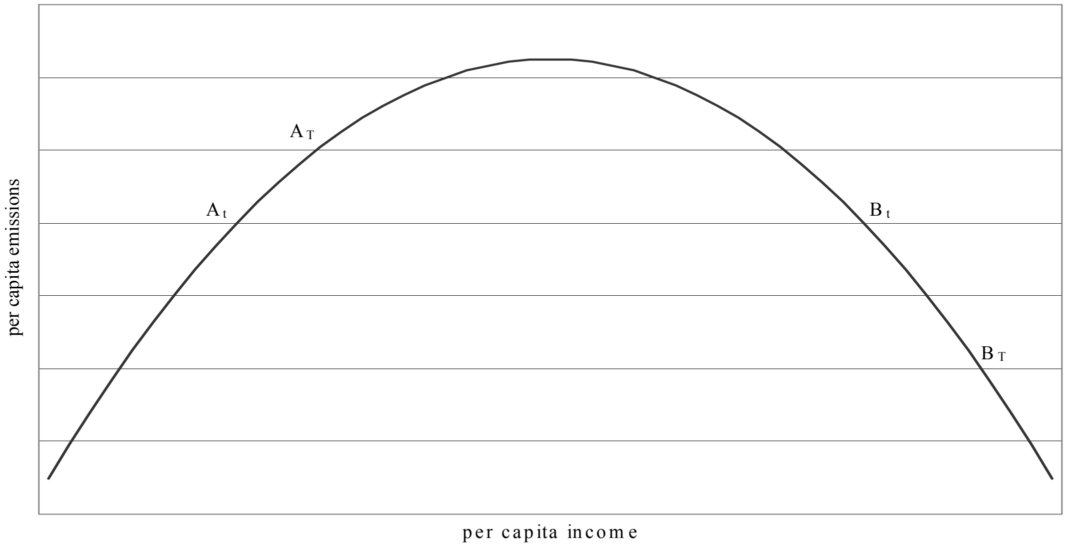


Figure A-1b. EKC Case A-II with Income Divergence: Initial Per Capita Emissions of Are Greater in Developing Countries than in Developed Countries

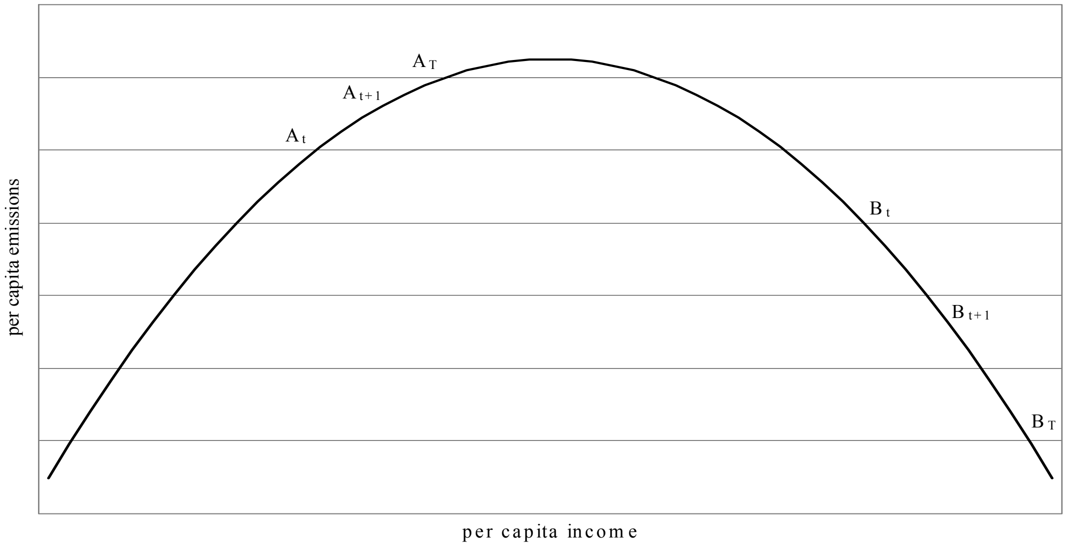


Figure A-1c. EKC Case A-III with Income Divergence: Initial Per Capita CO_2 Emissions Levels of Developed Countries Exceed Those of Developing Countries

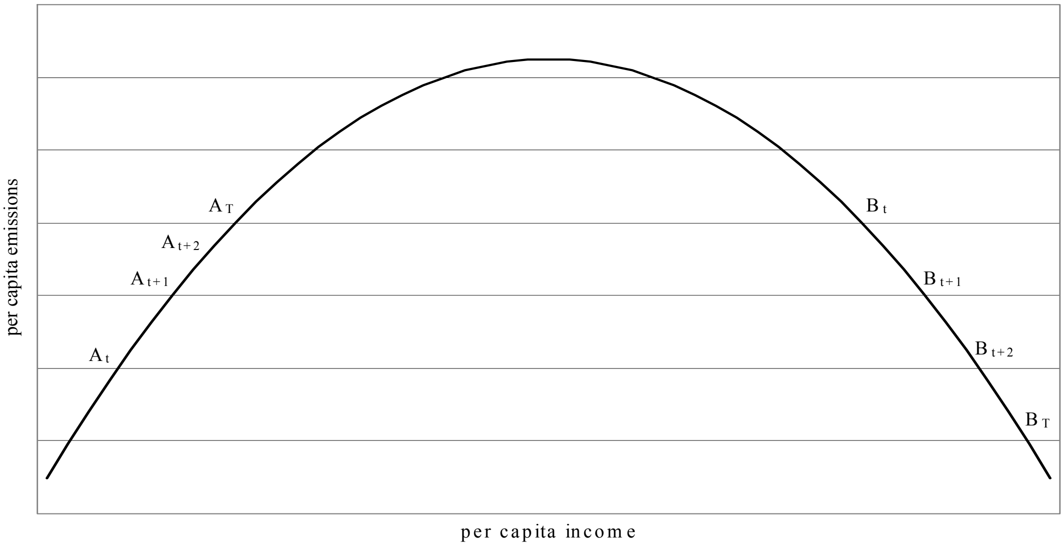


Figure A-1d. EKC Case A-IV with Income Divergence: Initial Per Capita Emissions of Developed Countries Exceed Those of Developing Countries, Concave Monotonic Relationship