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# STOKING THE FIRES? $CO_2$ EMISSIONS AND ECONOMIC GROWTH

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## ABSTRACT

Over the past decade, concern over potential global warming has focused attention on the emission of greenhouse gases into the atmosphere, and there is an active debate concerning the desirability of reducing emissions. At the heart of this debate is the future path of both greenhouse gas emissions and economic development among the nations. We use global panel data to estimate the relationship between per capita income and carbon dioxide emissions, and then use the estimated trajectories to forecast global emissions of $CO_2$.

The analysis yields four major results. First, the evidence suggests a diminishing marginal propensity to emit (MPE) $CO_2$ as economies develop; a result masked in analyses that rely on cross-section data alone. Second, despite the diminishing MPE, our forecasts indicate that global emissions of $CO_2$ will continue to grow at an annual rate of 1.8 percent. Third, continued growth stems from the fact that economic and population growth will be most rapid in the lower-income nations that have the highest MPE. For this reason, there will be an inevitable tension between policies to control greenhouse gas emissions and those toward the global distribution of income. Finally, our sensitivity analyses suggest that the pace of economic development does not dramatically alter the future annual or cumulative flow of $CO_2$ emissions.

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## 1. INTRODUCTION

Over the past decade, concern over potential global warming has focused attention on the emissions of greenhouse gases into the atmosphere. There is an active debate concerning the desirability of reducing emissions, the shape of which has become quite familiar. On the one hand are proposals to limit, perhaps sharply, the emission of greenhouse gases into the atmosphere in the near term. Proponents of dramatic action argue that the potential for catastrophic consequences is large, and that the persistence of carbon in the atmosphere necessitates prompt reductions. Their reading of the evidence suggests that there has been substantial and on-going change in the composition of the earth's atmosphere since the start of the Industrial Revolution, and that economic growth in countries at all levels of development appears likely to exacerbate the flow of emissions into the atmosphere.

Opponents of such policies point out that there is little hard evidence concerning the impact of anthropogenic greenhouse gas emissions on the global climate. Even if one accepts the evidence on overall emissions, isolating the anthropogenic portion of global change requires a completely-specified model of the "general circulation" process. Opponents of fast action emphasize that the predictions of existing models vary greatly (see, for example, Schelling [1992] and Solow [1991]), indicating that our scientific grasp of the issues is incomplete. Moreover, efforts to control or reduce greenhouse gas emissions may reduce economic growth, thus placing a disproportionate burden on lower-income nations. This line of reasoning often leads to a "no regrets" approach, favoring policies in the near term that have benefits independent of the ultimate seriousness of global climate changes (see, for example, Nordhaus [1992] and Shah and Larsen [1992]).

Our purpose is not to enter this debate. Instead, we emphasize that at its heart is the future path of both greenhouse gas emissions and economic development among the nations.

Baseline forecasts of economic growth and greenhouse gas emissions are a crucial component of global climate models, and thus of benefit-cost assessments of policies toward global climate change. There are many possible approaches to developing such forecasts. At one extreme, one might simply extrapolate emissions at historic growth rates. The main problem with such an approach is that it precludes any behavioral response to changing economic or atmospheric conditions. Indeed, the historic rate of emissions has hardly been constant through time. At the other end of the spectrum, one could parameterize a fully-specified general equilibrium model and use the period-by-period equilibria to track out a forecast over the desired horizon. The difficulty of such an approach lies in the enormous informational burden it places on researchers.

In this paper, we adopt an intermediate approach, estimating the reduced-form relationship between per capita income and emissions, and then forecasting aggregate emissions based on scenarios for income and population growth. In contrast to naive extrapolation, our approach embodies the historic interrelationships among trajectories for economic development, population growth, and emissions. Moreover, in contrast to structural models it is relatively parsimonious. Our estimated relationship between emissions and income permits us to explore not only the path of aggregate emissions, but also the distribution of emissions among nations without the need for *a priori* information on numerous parameter values. In this way it permits us to develop detailed information on the emissions-economic growth link across the globe. Our approach carries a cost as well: reduced forms are not well-suited for policy analysis. Therefore, we restrict our attention to the characteristics of the emissions baseline.

The relationship between pollution and economic development is the subject of a small, but rapidly growing literature. Recent evidence in Grossman and Krueger [1991] and

Selden and Song [1992] indicates that there is an "inverted-U" shape for the relationship between per capita Gross Domestic Product (GDP) and the levels of four important types of air pollution: suspended particulates, sulfur dioxide, oxides of nitrogen, and carbon monoxide (see also Shafik and Bandyopadhyay [1992]). Hettige, Lucas, and Wheeler [1992] find similar results using an index of the sectoral composition of industry weighted by the pounds of toxic materials released in each sector. To understand how inverted-U relationships might arise, note that each of these pollutants is characterized by significant health and environmental effects within the emitting country, and relatively low abatement costs. Thus, the inverted-U shape is consistent with a scenario in which industrial development initially leads to greater raw emissions of these pollutants, but net emissions eventually decline as the increase in income associated with further development raises the demand for health and environmental quality.

This literature raises the possibility of a comparable relationship between greenhouse gases and economic growth. If so, and if peak levels of pollution occur at low enough levels, it raises the tantalizing possibility that instead of there being a *trade-off* between greenhouse gas emissions and economic growth, faster growth could serve as part of the *solution* to the worldwide emissions dilemma. From an *a priori* perspective, there seem to be reasons both in favor and against the possibility of an eventual decline in emissions. On the one hand, introspection suggests important differences between greenhouse gases and the pollutants studied earlier. The effects of greenhouse gases are less restricted to local areas. Their global nature reduces the incentive to reduce or abate emissions unilaterally. Further, many of these pollutants are substantially more costly to abate, exacerbating the free-rider problem among countries. These reasons argue against a tendency for greenhouse gas emissions to decline at higher per capita incomes, instead suggesting that they will rise monotonically with income.

On the other hand, greenhouse gases are often produced jointly with other pollutants. Thus, emissions of greenhouse gases may fall as a byproduct of other abatement efforts. For example, efforts to improve automobile fuel efficiency may have as their primary goal improved urban air quality, but they would simultaneously reduce greenhouse gas emissions. Similarly, as economies develop, changes in the pattern of final demands toward increased consumption of services may have as an indirect consequence reduced fossil fuel intensity. These possibilities argue in favor of the possibility that emissions may ultimately stop rising, or even fall, as economies develop.

Thus, the character of the link between economic growth and greenhouse gas emissions is fundamentally an empirical issue. This paper investigates the income-emissions relationship for one important greenhouse gas: carbon dioxide ($CO_2$). We exploit a rich panel of country-specific data for the years 1951-1986 to estimate the link between GDP per capita and emissions. As in most applications, access to panel data permits a richer econometric analysis, which, in this instance, leads to substantially different results than obtained using cross-sectional analysis.[1] For example, we find a diminishing marginal propensity to emit (MPE) $CO_2$ as economies develop, a result that does not arise in studies using cross-section data.

Partly as a result of the diminishing MPE, we forecast annual emissions growth that averages 1.8 percent annually until 2025, compared with 3.2 percent between 1955 and 1985. Our forecasts are in many cases very close to the baseline forecasts obtained from the leading structural models (Nordhaus and Yohe [1983]; Manne and Richels [1992]; and Reilly *et al.* [1987]). In this respect, our research provides independent confirmation of those studies.

However, our results suggest several new aspects to the analysis of greenhouse gas emissions. First, our sensitivity analysis suggests that variations in the rate of economic growth do not lead to dramatic changes in $CO_2$ emissions. For example, a cumulative decline in GDP of 11 percent between 1990 and 2025 would yield only a four percent to six percent decline in cumulative $CO_2$ emissions. Second, our forecast emphasizes the changing global distribution of $CO_2$ emissions, and thus highlights the tension between policies toward $CO_2$ emissions and the global distribution of income. Most of the world's population is concentrated in countries for which incomes, population, and emissions are simultaneously increasing at the fastest rates. Rapid emissions growth among these nations tends to offset the slowing growth of emissions in wealthier nations.

The organization of the remainder is as follows. In the next section, we outline the empirical task, describe briefly the data brought to bear on the question, and describe our results. Section 3 contains forecasts of carbon dioxide emissions based on our estimates. The final section summarizes our findings and their implications.

## 2. EMPIRICAL ANALYSIS

### 2.1 Specification

The empirical goal is to estimate a relationship of the form:

$$c_{it} = f(y_{it}) + \varepsilon_{it} \tag{1}$$

where $c_{it}$ denotes per capita emissions of carbon dioxide, $y_{it}$ denotes per capita GDP, $i$ is a country index, $t$ is a year index, and $\varepsilon_{it}$ is a stochastic error term. A number of issues arise immediately concerning this reduced-form specification. Perhaps the most fundamental is the exclusion from equation (1) of explanatory variables other than per capita GDP. It is important in this regard to distinguish between excluded variables that are endogenous consequences of economic growth and those that represent exogenous differences. Examples of the former include the composition of output and consumption, regulations and taxes influencing fossil fuel consumption, and evolving patterns of urbanization and sub-urbanization. The essence of our approach is that such factors *should* be omitted from this simple model, as our objective is to assess both the direct and indirect consequences of growth.

Of course, there are also likely to be exogenous, country-specific factors that affect emissions. For instance, climate, geography, resource endowments, and land area vary widely among countries, and will likely be correlated with emissions. Factors of this type will likely cause the error terms in (1) to be correlated across all periods for each country, and pooled time-series and cross-section estimates that ignore this correlation will be inefficient. Moreover, if these omitted variables are correlated with per capita GDP, then cross-section estimates of (1) will yield biased and inconsistent results (Mundlak [1978], Hsiao [1986]). For instance, many of the wealthiest countries in our sample are located in regions with relatively higher heating needs. The resulting positive correlation between $y_{it}$ and the "country effect" would impart an upward bias to the emissions-income relationship estimated from a cross-section. Following standard practice, we exploit the long panel of data available by including fixed, country-specific effects in our estimation.

Similarly, there are likely to be exogenous factors shared by all countries in a given period, but which vary across time. One important example is world energy prices, which exert an influence on carbon fuel consumption and $CO_2$ emissions common to all countries. We control for this feature of the data by the inclusion of year-specific intercepts in each of our equations. At the same time, this technique should control as well for such global features as macroeconomic fluctuations and technological trends.

Another feature of equation (1) is that it links carbon dioxide emissions to contemporaneously-produced GDP. On an *a priori* basis, we can think of little justification for an explicitly dynamic relationship. Our instincts notwithstanding, however, our empirical analysis investigates the role of lagged values of $c_{it}$ and $y_{it}$, and serial correlation in $\varepsilon_{it}$.

The main focus of our analysis is an emissions function that is quadratic in levels:

$$c_{it} = \beta_o + \beta_1 y_{it} + \beta_2 y_{it}^2 + \gamma_t + f_i + \varepsilon_{it} \tag{2}$$

(where the $f_i$ and $\gamma_t$ are the fixed country and year effects discussed above), or quadratic in the natural logarithms of $c_{it}$ and $y_{it}$:

$$\ln c_{it} = \alpha_o + \alpha_1 (\ln y_{it}) + \alpha_2 (\ln y_{it})^2 + \gamma_t + f_i + \varepsilon_{it}. \tag{3}$$

Throughout the remainder of the paper, we refer to the specification in (2) as "levels" and that in (3) as "logs."

The unabashedly empirical spirit of the investigation dictates that we guard against mistakes in specification and estimation. Thus, in what follows we pay particular attention to:

Order of the Polynomial. Equations (2) and (3) are second-order polynomials in the level and logarithm of $y_{it}$, respectively. Is the omission of third -- or higher -- order terms unnecessarily restrictive? Put differently, does the curvature of the quadratic dictate the nature of our results? Below, we examine the sensitivity of the estimates to alternative specifications of the polynomial.

Serial Correlation. Given lags in adjustment to changes in income or other economic shocks, it is entirely plausible that there is serial correlation in the $\varepsilon_{it}$. While correlation among the residuals may not affect the consistency of our coefficient estimates, adjustments for serial correlation will increase their efficiency. We examine the estimated residuals for equations (2) and (3), and implement a generalized least squares approach to correct for any serial correlation that we detect.

Simultaneity Bias. One might conjecture that the direction of causality runs from emissions (or the underlying fossil fuel use) to production as well, resulting in a correlation between $y_{it}$ and $\varepsilon_{it}$. One scenario that generates simultaneity is when policies to control emissions create a feedback from $CO_2$ emissions to output. If above-average emission rates induce policymakers to implement controls that have the effect of scaling back production, a correlation between $\varepsilon_{it}$ and $y_{it}$ would result. While no widespread $CO_2$ emissions-control policies were in effect during our sample period, other fuel-efficiency policies may work in this way as well. More generally, one might envision a wide variety of factors that could affect fossil fuel use and thereby affect income. If so, standard fixed-effect estimators of the coefficients in (2) and (3) will be inconsistent. To check for simultaneity bias, we employ a modification of the instrumental variables estimator proposed by Holtz-Eakin, Newey, and Rosen [1988] (HNR). In this approach, current and lagged values of $y_{it}$ and $y_{it}^2$ are used as instrumental variables in the estimation of equations (2) and (3). Under the assumption that contemporaneous values of the right-hand-side variables are orthogonal to the error term, the estimates will be consistent and efficient. Simultaneity bias, however, would manifest itself as a violation of the orthogonality assumption, and the HNR technique generates a chi-square statistic to test this hypothesis.

Dynamics. As noted earlier, our specification contains no lagged values of $c_{it}$ or $y_{it}$, leading to the potential for misspecification. Note, however, that in these circumstances the excluded lagged variables are effectively grouped with the error term in our equation. By construction, then, the error term in the misspecified equation will be correlated with past values of the dependent and independent variables. As in the case of simultaneity bias, this circumstance will generate violations of the orthogonality conditions of the type that the HNR technique is designed to detect, and we employ it for this purpose below.

## 2.2 Data Sources

The $CO_2$ emissions data for this study were provided by the Oak Ridge National Laboratory (ORNL) [1992]. The data include emissions from aggregate fossil fuel consumption and cement manufacture. ORNL has constructed the cement emissions data from cement manufacturing data compiled by the U.S. Bureau of Mines.[2] The data on fossil fuel emissions are constructed by applying $CO_2$ emissions coefficients to the United Nations fossil fuel consumption data series, which controls for changes in the form of fuel, imports and exports of fuel, and changes in fuel stocks (ORNL [1989]).[3]

Measuring carbon dioxide emissions in this way omits the indirect consumption of the fossil fuels embodied in a country's net imports.[4] While such discrepancies are possible, there is reason to believe that they are not large. Poterba [1992] presents evidence that in the United States the fossil fuel content of imported goods in 1985 contributed less than 12 percent of U.S. fossil fuel related emissions. The *net* import component must surely be even less. Thus, while trade-adjusted fossil fuel consumption estimates would be preferable, it seems unlikely that percentages of emissions due to net exports vary enough over time for this to be an important source of misspecification.

The income and population data used in this study are drawn from the Penn Mark V World Tables in Summers and Heston [1991]. In particular, the income measure we use is the *RGDPCH* series on real per capita GDP. An advantage of this series is it uses a common approach to measuring prices and a common unit of currency, so that real comparisons can be made among countries and over time. One disadvantage is that our sample is limited to the countries for which this series is available -- the Summers and Heston series includes multiple observations for only 131 of the 197 countries and territories in the ORNL sample.

Moreover, income data is available for a broad range of countries only through 1986, which we therefore take as the last year of our sample.

We exclude Kuwait -- which is an outlier in all dimensions -- and obtain an uneven panel of data on 130 countries for the years 1951 to 1986. There is data for all years for 108 countries.[5] The sample contains 73.7 percent, on average, of global $CO_2$ emissions due to fossil fuels consumption (net of gas flaring) and cement manufacturing. Apart from emissions due to land use change, our analysis therefore embodies the predominant sources of $CO_2$ emissions. Summary statistics for the variables used in our analysis are presented in Table 1 for the year 1985.

## 2.3 Estimation Results

We begin by estimating equations (2) and (3), controlling for fixed year-specific and country-specific effects. Examination of the estimated residuals shows substantial first-order serial correlation, suggesting that the residuals follow the process:

$$\varepsilon_{it} = \rho\varepsilon_{it-1} + \mu_{it}. \tag{4}$$

In what follows, we correct each equation for serial correlation by estimating $\rho$ in equation (4) and using the result, $\hat{\rho}$, to quasi-difference (2) and (3).[6] Using these corrected versions of the equations, we obtain the estimation results presented in Table 2.

We next test for the existence of the country fixed effects. Not surprisingly, the hypothesis that all countries share the same intercept is rejected by a wide margin. Test statistics for each specification are shown in Table 2.

Finally, for completeness we test the hypothesis that all years in the sample have a common intercept. The test statistics (reported in the last row of the table) indicate that the data reject this constraint.

Consider the estimates presented in column (1) of Table 2, showing the quadratic emissions function when estimated in levels. Estimated emissions initially rise with per capita GDP (as the linear term is positive), but eventually fall (as the quadratic term is negative), with the turning point occurring at $35,428 per capita in 1986 U.S. dollars. Qualitatively, then, the estimates are consistent with an inverted U-shape for the emissions-output relationship. The log specification (shown in column (3)) yields qualitatively similar results over the sample range of incomes; the MPE is positive, but declining. Here the quadratic term is not statistically significantly different from zero, and the estimated turning point occurs at a very high level of per capita income -- above $8 million.

Taken at face value, the finding that $CO_2$ may eventually diminish as income rises is somewhat reminiscent of estimated relationships in the literature on emissions and income: suspended particulates and sulfur dioxide (Grossman and Krueger [1991]; Selden and Song [1992]), carbon monoxide and the oxides of nitrogen (Selden and Song [1992]), and the toxic intensity of industrial composition (Hettige, Lucas, and Wheeler [1992]). Unlike these other pollutants, however, the turning points estimated herein rely on the out-of-sample properties of our estimated functions. Within the sample, we observe only a stabilization of emissions, at best.

An important issue is whether the quadratic specification is appropriate. It is straightforward to rule out the presence of fourth-order terms in both equations as well as linearity in the levels equation. We retain the quadratic term in the logs model in part because it is strongly significant in the higher-order equations and in part because we believe that the nature of this modelling exercise argues against imposing monotonicity.

Less clear-cut is the choice between the quadratic and cubic models. Consider first the cubic term in the levels model in Table 2 (column 2). While this term is statistically significantly different from zero, its quantitative impact is small -- it has very little impact on the character of the regression. Turning to the cubic term in the logs model, it too contributes little to the explanatory power of the regression and is not precisely estimated. Although its confidence interval excludes zero at the ten percent level, it includes a range of values that translate into substantially different trajectories for emissions.

To gain a feeling for the estimates, we plot all four functional forms in the two panels of Figure 1, along with the actual levels, for two important emitters at opposite ends of the global income distribution: the United States and China.[7] All four curves share important similarities. First, in all cases the MPE is a diminishing function of per capita income within the range observed for the entire sample. Second, the shapes of the curves are all quite similar within the ranges of the data for each country. Nevertheless, there are important differences. Looking first at the cubic in levels curve, it has the unattractive out-of-sample property that the MPE begins to rise once income exceeds the inflection point at $28,010 -- though in practice the cubic in levels and quadratic in levels curves yield virtually indistinguishable global forecasts. Turning to the cubic in logs model, the downturn in emissions beyond $13,594 of per capita income has a larger effect on our forecasts, especially for upper-income countries in the outlying years. However, at a heuristic level we are uncomfortable forecasting rapid declines in the emissions of upper-income countries based on estimates with such wide confidence intervals.[8] Because the cubic curves have unattractive out-of-sample properties, and because they contribute so little to the explanatory power of the regressions, we focus our attention below on the quadratic models.

As noted at the outset, the use of panel data permits a richer econometric specification, and our statistical tests reveal significant country effects. Controlling for country effects is more than a statistical nicety: Figure 2 demonstrates that the inability to control for country effects leads to a very different view of the emissions-GDP relationship. Panels A and B display the estimated quadratic levels and logs functions for selected countries in our sample (derived using the estimates in Table 2), and compares these with the same functional forms estimated using cross-section data for 1986 alone.[9] A Figure 2 makes transparent, the country-specific effects serve to shift the $CO_2$-GDP locus in an important way. In a cross-sectional analysis, this leads to an upward bias in the estimates of the slope, or MPE.[10,11]

By improving our estimates of the MPE, the use of appropriate statistical techniques leads to a different view of the distributional aspects of emissions. Using the cross-section, the richest countries appear to have the greatest MPE; whereas the fixed effects estimates suggest that the reverse is true. In this sense, controlling for fixed effects results in estimates that appear more optimistic over the long-run than those obtained from cross-sectional analysis. However, even the fixed-effects models have the capacity to generate high growth rates for global emissions over the foreseeable future, because the most rapidly growing economies also have the greatest MPE.

As noted earlier, one concern is that the estimated equations are subject to inconsistency due either to simultaneity bias or to misspecification of the dynamic structure. If so, all the coefficient estimates (including our first-stage estimates of $\rho$) are inconsistent. Using the HNR testing procedure as a generic test of our specification, however, we cannot reject the null hypothesis of orthogonality.[12] Our specification, while relatively parsimonious, appears sufficiently rich to capture the GDP-driven determination of carbon dioxide emissions.

## 3. EMISSION FORECASTS

In this section we use the estimated relationships to construct forecasts of global emissions over the period 1986-2100 due to fossil fuel consumption and cement manufacturing. Given our approach, we feel that the forecasts are most useful over the "near term" (i.e., over the next several decades). As discussed further below, over longer horizons assumptions concerning trends in the emissions-GDP relationship ultimately dominate the forecast. Over the shorter period, however, our forecasts reveal the interplay between the likely pattern of global economic development and the growth and distribution of global $CO_2$ emissions.

### 3.1 Forecast Method

We begin by forecasting per capita GDP for each country in our sample. In constructing these forecasts, our main objective is to provide a plausible scenario for growth that incorporates the convergence in per capita GDP growth rates that has been observed by many researchers.[13] To achieve this, we pool our data and estimate the following flexible functional form:[14]

$$\ln(y_{it+1}) - \ln(y_{it}) = \alpha_{0t} + \alpha_1 \ln(y_{it}) + \alpha_2 [\ln(y_{it})]^2 + \tau_{it} \tag{5}$$

The results of this regression are reported in Appendix A, and the resulting curve is graphed in Figure 3. As Figure 3 demonstrates, we find a "take-off" to rapid growth, with the growth rate of per capita GDP peaking at 1.76 percent when per capita GDP is approximately $6,900 (in 1986 U.S. dollars). Beyond that point, growth rates diminish smoothly, so that at $30,000 of per capita GDP we forecast annual per capita income growth of only 1.30 percent. While we view this as a plausible scenario for the evolution of per capita GDP, we also construct scenarios in which growth is more rapid and slower. In these, per capita GDP growth rates are increased or decreased relative to the central case by 0.5 percentage points per annum.

Our population forecasts are taken from *Population Projections, 1992-93* (World Bank [forthcoming]). Like our per capita GDP forecasts, the population forecasts reflect decelerating growth rates in response to economic development, with highest growth rates typically found among the poorest countries. The "global" population growth rate (i.e., computed per annum for the countries in our sample) decelerates from 1.81 percent in 1986 to 1.58 percent in 2000, to 0.74 percent in 2050, and to 0.21 in 2100. Taken together, the per capita GDP and population forecasts generate uniformly decelerating annual growth rates for global GDP (again, computed for the countries in our sample). Starting in 1986, global GDP growth slows from 2.78 percent per year to 2.62 percent in 2000, to 1.89 in 2050, and to 1.42 in 2100.

In deriving forecasts over such a long period, one must inevitably confront the nature of the trends in the variables of interest. In our approach, this issue manifests itself as the need to "forecast" the year-specific intercepts. Such an undertaking exceeds the scope of this analysis. Instead, we construct our main forecasts by setting the year effect at its 1986 level, and then examine the sensitivity of our results to alternative assumptions.

### 3.2 Forecasts of Carbon Dioxide Emissions

Given the income and population forecasts, it is relatively straightforward to compute aggregate emissions for the 130 countries in our forecasting sample (using our country-specific fixed effects estimates). Moreover, the ratio of emissions from these countries to total global emissions has remained remarkably constant over the past three decades.[15] For this reason, we simply scale these forecasts up to the global totals using the 1986 ratio (71.8 percent) in order to facilitate comparisons with other forecasts.

The "Base Case" rows in Table 3 present our forecasts of global carbon dioxide emissions. The unambiguous message is that despite the diminishing MPE, continued future economic growth will cause rapid increases in aggregate $CO_2$ emissions. To understand how high emissions growth can arise, it is useful to decompose global emissions growth as follows. Let $C_{it} \equiv c_{it} n_{it}$ be the total emissions from country $i$ in year $t$, where $c_{it}$ is per capita emissions and $n_{it}$ is population. If global emissions are denoted by $C_t \equiv \Sigma_i C_{it}$, then one can easily derive the following identity:

$$\frac{\dot{C}_t}{C_t} = \sum_{i=1}^{N} s_{it} \left( \eta^i_{c,y} \frac{\dot{y}_{it}}{y_{it}} + \frac{\dot{n}_{it}}{n_{it}} \right) \tag{6}$$

where $\eta^i_{c,y} \equiv dln(c_{it}) / dln(y_{it})$ is the country-specific GDP elasticity of emissions, $s_{it} \equiv C_{it} / C_t$ is the country's share of global emissions, $\dot{y}_{it} / y_{it}$ is the country's per capita income growth rate, and $\dot{n}_{it} / n_{it}$ is the country's population growth rate. (The superscript "•" denotes derivative with respect to time.) Given the skewed distribution of global income, a large percentage of the world's population is located in economies experiencing the most rapid rates of income and population growth. (Indeed, countries with per capita GDP below $6,900 are forecast to experience accelerating per capita GDP growth.) From our emissions-GDP relationships, these countries also have the greatest emissions elasticities. As these countries' shares of total emissions grow, the result is continued rapid global emissions growth. In sum, while the inverted-U shape of the estimated emissions function gives hope that one could *eventually* "outgrow" the emissions problem, as a practical matter the next section illustrates that this effect does not come into play in the foreseeable future.

### 3.3 Sensitivity Analysis

How sensitive are future $CO_2$ emissions to economic growth? The remaining rows of Tables 3 show the sensitivity of our forecasts to faster and slower rates of GDP growth. Consider the line for "Faster Per Capita GDP Growth" in Table 3. To compute this, in each year (and for each country) we add 0.005 to the per capita GDP growth rate predicted by equation (5). Since the resulting higher level of GDP feeds back into future growth, this does not translate directly into a 0.5 percentage point increase in economic growth. Under this scenario, for example, world GDP is 21.1 percent higher in 2025, while cumulative GDP between 1990 and 2025 is 13 percent higher. (Simulations for slower economic growth are computed in a symmetric fashion.)

Not surprisingly, the results in Table 3 indicate that both our levels and log equations forecast higher carbon dioxide emissions as a result of faster growth. Focusing for the moment on the year 2025, the levels equation suggests that faster growth will raise $CO_2$ emissions by roughly 11 percent. The log equation indicates a similar impact. It is clear that more rapid growth does not "solve" the emissions problem. More rapid growth simply causes emissions to rise, while slower growth causes emissions to fall. From a climatic perspective, however, the annual flow of emissions is less important than the cumulative emissions into the atmosphere. Table 4 looks at the impact from this perspective. Again focusing on 2025 as an example, the forecast indicates that cumulative emissions after 1990 will rise, relative to the base case, by between four percent (in the log version) and six percent (in the levels version).

The results for slower growth are comparable. Reducing the pace of economic growth according by the method of our simulation lowers the flow of carbon dioxide emissions by approximately nine percent in 2025 (Table 3), with a cumulative effect of between four and six percent lower $CO_2$ by 2025 (Table 4). The output cost of such a change is that GDP is 17.6 percent lower in 2025, and the cumulative foregone output totals to 11.3 percent of the baseline output between 1990 and 2025. Thus, while changes in the rate of per capita economic growth as large as 0.5 percentage points have an effect on carbon dioxide emissions, the effect seems relatively modest.

As another way to see this, consider the final column of Table 4. The entries in this column, labelled $\tilde{T}$, indicate the year in which cumulative emissions reach the level in the year 2050 under the baseline forecasts. (Thus, $\tilde{T}$ is definitionally equal to 2050 for the baseline forecasts.) As the table indicates, slower growth "defers" the accumulation of $CO_2$ emissions by only a few years: five in the levels equation and four in the log version.

In addition to exploring the sensitivity of our forecasts to changes in the pace of economic development, it is also of interest to explore alternative assumptions concerning the evolution of the year-specific intercepts. As mentioned above, in our central forecasts we fix the year effect at its estimated level in the last year of the sample. In doing so, we explicitly rule out any effects associated with changes in fossil fuel prices or technological progress (apart from those which are embodied in our GDP forecasts).

With regard to changes in fossil fuel prices, a general increase in fossil fuel prices due to reserve depletion would restrain demand and clearly cause $CO_2$ emissions to be lower than we forecast. However, total fossil fuel reserves are large, even relative to the consumption our model predicts.[16] Moreover, the fossil fuels that are likely to experience the sharpest price increases (e.g., petroleum) also tend to have the lowest emissions per unit of energy. Thus, prices might even evolve in a manner that causes an increase in emissions, rather than a decline.

With regard to technological change, it seems quite reasonable that some innovations would take the form of increased energy efficiency, allowing a given level of global GDP to occur at lower levels of emissions. However, technological breakthroughs can also take the form of reducing the costs of extracting fossil fuels, or offering new ways to benefit from their consumption. Thus, neither the magnitude, nor even the sign of such change can be predicted with any confidence.

Given our *a priori* uncertainty concerning the impact of changes in prices and technology on future emissions, it is useful to consider the sensitivity of our results to alternative assumptions concerning the year effects. In particular, our strategy is to use our estimates of the year-specific intercepts to gain an insight into the potential range of variation one might expect in the future. One way to use this information is simply to compute the trend implicit in the estimated year effects, thereby enabling one to extrapolate these influences into the future. Perhaps not surprisingly, the estimated trend is sensitive to the period used for estimation and typically has large standard errors.[17] Thus, we pursue two alternative methods.

In the first, we gauge the impact of trend growth in the year effects. To do so, we compute the standard deviation of the year effects, $\sigma_\delta$. Next, we assume that the year effect at the end of our forecast period (2100) is, alternatively, higher or lower by two standard deviations ($2\,\sigma_\delta$). We "forecast" the intervening values for the year effects by assuming the year effect equals its actual value in the first year, but rises linearly to $2\,\sigma_\delta$ (or falls linearly to $-2\,\sigma_\delta$) by 2100. In the second sensitivity test, we use the same intercept in each year of the forecasts, but we alternately replace the 1986 value with the minimum and maximum of the estimated intercepts from the period 1970-86.[18]

The results of these two approaches are presented in Tables 3 and 4. Clearly, changes in the year effects that are reasonable from a historical perspective would have quantitatively important implications for our forecasts. This is particularly true if the full impact of the shock is felt in the first period of the forecast, as in our "Upward Shift" and "Downward Shift" scenarios. Nevertheless, in none of the cases is the pace of cumulative emissions dramatically affected (see the values of $\widetilde{T}$ in Table 4). That is, if one considers the cumulative emissions as of 2050 in the baseline scenarios of both the levels and logs models, note that these levels are always reached prior to 2064, even in the slowest scenarios, and no earlier than 2040, even in the fastest scenarios.

Our tentative conclusion is that fuel price changes or technological innovations within the historic range should not unduly affect the accumulation of $CO_2$ that we forecast. Indeed, this conclusion regarding fuel prices echoes findings by other researchers that $CO_2$ accumulation can be slowed only by taxes that are large relative to historic fossil fuel prices (e.g., Nordhaus and Yohe [1983, p.98]).

### 3.4 Comparison with Other Forecasts

Figure 4 graphs our levels and log forecasts along with the baseline forecasts from three well-known models: Nordhaus and Yohe [1983], Manne and Richels [1992], and Reilly *et al.* [1987].[19] All five forecasts present essentially the same picture. Given the very different method that we use to construct these forecasts, we interpret our findings as offering independent confirmation of these more structural, yet in some sense less "data-driven," approaches. In contrast, forecasts based on naive extrapolation yield substantially higher forecasts (Nordhaus and Ausabel [1983] survey this literature). We find it interesting that by simply keeping track of the interactions between income, population, and emissions, it is possible to construct extrapolations that very nearly approximate the findings of the more structural models, at much lower analytic cost.

### 3.5 Changes in the Global Distribution of $CO_2$ Emissions

Because our model embodies the historic development trajectory, we feel our approach offers particular insight into the distributional features of future $CO_2$ emissions. The changing shares of global $CO_2$ emissions can be clearly seen in Figure 5, which shows the percentage shares of total emissions that we forecast for the bottom two quintiles, the third and fourth quintiles, and the top (fifth) quintile of the global income distribution.[20] As the discussion above suggests, the third and fourth quintiles constitute the main source of global emissions growth in the early decades of the forecast, with the first and second quintiles playing a growing role in the subsequent decades. While emissions growth rates are highest among the poorest countries, their initial shares are very small. As a result, their contribution to overall growth is low until the relatively distant future. This pattern is particularly evident in the levels forecasts, where the rapidly diminishing MPE causes the top quintile's share of global emissions to fall below that of the third and fourth quintiles.

We urge caution in interpreting these results. In particular, the results do not necessarily imply that international efforts to reduce emissions should be targeted at slowing emissions growth in the countries with the most rapid growth. Efficiency concerns demand instead that reductions occur where the marginal abatement cost is lowest, while equity concerns would suggest that the burden be borne disproportionally by those most able to pay. Indeed, the results in Figures 5 raise a note of caution that any abatement mechanism linked to contemporaneous emissions would likely impose disproportionate burdens on the developing nations.

## 4. SUMMARY AND IMPLICATIONS

In this paper we present estimates of the relationship between $CO_2$ emissions and GDP derived from panel data, and use these estimates to forecast global emissions. Our estimates and forecasts yield four major results. First, the evidence suggests a diminishing marginal propensity to emit $CO_2$ as economies develop -- a result masked in analyses that rely on cross-section data alone. Second, despite the diminishing MPE, our forecasts indicate that global emissions of $CO_2$ will continue to grow at an annual rate of 1.8 percent, comparable to other leading forecasts of $CO_2$. Third, the source of continued growth is the fact that economic and population growth will be most rapid in the lower-income nations that have the highest MPE. For this reason, there will be an inevitable tension between policies to control greenhouse gas emissions and those toward the global distribution of income. Finally, our sensitivity analyses suggest that the overall pace of economic development does not dramatically alter the future annual or cumulative flow of $CO_2$ emissions.

## Notes

1. See the *World Development Report* [1992] and the background paper for this report by Shafik and Bandyopadhyay [1992]

2. Cement-related emissions are approximately two percent of the total in each year.

3. Because gas flaring is an activity more closely associated with production of fuel than its consumption, we have netted this out of our dependent variable. In any event, gas flaring only represents approximately one percent of total emissions.

4. For instance, if country *A* consumes goods produced using fossil fuels in country *B*, the $CO_2$ emissions would be credited to country *B*. It would perhaps be preferable to credit such emissions to country A, though this need not pose an undue problem for our aggregate forecasts.

5. Because of changes in political boundaries one must reconcile a few inconsistencies between the series on income and that for $CO_2$. First, we add the $CO_2$ emissions of the Ryukyu Islands to Japan's total for the years prior to 1972 (the year that the islands were incorporated into Japan). Second, we exclude East and West Pakistan through 1971, but include Bangladesh and Pakistan separately after 1971. Third, we combine the emissions of Peninsular Malaysia, Sarawak, and Sabah prior to their unification in 1969 (but we exclude from our sample the combined emissions reported for Malaysia-Singapore prior to 1957). Fourth, we combine the emissions of Panama (excluding the Canal Zone) with those of the Canal Zone. Fifth, we combine the emissions of Tanganyika and Zanzibar prior to their unification in 1969. Finally, we concatenate the series for Zimbabwe and Rhodesia-Nyasaland.

6. The remaining autocorrelation among the residuals from the quasi-differenced model is negligible, suggesting that this is the appropriate correction.

7. To construct these figures, we have used the mean of the year effects estimates for the years during which data was available for use in the estimation. Triangles denote (approximately) duplicate values. Note that the scales in the two figures differ.

8. For instance, increasing the point estimate for $\alpha_3$ by its standard deviation results in a a turning point of nearly $21,000.

9. An example of such cross-sectional results can be found in the *World Development Report* [1992]. Also, the background paper for that report, by Shafik and Bandyopadhyay [1992], presents pooled time series and cross-section results for the ORNL data.

10. We chose 1986 for purposes of exposition alone. The substantive points are not sensitive to the year chosen.

11. Indeed, close examination of Figure 2-B shows that the two approaches may even yield second derivatives with different signs.

12. To implement the HNR method, we quasi-difference to eliminate serial correlation in $\varepsilon_{it}$, moving the lagged emissions term to the right-hand side:

$$c_{it} = \beta_0(1-\rho) + \rho c_{it-1} + \beta_1(y_{it} - \rho y_{it-1}) + \beta_2(y_{it}^2 - \rho y_{it-1}^2)$$
$$+ (\gamma_t - \rho\gamma_{t-1}) + f_i(1-\rho) + \mu_{it}.$$

We then first-difference, thereby eliminating the fixed nation-effects:

$$\Delta c_{it} = \rho\,\Delta c_{it-1} + \beta_1(\Delta y_{it} - \rho\,\Delta y_{it-1}) + \beta_2(\Delta y_{it}^2 - \rho\,\Delta y_{it-1}^2)$$
$$+ (\Delta\gamma_t - \rho\,\Delta\gamma_{t-1}) + \Delta\mu_{it},$$

and estimate the resulting equation using instrumental variables to accommodate the correlation between $\Delta c_{it-1}$ and $\Delta\mu_{it}$. In our application, we choose as instrumental variables $y_{it}$ and $y_{it}^2$, as well as first and second lags of these variables. We then estimate the parameters of the equation under the null hypothesis that these instrumental variables are orthogonal to the error term. If GDP and emissions are simultaneously determined, this will be manifested as a correlation between contemporaneous and lagged values of $y_{it}$, $y_{it}^2$ and $\mu_{it}$. Similarly, if the correct specification of the underlying relationship contains additional lagged values of $c_{it}$, $y_{it}$, or $y_{it}^2$ these also will be correlated with the instrumental variables. The test statistics, each distributed as a chi-square with 22 degrees of freedom, are 29.6 and 31.4 for the levels and log specifications, respectively.

13. The idea of convergence is by no means uncontroversial. Baumol [1986] and Mankiw, Romer, and Weil [1992] argue that the data support convergence. However, DeLong [1988] critiques the method used by Baumol, while Barro [1991] argues that the international data used by Mankiw, Romer, and Weil are inconsistent with the convergence hypothesis. Levine and Renelt [1992] argue that the cross-country regressions are too sensitive to specification difference to resolve the issue.

14. The inclusion of the quadratic term permits us to accommodate the empirical significance of "basket case" countries that do not experience rapid growth despite their very low income per capita.

15. Between 1962 and 1986, the percentage of global emissions contained in the sample varies within a very narrow range, from 71.7 percent to 73.9 percent, tending to decline over the period. The one exception is 1973, when the sample only contains 67.7 percent of global emissions. We speculate that this value results from the OPEC shock. The Eastern bloc nations are relatively under-represented in our sample, yet they also escaped the main impact of the OPEC price hike.

16. Cline [1992] surveys the literature on fossil fuel supply, concluding that "there should be at least 7,000 gigatons of carbon (GtC) available from coal at moderate prices, and 14,000 gigatons of carbon available at prices still below levels that hold emissions to low levels" (page 45) (i.e., 80 percent of the 1990 rate). Both numbers are well in

excess of the cumulative emissions from all sources that we forecast for the next century.

17. For instance, using all of the year effects produces an upward-sloping trend (with coefficient estimates that are significantly different from zero). In contrast, if one believes that there was a change of regime in 1973 and includes only the year effects starting in that year, the point estimate of the trend is negative, but has wide confidence intervals and is not significantly different from zero.

18. These minimum and maximum values might be viewed as capturing at least some of the impact of the oil shocks, insofar as the minimums occur in 1981 (levels model) and 1974 (logs model), while the maximums occur in 1979 (levels model) and 1978 (logs model). While not exact, this corresponds, with short lags, to oil price peaks in 1973 and 1979.

19. See also Edmonds and Reilly [1983].

20. Quintiles were constructed by ranking the total global population in 1986 by the mean per capita GDP in the country in which each individual resided. No attempt was made to readjust quintiles in each year to reflect differences in population growth rates.

TABLE 1

Summary Statistics[a]

| Variable | Mean | Standard Deviation |
|---|---|---|
| Per Capita Emissions ($c$) (Metric Tons of Carbon) | .944 | 1.349 |
| Per Capita GDP ($y$) (1986 U.S. Dollars) | $4,343 | 4,292 |
| Population ($n$) (Millions) | 33.471 | 115.495 |

| | |
|---|---|
| Number of Countries in Sample | 130 |
| Number of Complete Time Series | 108 |
| Percentage of Global Fossil Fuel and Cement Emissions (net of Gas Flaring) Included in Sample[b] | 73.7 |
| Percentage of Total Anthropogenic $CO_2$ Emissions from All Sources Included in the Sample[c] | 47.9 |

[a]Computed for 1985, the last year of the sample for which there is a complete cross section of countries.
[b]Average for the period 1951-1986.
[c]Computed for 1987 (Source: World Resources [1991]). Other sources of emissions can be grouped under the rubric of land use change.

TABLE 2

Estimated Emissions Functions

| | Levels | | Logs | |
|---|---|---|---|---|
| | Quadratic | Cubic | Quadratic | Cubic |
| $\beta_o$ | .31797* | .20744 | -.40682** | -.42628** |
| | (.18224) | (.18319) | (.17531) | (.17469) |
| $\beta_1$ | .15212*** | .21420*** | .52037*** | .55078*** |
| | (.013671) | (.02452) | (.05039) | (.05057) |
| $\beta_2$ | -.002152*** | -.00714*** | -.02895 | .115149*** |
| | (.00034) | (.00167) | (.01949) | (.03416) |
| $\beta_3$ | --- | .000085*** | --- | -.05637*** |
| | | (.00002789) | | (.01099) |
| $R^2$ | .759 | .759 | .842 | .843 |
| *OBS* | 3754 | 3754 | 3754 | 3754 |
| $F$ ($\underline{f}=\underline{0}$) | 33.68*** | 33.78*** | 22.58*** | 21.65*** |
| $F$ ($\underline{\gamma}=\underline{0}$) | 2.43*** | 2.32*** | 5.34*** | 5.21*** |

*** Significantly different from zero at .01 level.
** Significantly different from zero at .05 level.
* Significantly different from zero at .10 level.

TABLE 3: Global Emissions Forecasts and Sensitivity Analysis

Annual $CO_2$ Emissions (Gigatons of Carbon)

| YEAR | 1985* | 1990 | 2000 | 2025 | 2050 | 2075 | 2100 |
|---|---|---|---|---|---|---|---|
| Quadratic in Levels | | | | | | | |
| Base Case | 5.5 | 5.9 | 7.0 | 10.2 | 13.8 | 17.5 | 21.1 |
| Faster Per Capita GDP Growth | 5.5 | 6.0 | 7.3 | 11.3 | 16.0 | 20.3 | 22.1 |
| Slower Per Capita GDP Growth | 5.5 | 5.9 | 6.8 | 9.2 | 11.6 | 14.0 | 16.5 |
| Upward Trend in $CO_2$ Emissions | 5.5 | 6.0 | 7.2 | 11.0 | 15.4 | 20.1 | 24.6 |
| Downward Trend in $CO_2$ Emissions | 5.5 | 5.9 | 6.8 | 9.4 | 12.1 | 14.9 | 17.6 |
| Upward Shift in $CO_2$ Emissions | 5.5 | 7.2 | 9.0 | 13.0 | 17.1 | 21.2 | 25.0 |
| Downward Shift in $CO_2$ Emissions | 5.5 | 4.7 | 5.0 | 7.4 | 10.4 | 13.8 | 17.2 |
| Quadratic in Logs | | | | | | | |
| Base Case | 5.5 | 6.4 | 7.7 | 10.5 | 13.0 | 15.2 | 17.2 |
| Faster Per Capita GDP Growth | 5.5 | 6.5 | 7.9 | 11.3 | 14.4 | 17.3 | 20.0 |
| Slower Per Capita GDP Growth | 5.5 | 6.4 | 7.5 | 9.8 | 11.6 | 13.1 | 14.5 |
| Upward Trend in $CO_2$ Emissions | 5.5 | 6.5 | 8.0 | 12.0 | 16.3 | 20.9 | 26.1 |
| Downward Trend in $CO_2$ Emissions | 5.5 | 6.4 | 7.4 | 9.2 | 10.3 | 11.0 | 11.4 |
| Upward Shift in $CO_2$ Emissions | 5.5 | 7.3 | 9.2 | 12.6 | 15.6 | 18.2 | 20.7 |
| Downward Shift in $CO_2$ Emissions | 5.5 | 5.7 | 6.6 | 9.0 | 11.1 | 12.9 | 14.7 |

* Actual Emissions (Oak Ridge National Laboratories [1992]).

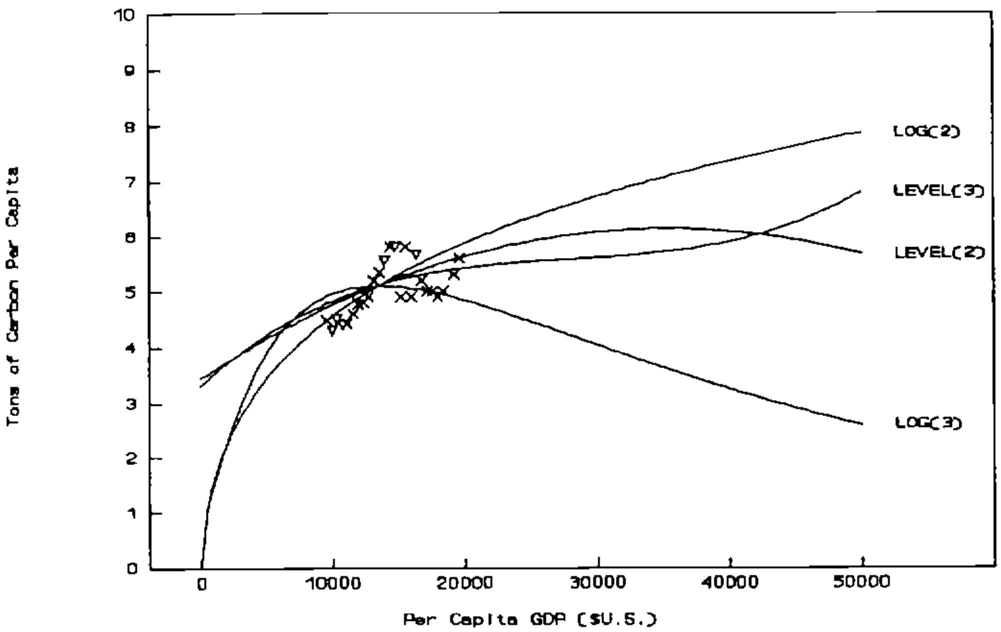
TABLE 4: Cumulative Emissions after 1990 (Gigatons of Carbon)

| YEAR | 2000 | 2025 | 2050 | 2075 | 2100 | $\tilde{T}$ * |
|---|---|---|---|---|---|---|
| Quadratic in Levels | | | | | | |
| Base Case | 65.3 | 281.2 | 581.8 | 973.2 | 1,458.0 | (2050) |
| Faster Per Capita GDP Growth | 66.9 | 299.1 | 641.2 | 1097.1 | 1,635.0 | 2047 |
| Slower Per Capita GDP Growth | 63.7 | 264.2 | 524.6 | 844.1 | 1,226.0 | 2055 |
| Upward Trend in $CO_2$ Emissions | 66.3 | 294.1 | 625.4 | 1,070.3 | 1,632.1 | 2048 |
| Downward Trend in $CO_2$ Emissions | 64.3 | 268.2 | 538.0 | 876.1 | 1,283.9 | 2054 |
| Upward Shift in $CO_2$ Emissions | 82.4 | 358.3 | 735.6 | 1,215.2 | 1,795.0 | 2041 |
| Downward Shift in $CO_2$ Emissions | 48.0 | 203.2 | 426.2 | 728.6 | 1,117.4 | 2064 |
| Quadratic in Logs | | | | | | |
| Base Case | 71.7 | 301.2 | 596.2 | 948.2 | 1,354.0 | (2050) |
| Faster Per Capita GDP Growth | 73.1 | 314.5 | 636.9 | 1,033.3 | 1,500.1 | 2048 |
| Slower Per Capita GDP Growth | 70.4 | 288.3 | 557.0 | 866.3 | 1,212.6 | 2054 |
| Upward Trend in $CO_2$ Emissions | 73.5 | 324.9 | 679.7 | 1,144.5 | 1,733.0 | 2045 |
| Downward Trend in $CO_2$ Emissions | 70.0 | 279.6 | 525.1 | 791.9 | 1,071.9 | 2057 |
| Upward Shift in $CO_2$ Emissions | 84.7 | 360.0 | 714.0 | 1,136.4 | 1,623.3 | 2043 |
| Downward Shift in $CO_2$ Emissions | 62.1 | 258.2 | 510.1 | 810.7 | 1,157.2 | 2058 |

* $\tilde{T}$ = Year in which cumulative emissions first exceeds the cumulative base case emissions as of 2050.

FIGURE 1: Actual and Fitted Values for the Four Functional Forms
(Duplicate values indicated by "▿")

A. United States




B. China

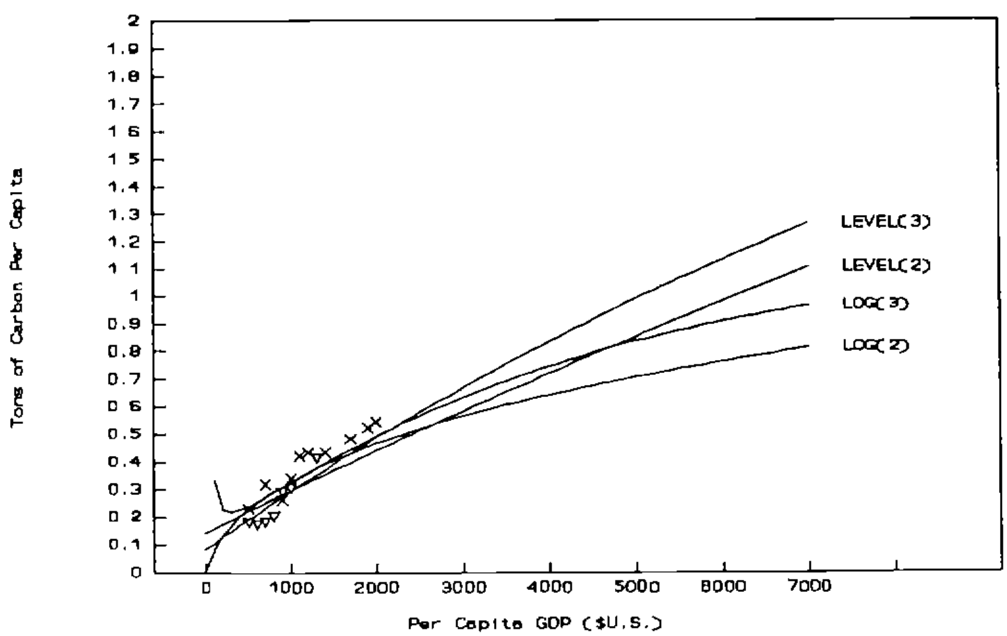
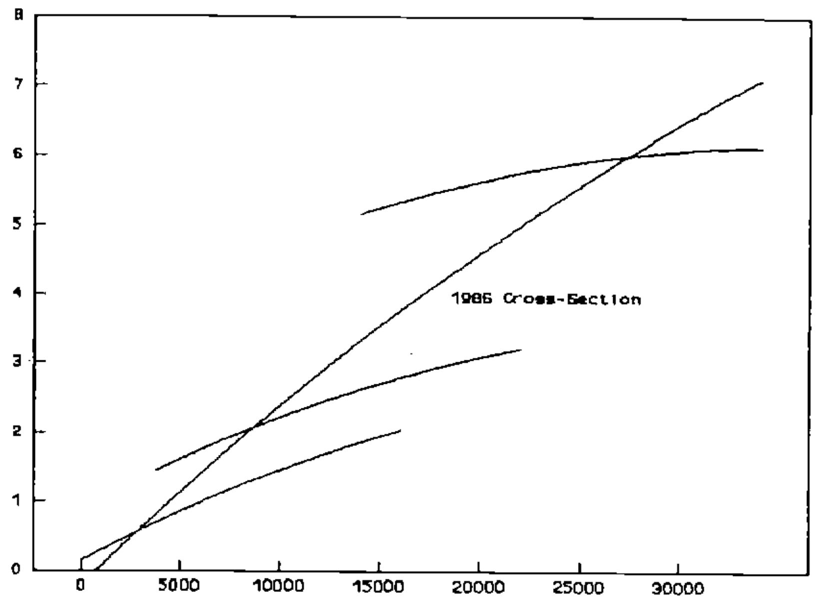


FIGURE 2: 1986 Cross Section Versus Fixed-Effect Estimates

A. Quadratic in Levels




B. Quadratic in Logs

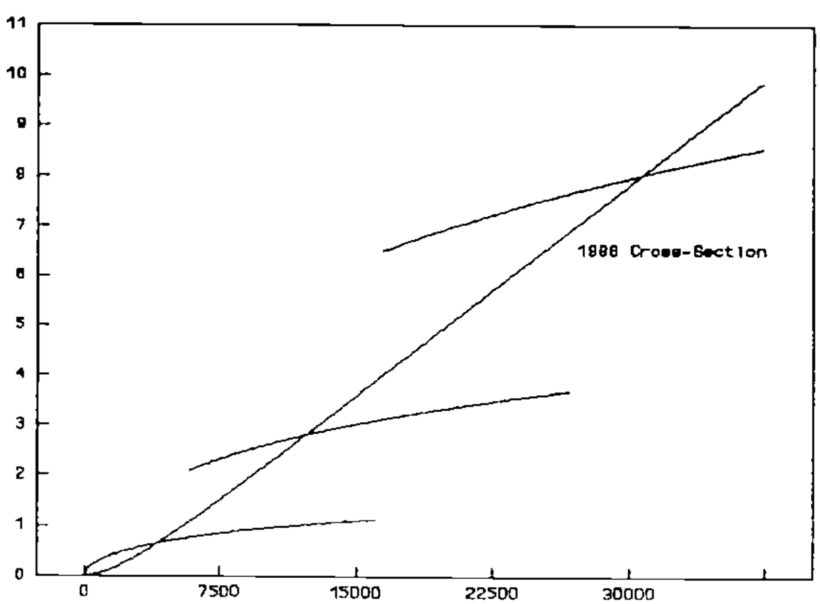


FIGURE 3: Per Capita GDP Growth Rate Forecasts

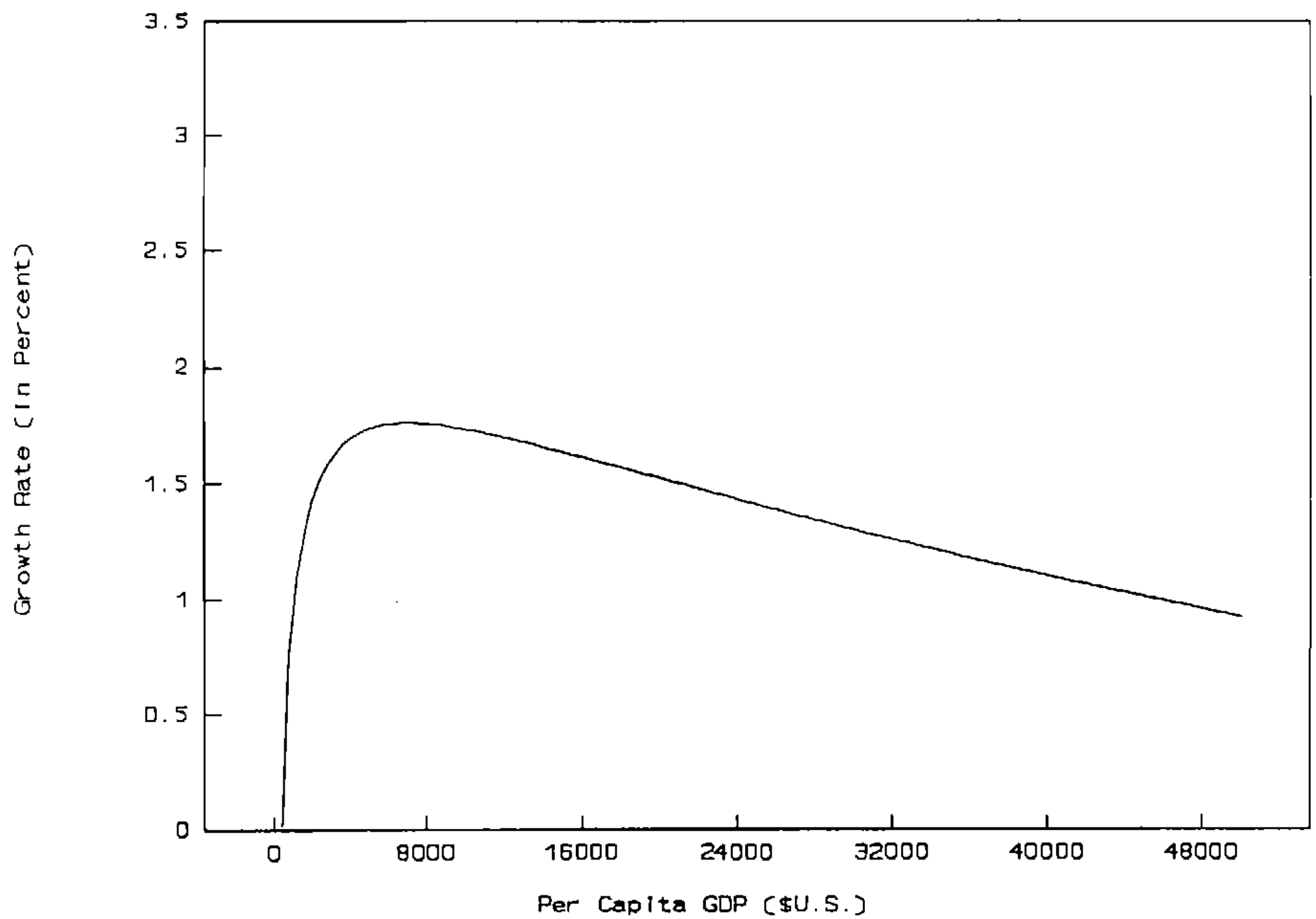
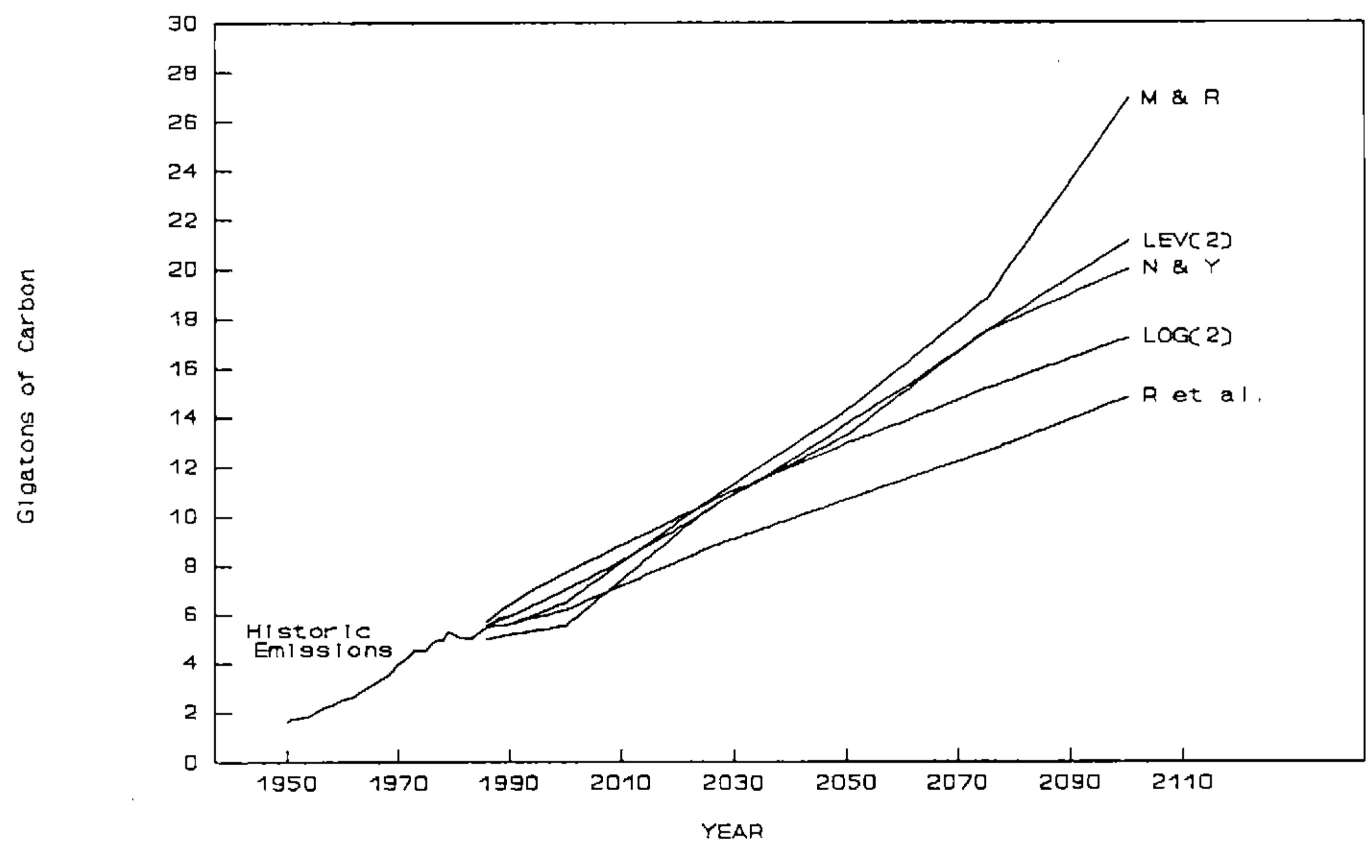


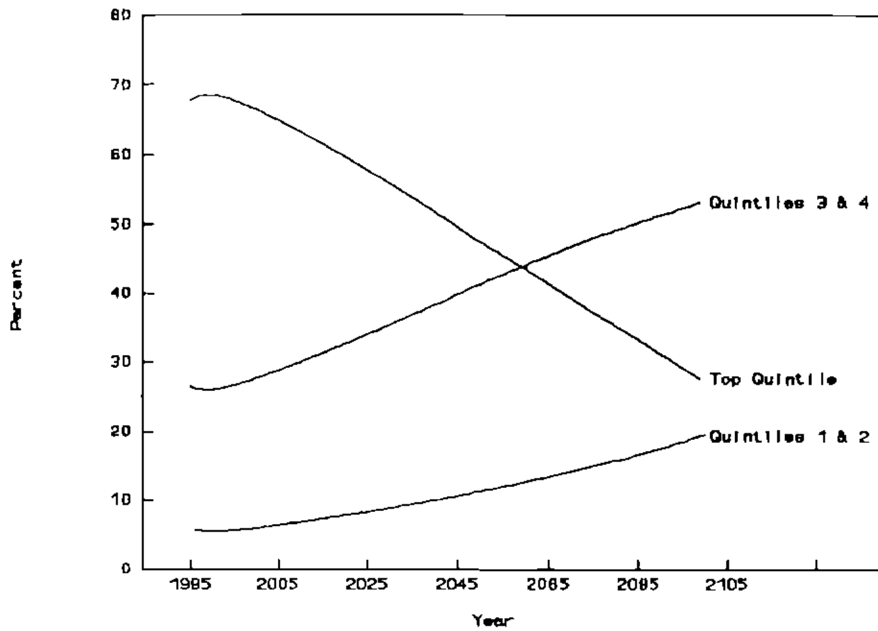
FIGURE 4: A Comparison of Global $CO_2$ Forecasts



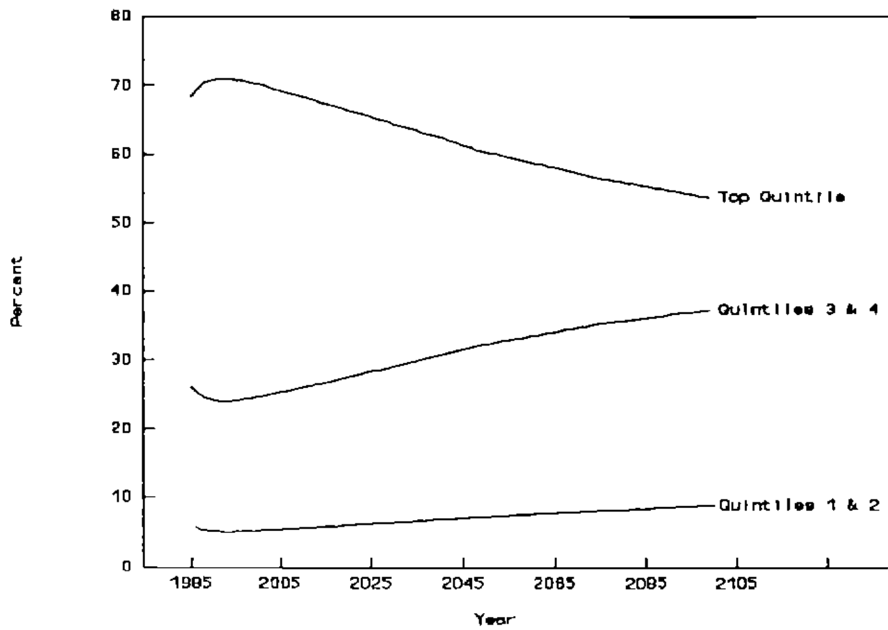

Sources: Nordhaus and Yohe [1983], Reilly *et. al* [1987], and Manne and Richels [1992].

FIGURE 5: Shares of Global $CO_2$ Emissions, by Quintile

A. Quadratic in Levels




B. Quadratic in Logs



APPENDIX A

Per Capita GDP Growth Rate Curve

| | $\ln(1 + \dot{y}_t)$ |
|---|---|
| INTERCEPT* | .01783*** (.00604) |
| $\ln(y_t)$ | .00822*** (.00186) |
| $\ln(y_t)^2$ | -.00212** (.00096) |
| $\ln(n_t)$ | -- |
| $F(\delta_{ot} = \delta_o)$ | 5.89 |
| $R^2$ | .056 |
| $DW$ | 1.76 |
| $OBS$ | 3719 |

*Computed as $\Sigma \hat{\delta}_{ot} / T$

***Significantly different from zero at .01 level.

**Significantly different from zero at .05 level.

*Significantly different from zero at .1 level.

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