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Carbon emissions and economic development: future trajectories based on historical experience

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ABSTRACT: This paper estimates the historic relationship between carbon emissions and GDP using data across countries and across time. We combine this relationship with plausible projections for GDP and population growth to construct a model that offers insights into the likely path of global emissions in the next century. In addition, we experiment with a method for incorporating oil prices into the model. Our analysis provides independent confirmation of the business-as-usual forecasts generated by the larger structural models.

1. Introduction

Carbon dioxide, the primary and best-studied greenhouse gas, has increased in atmospheric concentration by about 30 per cent from the start of the industrial revolution to 1992, a rise that is primarily attributable to fossil fuel combustion and changes in land use.[1] There is a growing consensus regarding the adverse climatic effects of anthropogenic emissions, with the Intergovernmental Panel on Climate Change (IPCC, 1996a) stating for the first time that 'the balance of evidence suggests that there is a discernible human influence on global climate'. Given the high stakes of global climate change, the international community has turned its attention toward forging a response.

Reliable baseline forecasts of carbon emissions are critical to the formation of sound global policy with respect to greenhouse emissions. A variety of forecasting methods exist. At one end of the spectrum are time-series models that essentially extrapolate from historical global emissions totals (e.g., JASON, 1979) or models that distribute a fixed total quantity of carbon emissions across time (e.g., Rotty, 1979). At the other end of the

No official endorsement of the views in this paper by any agency of the U.S. government is intended or should be inferred.

[1] See, for instance, Intergovernmental Panel on Climate Change (1996a).

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spectrum are structural models that seek to capture the underlying supply and demand relationships driving global emissions. For instance, see IPCC (1992) and the references cited therein.

This paper focuses on an intermediate approach, developed by Holtz-Eakin and Selden (HES, 1995), in which panel data estimates of the historic relationship between per capita carbon emissions and per capita gross domestic product (GDP) are combined with projections for GDP and population growth to generate scenarios for global carbon emissions.[2] In essence, the approach hypothesizes the existence of a common carbon–GDP development trajectory that can be used to construct scenarios for future emissions. While structural models provide valuable frameworks for evaluating mitigation policies, the strength of the HES approach lies in its simplicity in capturing what we believe to be the primary forces, as proxied by GDP, that underlie baseline carbon emissions. To date, the model has a strong track record. Heil and Selden (1996) examine the accuracy of its baseline predictions between 1985 (the last year for which HES had data) and 1992, finding a mean absolute percentage error of only 1.4 per cent for the quadratic in levels model.

In addition to examining the relationship between carbon emissions and GDP, another objective of this paper is to investigate the effect on carbon emissions of global fossil fuel prices. The period of analysis was one of considerable volatility for fossil fuel prices, and Moomaw and Unruh (1997) argue that global energy price increases after the 1973 oil price shock may have had an important effect on emissions. To incorporate the effects of energy price changes into our model, we use Hanushek's (1974) method to regress the estimated year effects from the emissions–GDP model on global energy prices as proxied by the price of oil delivered to US refiners. We then use this subsidiary equation to consider the impact on global carbon emissions of alternative assumptions regarding energy prices.

We find that per capita carbon emissions are monotonically increasing in per capita GDP in the sample range, exhibiting a diminishing marginal propensity to emit. Outside the sample range, per capita emissions rise monotonically in our logarithmic model, whereas they exhibit an inverted-U shape in the levels model, turning down at $36,044 in per capita GDP. Although a large number of higher-income countries eventually pass the turning point in the levels model, rapid income and population growth among the lower-income countries, combined with their high marginal propensity to emit, leads to high emissions forecasts in both models throughout the twenty first century. Projected emissions are quite similar to the IPCC IS92a reference case forecast.

Finally, while higher oil prices tend to reduce carbon emissions, this relationship is only statistically significant in our levels model, not the logarithmic model. Moreover, the magnitude of this effect is small. This should not be interpreted as evidence that increased within-country energy prices would have little impact on carbon emissions. Our global oil

[2] HES in turn build on the forecasting method in Selden and Song (1994). For other related analyses of carbon–GDP trajectories, see also Schmalensee, Stoker and Judson (1995) and Moomaw and Unruh (1997).

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price measure is only imperfectly correlated with domestic energy prices, due to the wide range of energy taxes, subsidies, and other distortions that many countries impose.[3] Nevertheless, our results suggest that scarcity-driven global energy price increases are unlikely to slow global emissions growth in the foreseeable future—apart from any effect that such prices changes might have on GDP.

The next section presents our methodology. The third section presents our data sources and the results of specification tests. The fourth section presents our estimates of the carbon–GDP relationship. The fifth section presents our forecasts, and the sixth concludes the paper.

2. Methodology

A growing body of research examines the relationship between economic activity and environmental quality.[4] One salient result is that this relationship varies according to the pollutant in question. Some pollutants eventually decline with growing income—especially those with significant local impacts and relatively low abatement costs. In contrast, carbon emissions appear to increase monotonically within the range of income observed to date (Shafik, 1994; HES, 1995; and Schmalensee, Stoker and Judson, 1995).

In this paper, we use panel data to estimate

$$c_{it} = \beta_0 + \beta_1 y_{it} + \beta_2 y^2_{it} + \gamma_t + f_i + \epsilon_{it} \quad (1)$$

c_{it} = per capita carbon emissions
y_{it} = per capita real GDP
γ_t = fixed year effects
f_i = fixed country effects

where t and i are year and country indexes, respectively. Essentially, in estimating a model of this form we are assuming that the overlapping development experiences of the 135 countries we observe can be combined to form a common development trajectory (albeit with individual country and year intercepts). This relationship can then be used to predict carbon emissions, conditional on per capital GDP. The resulting emissions scenarios help to answer the question of how global emissions would evolve if countries were to follow this common development path in a business-as-usual scenario.

The model encompasses several important features. First, the model's sole regressor, per capita GDP, is best interpreted as a proxy for a range of factors that may be related to carbon emissions. Thus, the effect of per capita GDP may combine both the overall scale effects of economic activity and any structural or public policy changes that vary systematically with income. We exclude other explanatory variables, such as the share of manufacturing in GDP, energy taxes and subsidies, and the ownership of private vehicles. Such variables may help to explain carbon emissions, but they may also be endogenously related to per capita GDP.

Second, the specification in (1) includes both year and country dummies.

[3] See, for instance, Kosmo (1989) and Larsen and Shah (1992).
[4] HES provide a review of the early literature.

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Year dummies help control for effects common to all countries in a given year, such as the global level of economic activity, the development of technology, and global fuel prices. Country dummies help control for time-invariant country characteristics that may be correlated with both GDP and carbon emissions, such as population density, resource endowment, and climate, all of which change only slowly over time. In addition, the inclusion of country fixed effects can help control for a wide range of institutional and political differences between developing and developed countries that may affect carbon emissions and that may persist even as developing country incomes rise.

Third, we estimate (1) in per capita terms to help reduce heteroskedasticity and to avoid placing undue weight on the observations from a few high-population countries. Even so, we find considerable evidence of heteroskedasticity across countries, which we correct using generalized least squares. In addition, we correct for first-degree autocorrelation. A fourth consideration is the functional form in (1). Although we focus on quadratic models, we test higher-order polynomial forms to ensure an appropriate specification. In addition, we estimate (1) in both levels and natural logarithms.

Finally, it is important to note that GDP, treated as an explanatory variable in (1), may itself be affected by carbon emissions in at least three ways. Within any given country, carbon emissions and GDP may be simultaneously determined, with GDP being at least in part an endogenous function of the energy use underlying carbon emissions. In this respect, HES provide partial support for the specification in (1) using an instrumental variables approach.[5] In addition to possible within-country simultaneity, GDP may also be affected by *global* carbon emissions through changes in climate (see, for instance, Nordhaus, 1991). To help the reader evaluate this possibility, we present alternative scenarios for slower GDP growth. Yet another possible link between carbon emissions and GDP may be through the economic impacts of global carbon mitigation policies. Note, however, that our intent is to present business-as-usual scenarios, and thus the effects of such policies remain properly outside the scope of our analysis.

3. Data and specification tests

Data sources

Data on carbon emissions across countries and across time come from the sixth release of the Oak Ridge National Laboratory dataset (ORNL6, docu-

[5] HES employ the estimator proposed by Holtz-Eakin, Newey, and Rosen (HNR, 1988). The HNR approach transforms the equation to be estimated in two steps, first using a Cochrane–Orcutt transformation to remove serial correlation and then taking first differences to remove the country fixed effects. This transformed and differenced equation is then estimated using appropriated lagged and differenced values of income and carbon as instruments, thereby providing a consistent estimator that can be used to construct a Hausman test for the endogeneity of GDP. HES were unable to reject the null hypothesis of exogeneity (for details see Holtz-Eakin and Selden, 1992).

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mented in Boden, Marland, and Andres, 1995). These data include emissions from fossil fuels and cement manufacture, which, apart from emissions associated with land use changes, represent the major sources of anthropogenic carbon emissions.[6] Purchasing power parity adjusted real GDP data are provided by the Penn World Tables Mark 5.6 (PWT56), described in Summers and Heston (1991).[7] Population data from PWT56 are used to compute per capita emissions from the aggregate country estimates in ORNL6.

The result is an uneven panel of data for 135 countries, containing 4,491 observations that span the period 1951–1992. In general, the OECD data series are complete; whereas many developing country series do not begin until the early 1960s, and many end in the late 1980s. Any stratification, however, is likely to be exogenous, insofar as it is typically the income data that are lacking (rather than emissions data).

Several nations are excluded from the sample for reasons other than data availability. We exclude the former Soviet Union (FSU) and the Eastern European economies in transition, because of concerns about data quality. Also, historic trends in these countries are unlikely to persist into the future, so that their inclusion might distort emissions scenarios.[8] In addition, we exclude the five South Africa Customs Union states, because data limitations prevent ORNL6 from correctly allocating imported fossil fuel use among those countries. Finally, Kuwait is excluded from the sample, because it is an outlier in both emissions and GDP.[9]

[6] Using estimates from IPCC (1990) and World Resources Institute (1996), between 77 and 83 per cent of total anthropogenic emissions come from fossil fuel use and cement manufacture (the remainder associated primarily with land use change). We omit emissions from bunker fuel storage. Also, we omit emissions from gas flaring. Gas flaring emissions are highly concentrated in a few countries with large oil endowments and are more closely associated with liquid fuel production than with its use. Moreover, differences across countries in this respect will not be captured by the country fixed effects. Countries with the most gas flaring emissions begin the analysis period with low levels of both gas flaring emissions and GDP, so that increases in the former would tend to be captured by the latter rather than by the country effects. For purposes of projecting emissions, the issue is whether one believes that all countries will have gas flaring emissions equal to those of the OPEC nations once they reach similar levels of income. In any event, gas flaring emissions were only 1.1 per cent of global carbon emissions from fossil fuel and cement in 1992, and by scaling our aggregate forecasts to global totals *inclusive* of gas flaring (see section 5), we are able to capture gas flaring emissions in a manner that does not bias the estimated carbon–GDP relationship.

[7] In a few cases, the (new) PWT56 is less complete than the (old) Penn World Tables Mark 5 (PWT5), in which case values from the older version are used to impute missing values (by index-linking the two data sources).

[8] For this same reason, we include West Germany, but exclude East Germany (projecting emissions for the former as if unification had not occurred).

[9] In addition we follow HES (1995) in adding the carbon emissions for the Ryukyu Islands to those of Japan before 1972 (when they were incorporated as part of Japan). Next, East and West Pakistan are omitted from the data through 1971, but Bangladesh and Pakistan are taken as separate countries starting in 1972. Third, carbon emissions from Peninsular Malaysia, Sarawak, and Sabah are summed for

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The ORNL6 data are compiled from fuel use statistics extracted from the United Nations Energy Statistics Database and from hydraulic cement production estimates supplied by the US Department of Interior's Bureau of Mines. Each country's annual fuel use is estimated by considering fuel production, fuel trade, fuel bunkers, and changes in stocks. For each fuel type (solid, liquid, gas), annual carbon emissions are computed as the product of the quantity of fuel consumed, the fraction of the fuel that is oxidized (constant within fuel type), and the carbon content factor (constant within fuel type). Carbon from cement manufacture is computed as the product of the amount of cement produced, a constant average calcium oxide content fraction, and a constant factor to convert calcium oxide into carbon dioxide equivalents (Boden, Marland, and Andres 1995). Because the carbon properties of fuel types are relatively consistent across countries and across time, ORNL's use of constant emission factors is believed to result in relatively little loss of accuracy.

Specification tests: unit roots

The presence of unit roots can be a source of misspecification in regression analysis, in some cases leading one to infer a significant relationship where none actually exists. Conventional estimation techniques are predicated on the assumption that shocks in time series data are transitory so that the data eventually revert to their central tendencies (stationarity). In contrast, data series containing unit roots can drift arbitrarily far from their central tendencies. Regressing one such series on another could give the appearance of a strong correlation despite the relationship being spurious. In such cases, differencing or cointegration methods are required to obtain unbiased estimates and standard errors.

We test the null hypothesis that unit roots are present using the panel data test developed by Im, Pesaran, and Shin (IPS, 1995). The IPS method averages the augmented Dickey–Fuller t-statistics from each country in the panel, using this average t-statistic to construct a test of the unit root null hypothesis for the panel as a whole. In our use of the IPS test, we modify the approach to allow for the possibility of a structural break associated with the oil price shock in 1973, as was found in US GDP data by Perron (1989). To allow for this structural break in as non-parametric a manner as possible, we simply split the sample, testing the panel of data prior to 1974 separately from the panel of data after 1974. Using this approach, we are able to reject at high levels of significance the presence of unit roots for both per capita carbon emissions and per capita GDP (details provided in Heil and Selden, forthcoming). Moreover, as a further guard against misspecification we employ quasi-first differenced estimators (as described below).

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the years preceding their unification in 1969 (but the combined emissions reported for Malaysia-Singapore before 1957 are excluded). Fourth, we add emissions from the Canal Zone to those from the rest of Panama. Fifth, we sum the carbon emissions of Tanganyika and Zanzibar prior to their unification in 1969. Sixth, we concatenate the emissions time series for Rhodesia-Nyasaland and Zimbabwe. Finally, we use the PWT5 GDP data for Afghanistan, because that country was dropped from the PWT56.

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Specification tests: serial correlation

Analysis of the residuals from ordinary least squares (OLS) estimation reveals the presence of a serial correlation for both the levels and the logarithmic specifications. For this reason, we implement a Cochrane–Orcutt transformation, estimating the model in quasi-first differenced form. The estimated correlation coefficients used to transform the data are $\hat{\rho} = 0.811$ (levels) and $\hat{\rho} = 0.818$ (logarithms).[10] Analysis of the residuals of the transformed model reveal no remaining evidence of serial correlation.

Specification tests: heteroskedasticity

Both the levels and logarithmic models exhibit evidence of heteroskedasticity, despite being estimated in per capita terms. This is perhaps not surprising, given that per capita incomes vary so widely across countries. White's test strongly rejects the null hypothesis of homoskedasticity for both the levels and the logarithmic models.[11] For the levels model, a Goldfeld–Quandt comparison of residual variances for high- versus low-income countries suggests that the heteroskedasticity may be at least partially related to income levels. However, this is not the case for the logarithmic model. To reduce the possibility of misspecification we employ a non-parametric heteroskedasticity correction, using the residuals from the Cochrane–Orcutt transformed regression to compute each country's mean squared residual, the reciprocals of which we then use as weights in the final estimation (see, for instance, Greene, 1993, ch. 14). While the two models yield qualitatively similar estimates and forecasts, we focus on the weighted results to avoid biased standard errors and because the coefficient estimates from the weighted model are efficient in the presence of heteroskedasticity.

Specification tests: significance of year and country effects

Country effects can help control for time-invariant country characteristics and improve the model's country-by-country fit. Year effects help control for factors common to all countries in a given year, and they form the basis for our subsidiary oil price regression. Using F-tests, we examine the null hypotheses that (a) the country effects are jointly equal to zero, and (b) the year effects are jointly equal to zero. Both hypotheses are rejected by a wide margin. Therefore, we include both country and year effects in all estimates presented below.

[10] The serial correlation coefficients are estimated by regressing residuals on their lagged values and a constant term. The constant term is included because of the uneven nature of the panel (although similar results can be obtained by including year effects or by simply regressing the residuals on their lagged values). Breusch–Godfrey estimates yielded similar values.

[11] Following Greene (1993, p. 393), we use the squared residuals from the first regression in an auxiliary regression such that $e^2_{it} = \beta_0 + \beta_1 y_{it} + \beta_2 y^2_{it} + \beta_3 y^3_{it} + \beta_4 y^4_{it} + \gamma_t + f_i + \xi_{it.}$ The product of the resulting R^2 and the number of observations is distributed χ^2 with 179 degrees of freedom. The levels model χ^2 statistic is 2252.9 and the logarithmic model χ^2 is 1259.3. Both easily surpass the 95 per cent critical value of 146.6 (for 120 degrees of freedom).

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Specification tests: cubic versus quadratic models

We test the quadratic specification by adding cubic terms of both the levels and logarithmic models. The estimation results are presented in appendix A. In the cubic-in-levels model, neither the cubic term itself nor the quadratic term is significantly different from zero, and examination of the emissions trajectories reveals little difference between the two specifications. In the cubic-in-logarithms model, while all coefficients are significantly different from zero, examination of its emissions trajectories reveals unattractive properties, with emissions rising rapidly at initial levels of development and declining sharply out of sample. Given these results, we focus on quadratic specifications for both models.

4. Final estimation results

Table 1 presents our final estimation results (corrected for autocorrelation and for heteroskedasticity across countries). Both the levels and logarithmic models fit the data closely, with R^2 statistics of 0.84 and 0.87, respectively, and with all coefficients significantly different from zero. The bottom row of table 1 presents the estimated turning points—the level of per capita GDP at which carbon emissions peak. For the levels model, the turning point occurs at $36,044—a level of per capita income that we predict many higher-income countries will reach during the next century. In contrast, the turning point in the logarithmic model occurs well out of sample (at over $2 million), implying that carbon emissions, for all practical purposes, are monotonically increasing in GDP. Most fundamentally, however, note that whether the levels or logarithmic model is chosen all the countries in our sample currently rest on the upward-sloping portion of their inverted-U curves, suggesting that per capita emissions—not to mention aggregate emissions—will continue to rise around the world for some time to come even if emissions in high-income countries eventually turn down.

Table 1. *GDP–carbon emissions estimation results*

	Levels	*Logarithms*
Intercept	0.057641**	−0.150408**
	(0.01218)	(0.02568)
GDP	0.131417**	0.576233**
	(0.00707)	(0.03637)
GDP^2	−0.001823**	−0.037179*
	(0.00035)	(0.01339)
R^2	0.842	0.870
Observations	4491	4491
F ($\gamma_t = 0$)	2.001**	4.711**
F ($f_i = 0$)	42.554**	29.663**
Turning point	$36,044	$2.3 million

Notes: Standard errors in parentheses.
* Significantly different from zero at the 5 per cent level.
** Significantly different from zero at the 1 per cent level.
Source: Authors' calculations.

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5. Global carbon emissions

The equations estimated in the previous section can be combined with projections for GDP and population to construct country-by-country emissions predictions that we then aggregate to the global level. Our objective is not so much to provide point forecasts of emissions in a particular year—although we are optimistic that our near-term forecast accuracy may be at least as successful as that of HES. Certainly, it is not possible to forecast GDP growth accurately over long periods, much less energy prices or the development of technology. Rather, our primary intent is to offer insights into the implications of historic emissions–GDP relationships given a range of plausible scenarios for key variables associated with emissions. This is of particular importance given non-linearities not only in the emissions–GDP relationship, but also in the relationships between the *level* of GDP, on the one hand, and the *growth rates* of GDP and population, on the other.

Population projections

Population forecasts by country are obtained from the *World Population Projections 1994–95* (World Bank, 1994). On average, these projections are lower than the 1989 World Bank projections used by the IPCC in their IS92a reference scenario (Pepper *et al*., 1996). This is primarily due to downward revisions in projected population growth for China. Table 2 compares the major population projection scenarios at the global level. The 1994–1995 World Bank projections are very close to the United Nations Population Division (1995) medium growth scenario and the US Census Bureau forecasts (in Pepper *et al*., 1996).

Per capita GDP scenarios

We construct scenarios for per capita GDP growth by using the 1951–1992 GDP data to compute ordinary least squares estimates of the following growth model (with standard errors in parentheses)

$$\ln(y_{it+1}/y_{it}) = \underset{(0.0071)}{-0.00077} + \underset{(0.0018)}{0.0105}\ln(y_{it}) \underset{(0.0009)}{-0.00304}\ln(y_{it})^2 + u_{it}\ (R^2 = 0.0549) \quad (2)$$

The model allows for varying growth rates at different per capita income levels, with a take-off to rapid, sustained growth followed by a gradual

Table 2. *Comparative global population forecasts (in millions)*

Year	*WB94–95*[a]	*WB1989*[b]	*UN94 medium*	*US census96*
1990	5,266	5,252	5,285	5,282
2000	6,114	–	6,158	6,092
2025	8,121	8,414	8,294	7,947
2050	9,578	–	9,833	9,363
2075	10,481	–	–	–
2100	10,958	11,312	–	–

Notes: [a] Population projections used in this study. [b] Projections used for IPCC IS92a.
Sources: World Bank (1994), United Nations Population Division (1995), Pepper *et al*. (1996).

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slowing of growth rates at higher income levels.[12] Growth rates reach a peak of nearly 2.6 per cent when per capita income equals $5,600, diminishing thereafter to 2.0 per cent at $21,000, and to 1.5 per cent at $35,600. In addition to this baseline scenario, we also consider the effect on global carbon emissions of faster and slower GDP growth. In particular, we note that our slow growth scenario reduces GDP by an amount that is substantially greater than the estimated damages caused by a doubling of atmospheric carbon concentrations.[13] Thus, we believe our slow growth scenario may provide a bound of sorts on any feedback effects that climate may have on GDP.

The year effect–oil price model

In our baseline scenarios, we hold the year effect constant at its 1992 level. A potential weakness of this approach is that the year effects may capture any changes in emissions associated with long-term trends in energy intensity, so that holding the year effects fixed at the 1992 level would fail to capture the on-going impact of such trends. Another potential problem is that the year effects may capture the direct impact of world energy prices on emissions, so that holding the year effect fixed would fail to capture emissions reductions that could arise in the event such prices move higher. To examine these issues, we use the estimated year dummy coefficients from the levels and logarithmic models as the dependent variables in a pair of subsidiary regressions

$$\text{Levels:} \quad \hat{\text{yr}}_t = \underset{(0.01088)}{0.035897} - \underset{(0.00042)}{0.000720}\, p_t + \underset{(0.00015)}{0.000641}\, t + v_t \; (R^2 = 0.554) \tag{3a}$$

$$\text{Logarithms:} \quad \hat{\text{yr}}_t = \underset{(0.02410)}{-0.231142} - \underset{(0.01304)}{0.010207}\, p_t + \underset{(0.00044)}{0.002262}\, t + v_t \; (R^2 = 0.638) \tag{3b}$$

where t is a time trend, and where p_t is the price of crude oil delivered to US refiners in each year measured in 1994 US dollars.[14] We believe that the US oil price is a reliable proxy for the world oil price and may be correlated with world energy prices more generally, so that (3a) and (3b) yield unbiased estimates of the *average* effect of world prices on emissions.

To estimate (3a) and (3b), we employ Hanushek's (1973) method, which exploits the fact that the year effect estimates are correlated through the coefficient covariance matrix from the main model. Hanushek's method uses this information to identify the covariance matrix for the error terms in (3a,b), which is then used to implement generalized least squares. The resulting estimates have the expected signs for oil prices, but the oil price coefficient is only statistically significantly different from zero in the levels

[12] See HES (1995) for a discussion of the debate over GDP convergence.

[13] The slower growth scenario reduces GDP growth by half a percentage point per year. In contrast, the IPCC (1996b) report cites a range of 1.5–2 per cent of world GDP per year as its best estimate of the likely damage associated with a doubling of atmospheric concentrations of carbon dioxide.

[14] Prior to 1968 we use the wellhead price of US crude oil, index-linked to the refiner prices used in subsequent years (Energy Information Administration, 1994).

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model (standard errors in parentheses).[15] In contrast, the trend term is highly statistically significant in both equations.

In interpreting these results, we caution the reader that domestic energy prices in other countries can differ greatly from world prices, so that the oil price coefficients from these regressions should *not* be interpreted as measures of the responsiveness of emissions to within-country energy price changes. As we noted earlier, carbon may in fact increase less than linearly with GDP precisely because energy policies—including countries' responses to the oil price increases—may be historically correlated with GDP (see Moomaw and Unruh 1997). Certainly the relatively weak relationships in (3a, b) between carbon and global energy prices in no way diminish the critical importance of understanding how changes in domestic energy policies (apart from those historically correlated with GDP) might be used to help mitigate global carbon emissions relative to the levels we project if countries develop along the historical carbon–GDP trajectory.

To construct year effect projections from equations (3a,b) we use the high, medium and low oil price scenarios produced by the US Energy Information Administration (EIA 1996) for the period 1996 to 2015. Beyond 2015, we hold the year effect constant at its 2015 value, in part to limit the effect of the trend and in part because the EIA oil price projections do not extend beyond that point.[16] To test the robustness of this approach, we also examine scenarios in which oil prices continue to rise at a rapid pace for the rest of the twenty first century. In addition, we construct carbon emissions scenarios in which high (low) oil prices are combined with slow (fast) GDP growth, thereby allowing for the likely possibility that oil prices and GDP growth are linked.

Annual global emissions

In each year, per capita emissions for each country are obtained using projected per capita GDP and the various year effect scenarios. We then combine these with population projections to yield country-level aggregate emissions that we sum to the global level.[17] We adopt the standard forecasting practice of exploiting the quasi-differenced form of the main equations, using each country's actual 1992 emissions as the starting point from which future emissions trajectories evolve. Table 3 begins by presenting global carbon emissions to the year 2100 when holding the year

[15] Since we estimate the main model in quasi-first differenced form, we estimate models (3a) and (3b) in quasi-first differenced form as well. In addition, note that we obtain similar point estimates but larger standard errors if we also include the means of the other explanatory variables (income and income squared) in (3a,b). for this reason, the statistical significance of oil prices is open to debate even in the levels model.

[16] In 2015, the low, medium, and high oil price projections are $16.07, $25.43, and $33.89 per barrel, respectively (in 1994 dollars).

[17] We scale up emissions from the countries in our sample to a global total by multiplying our estimate by the inverse of the share of global emissions, inclusive of gas flaring emissions, that our sample captures in 1992 (72.8 per cent).

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Table 3. *Global carbon emissions forecasts 1992–2100 (billions of metric tons)*

Year	*1992*[a]	*2000*	*2025*	*2050*	*2075*	*2100*
Quadratic in levels specification						
Baseline	6.04	7.05	10.61	14.72	19.43	23.87
Fast GDP growth	6.04	7.17	11.39	16.31	21.10	22.50
Slow GDP growth	6.04	6.92	9.86	12.98	16.62	20.68
Forecasts with year effect projections						
High energy prices	6.04	7.13	11.27	15.51	20.30	24.77
Medium energy prices	6.04	7.16	11.32	15.58	20.37	24.85
Slow energy prices	6.04	7.19	11.40	15.67	20.47	24.96
High energy prices and slow GDP growth	6.04	7.01	10.51	13.77	17.49	21.58
Low energy prices and fast GDP growth	6.04	7.31	12.17	17.26	22.14	23.58
Quadratic in logarithmic specification						
Baseline	6.04	7.35	10.63	13.40	16.02	18.42
Faster GDP growth	6.04	7.47	11.26	14.63	17.79	20.55
Slower GDP growth	6.04	7.24	10.01	12.20	14.25	16.18
Forecasts with year effect projections						
High energy prices	6.04	7.75	13.97	17.74	21.22	24.39
Medium energy prices	6.04	7.77	14.00	17.79	21.27	24.45
Slow energy prices	6.04	7.79	14.08	17.88	21.39	24.58
High energy prices and slow GDP growth	6.04	7.62	13.16	16.15	18.87	21.43
Low energy prices and fast GDP growth	6.04	7.92	14.92	19.52	23.74	27.42

Note: [a] 1992 figure are actual global carbon emissions from fossil fuel combustion and cement manufacture.
Source: Authors' calculations.

effects constant in all future years at the 1992 level. The baseline case uses per capita GDP growth rates obtained from equation (2). The faster and slower growth scenarios are obtained by adding or subtracting 0.5 per cent from the baseline per capita GDP growth rates in each year.

In the baseline levels model, global carbon emissions grow by approximately 1.8 per cent per year through 2000, with the growth rate declining to 1.5 per cent by 2025 and 0.7 per cent by 2100. These growth rates are slower than the 3.2 per cent average growth rate between 1950 and 1992, but they are nevertheless sufficient to produce large increases in cumulative emissions (see below). In particular, these increases in global emissions occur even though many of the higher-income countries are on the downward-sloping portions of their inverted-U curves by 2050. Selden and Song (1994) show that global emissions of local pollutants can continue to increase for long periods, despite the presence of turning points at moderately low income levels, due to the skewed global income distribution and the rapid emissions increases in developing countries. This is even more true for carbon emissions in the levels model due to the much higher turning point.

Comparing baseline emissions from the levels and logarithmic models,

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we see that the two sets of projections are very similar through 2025. After that point, however, the logarithmic model yields slightly lower emissions than the levels model. This is largely due to the fact that the logarithmic specification perpetuates initial differences among countries in percentage terms, so that countries can diverge in absolute terms from the central or average emissions trajectory as their incomes rise. Several of the most populous developing countries start the analysis with carbon emissions that are slightly below the average trajectory. While these initial differences are small in absolute terms, they are large in percentage terms. The logarithmic model perpetuates these differences in percentage terms, resulting in growing absolute departures below the central trajectory. To some extent, this property of the logarithmic model violates the basic premise of our analysis that we are simulating the future emissions of developing nations based on the historical experiences of middle- and upper-income countries. For this reason, we believe that the predictions from the levels model are more consistent with our stated conceptual approach. More fundamentally, however, note that the pace of global carbon emissions is predicted to be rapid *whichever* functional form proves to be more reliable.

Turning next to our sensitivity analysis, the results in table 3 show that faster GDP growth leads to increased emissions through 2075 for both models. In the levels model, however, faster GDP growth causes larger declines associated with countries passing the turning point, so that by the end of our analysis (after 2093) the global emissions trajectory in the fast growth scenario dips below that of the medium growth scenario.

When we include projected year effects, the resulting global emissions are uniformly higher, even in the high oil price scenario. While higher oil prices tend to reduce emissions, this effect is small for the range of price changes we consider, and the model is dominated instead by the upward trends identified in (3a,b).[18] As discussed above, one possible explanation for the low price sensitivity of carbon emissions is that many countries stabilize domestic energy prices in the face of changing world prices, so that the latter would be an imperfect measure of the former. Another potential explanation is that at least part of the energy price effect may be through its impact on GDP. For this reason, it is probably most useful to examine higher energy prices in conjunction with slow GDP growth (see table 3).

The upward year effect trend also deserves comment. There is considerable evidence that energy and carbon intensities diminish as economies grow (as result confirmed by our finding of a diminishing marginal propensity to emit), and that energy and carbon intensities have declined over time holding income and the mix of economic activity constant.[19] Viewed against this backdrop, the upward trend we find in the year effects is perhaps surprising. One explanation, however, may be that the *mix* of production and consumption has changed over time, toward a greater

[18] Indeed, even allowing oil prices to rise by 2 per cent a year to $137 per barrel in 2100 reduces carbon emissions in that year by only 5.7 and 1.7 per cent in the levels and logarithmic models, respectively, delaying cumulative global emissions by only a brief period of time.

[19] See Greening, Davis, and Schipper (1998) and the references cited therein.

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intensity of manufacturing, electricity generation, and/or motorized transportation (holding everything else, including income, constant). Note in this regard, however, that the late-developing countries typically have below-average country effects, more than offsetting the upward year effect trend, so that emissions intensities of the developing countries are typically below those exhibited by the developed countries when they were at similar levels of income. Clearly, additional research is needed on the determinants of carbon–GDP trajectories. For the purposes of this paper, however, we conclude that the pace of carbon emissions growth is unlikely to be slowed by either world energy price increases or long-term trends in energy intensity captured in the year effects.

Comparison with other models

Figure 1 plots the global emissions from the baseline scenarios of our levels and logarithmic models, along with the business-as-usual emissions trajectories predicted by several other models. Our baseline projections are quite similar to those by HES (1995), especially through 2025. The similarity suggests the basic model is robust to: (i) seven additional years of data from a period of substantially lower oil prices, (ii) important revisions to the income and emissions data, and (iii) changes in the sample of coun-

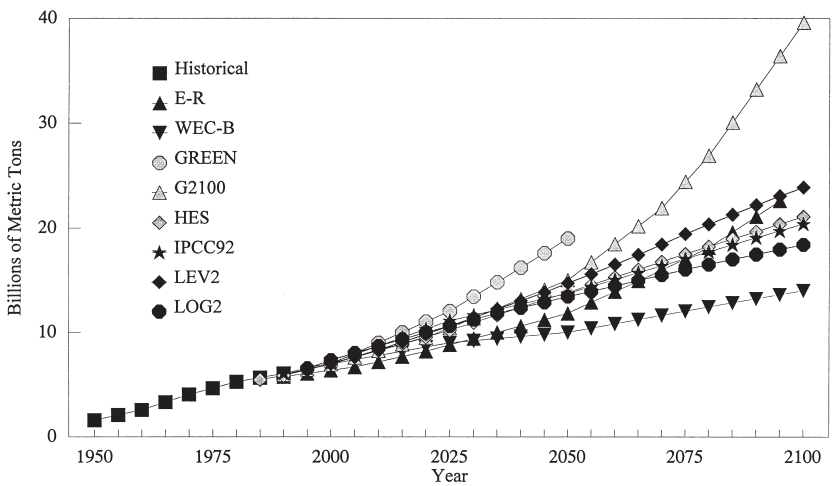


Figure 1. *Comparison of annual emissions forecasts*

Note: 'Historical' is the 1950–1992 series from ORNL6. 'IPCC92' is the IPCC IS92a reference scenario (IPCC, 1992). 'GREEN' is the OECD general equilibrium model as run in Burniaux *et al*. (1992). 'G2100' is Global 2100, the primary model constructed by Manne and Richels (1992). 'E-R' is the Edmonds–Reilly model (see Barns, Edmonds, and Reilly, 1992). 'WEC-B' refers to the World Energy Council scenario B model (WEC, 1995). 'HES' is the Holtz-Eakin and Selden levels forecast (HES, 1995). 'LEV2' and 'LOG2' are our quadratic in levels and quadratic in logarithms models, respectively.

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tries used in estimating the model. Our baseline scenarios are also broadly consistent with the business-as-usual predictions of the leading structural models. In particular, IPCC IS92a, perhaps the most widely cited reference scenario, traces a middle path between our two baseline emissions trajectories. Because we employ such a different approach, we believe that our findings provide valuable independent confirmation of the business-as-usual forecasts from the structural models.

Cumulative global emissions

Given the long life span of carbon dioxide in the atmosphere, cumulative carbon emissions are the salient unit of analysis with regard to global climate (rather than annual emissions *per se*).[20] Table 4 presents cumulative global carbon emissions after 1990. The cumulative emissions scenarios reflect the patterns in annual emissions examined above. The logarithmic model predicts slightly higher cumulative emissions than the levels model

Table 4. *Cumulative global carbon emissions after 1990 (billions of metric tons)*

Year	*2000*	*2025*	*2050*	*2075*	*2100*
Quadratic in levels specification					
Baseline	65.2	285.8	603.3	1,030.6	1,575.4
Fast GDP growth	65.8	297.1	644.6	1,115.6	1,672.2
Slow GDP growth	64.7	274.8	561.3	931.2	1,398.3
Forecasts with year effect projections					
High energy prices	65.6	296.3	632.0	1,080.1	1,647.1
Medium energy prices	65.8	297.7	635.0	1,084.9	1,653.7
Slow energy prices	65.8	299.1	638.5	1,090,8	1,662.2
High energy price and slow GDP growth	65.1	285.3	590.1	980.7	1,470.0
Low energy prices and fast GDP growth	66.3	310.4	679.9	1,175.8	1,759.0
Quadratic in logarithmic specification					
Baseline	66.8	293.7	596.3	965.2	1,397.3
Faster GDP growth	67.3	303.5	629.6	1,036.5	1,517.8
Slower GDP growth	66.3	284.1	563.7	895.0	1,276.4
Forecasts with year effect projections					
High energy prices	68.2	345.0	745.1	1,233.7	1,805.8
Medium energy prices	68.3	345.8	747.1	1,236.9	1,810.5
Low energy prices	68.4	347.1	750.5	1,243.0	1,819.6
High energy prices and slow GDP growth	67.7	333.1	702.8	1,141.6	1,646,6
Low energy prices and fast GDP growth	68.9	359.3	794.1	1,337.1	1,979.5

Source: Authors' calculations.

[20] No single figure can be given for the duration of the influence of carbon in the atmosphere due to uncertainty regarding the uptake rates of the various carbon sinks. However, a standard benchmark used in the literature is 100 years. The IPCC uses this benchmark, but also considers a range for duration of 50 to 200 years. See, for instance, IPCC (1990, p. xvii).

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through 2025, but these positions are reversed by 2050. One implication of table 4 is that cumulative emissions, like annual emissions, are not overly sensitive to the rate of GDP growth. In particular, we cannot simply grow our way out of the emissions problem—even in the levels model with its inverted-U shape. Rather, faster GDP growth exacerbates the problem, raising cumulative global emissions through 2100.

Carbon emissions by income groups: 1992, 2025, and 2100

Table 5 presents carbon emissions by income group for the years 1992, 2025, and 2100. We group countries according to their 1992 per capita GDP using thresholds defined by the World Bank.[21] We hold these income groupings fixed throughout the analysis, rather than adjusting group membership to reflect changes in income. Only countries in the sample used to estimate the model are included in this analysis.

Overall, our sample's population grows by approximately 50 per cent

Table 5. *Population, GDP, and emissions forecasts, by income group*

Income group	*Low*	*Lower-middle*	*Upper-middle*	*High*	*Total amounts*[a]
Population share					
(1992)	0.57	0.20	0.06	0.17	4,829
(2025)	0.60	0.22	0.06	0.12	7,308
(2100)	0.64	0.22	0.05	0.09	9,914
Aggregate GDP share					
(1992)	0.17	0.13	0.09	0.60	20,213
(2025)	0.20	0.18	0.12	0.50	52,487
(2100)	0.35	0.28	0.12	0.25	234,504
Aggregate carbon emissions					
Actual (1992)	0.99	0.38	0.40	2.72	4.49
Levels (2025)	1.88	1.21	0.77	3.95	7.81
Levels (2100)	9.09	4.84	1.25	2.39	17.57
Logarithms (2025)	1.63	0.77	0.62	4.84	7.86
Logarithms (2100)	4.31	1.94	1.21	6.15	13.61
Emissions share					
Actual (1992)	0.22	0.08	0.09	0.61	4.49
Levels (2025)	0.24	0.16	0.10	0.51	7.81
Levels (2100)	0.52	0.28	0.07	0.14	17.57
Logarithms (2025)	0.21	0.10	0.08	0.62	7.86
Logarithms (2100)	0.32	0.14	0.09	0.45	13.61

Note: [a] Population totals are in millions, GDP totals are in billions of 1992 US dollars, and emissions are in billions of metric tons. All calculations are limited to the sample of countries used to estimate the models.
Source: Authors' calculations.

[21] The income thresholds we use in 1992 US dollars are $0–$1,509, $1,510–$4,394, $4,395–$8,810, and above $8,810. Because we use purchasing-power parity adjusted income to group the countries, our groupings differ slightly from those used by the World Bank.

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between 1992 and 2025, and it doubles between 1992 and 2100. On the surface, this would appear to explain a substantial portion of the overall growth in carbon emissions, which are projected to triple in the logarithmic model and quadruple in the levels model. However, much of the population increase occurs in the low- and lower-middle income groups, where per capita emissions in 1992 were only one-tenth those in the high-income countries. Therefore, the overall growth in emissions must be understood by examining not only the growth in population, but also the relative rates of income growth across countries.

It is important to distinguish between the international emissions distributions generated by the levels model and those generated by the logarithmic model. There are two main differences. First, in the levels model the marginal propensity to emit falls rapidly at higher income levels, with high-income countries experiencing a moderate reduction in total emissions by the end of the next century. In contrast, the marginal propensity to emit falls more gradually in the logarithmic model, remaining positive for all countries throughout the analysis. The second key distinction, as discussed above, is that the levels model implies convergence in percentage terms to a common carbon–GDP growth path, whereas in the logarithmic model several populous low-income countries are projected to have emissions that fall increasingly below the mean trajectory as their incomes rise.

In the levels model, the share of global emissions accounted for by the low-income countries rises modestly, from 22 per cent in 1992 to 24 per cent in 2025. Over the same period, the high-income share falls from 61 per cent to 51 per cent. This occurs despite a rise in per capita emissions in high-income countries from 3.4 metric tons to 4.4 metric tons. The change in shares is driven primarily by a doubling of per capita emissions in the lower-middle-income countries, from 0.4 metric tons to 0.8 metric tons. This, when combined with rapid population growth, results in more than a tripling of emissions in these countries.

By 2100, the reversal in emissions shares implied by the levels model becomes far more pronounced, with low- and lower-middle-income countries contributing 52 per cent and 28 per cent, respectively, versus the high-income share of only 14 per cent. By 2025, the low-income countries are well-embarked on a take-off to rapid GDP growth, and as a result their per capita emissions nearly double between 2025 and 2100, rising to 1.4 metric tons. In contrast, many of the high-income countries have begun to reduce emissions by 2050, and by 2100 per capita emissions in those countries fall below their 1992 levels (although per capita emissions in the high-income countries remain above those in the low-income countries).

In the logarithmic model, the global carbon emissions distribution remains relatively constant through 2025. Per capita emissions rise only modestly in the low-income countries. In contrast, per capita emissions in the high-income countries rise by 2 metric tons over the period. Even by 2100, the logarithmic model predicts that emissions shares in the low- and lower-middle-income countries will rise to only 32 per cent and 14 per cent, respectively; whereas the high-income share is predicted still to be 45 per cent. The reversal of shares predicted by the levels model does not

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occur in the logarithmic model. Thus, while the emissions distributions implied by the levels and logarithmic models are quite similar through 2025, they diverge substantially after that point.

It is difficult to say with any certainty whether the distributional patterns implied by the levels model or the logarithmic model will ultimately prove to be more accurate. On the one hand, the absolute decline in per capita emissions among high-income countries in the levels model may overstate to a moderate extent the reductions in energy intensity that those countries are likely to achieve absent coordinated global intervention. Certainly, it is a source of concern that these forecasts of emissions declines are based on a turning point that occurs out of sample. However, the downturns are mild, leaving emissions in the high-income countries only slightly below their current levels. On the other hand, the logarithmic model predicts per capita carbon emissions in several of the most populous developing nations to evolve along trajectories that lie far below those followed by higher-income countries before them. For this reason, we feel that the levels model yields distributional scenarios that are more consistent with our stated goal of examining carbon emissions under the assumption that there exists a common carbon–GDP trajectory across countries.

6. Concluding discussion

In this paper we use the latest available data on carbon emissions, GDP, and population to estimate a model that we then employ to construct country-by-country carbon emissions scenarios. The strengths of this approach are its simplicity and its reliance on the historical relationship between carbon emissions and GDP. At the same time, it is important to bear in mind that the model relies heavily on the assumption that emissions trajectories over the past four decades can be combined across countries to form a common development path. Of particular importance is the question of whether developing countries will in fact follow the same path as middle- and high-income countries before them. While the existence of a common development path in the future is difficult to determine based on historical data, we believe that it is useful to project the global emissions that would be likely to occur under the assumption that such a path exists. In particular, the resulting model provides a framework to examine the interaction between global trends in economic development, population growth, and carbon emissions. Moreover, to the extent that the assumption of a common development path is a reasonable one, we believe that our projections can provide important independent confirmation of the business-as-usual forecasts from the structural models.

A comparison of our cumulative emissions projections to historic emissions from fossil fuel combustion highlights the magnitude of the threat from continued global development along historical trajectories. In the 100-year period 1881 to 1990, cumulative emissions equalled 212 billion tons of carbon (Rotty and Marland, 1984, and ORNL6). By contrast, baseline cumulative emissions in our model between 1991 and 2100, a period of equal duration, are approximately 1500 billion tons of carbon—a sevenfold increase.

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Cumulative emissions of this magnitude imply large increases in mean global surface temperature—in the range 2 to 7 degrees centigrade (IPCC, 1996a). Even more unsettling is the *speed* with which these temperature increases would be likely to occur. Flavin and Tunali (1996) argue that a warming rate greater than 0.1° C per decade (or 1° C over the next century) would likely pose large ecological and economic risks. Whereas people and ecosystems are adaptable to slow climate evolution, rapid change can be far more damaging. In recent decades, the rate of temperature increase has been twice the threshold estimated by Flavin and Tunali. Using results presented in IPCC (1996a), our baseline forecasts translate into rates of temperature increase that exceed any estimated to have occurred within the past 10,000 years. In order to reduce the rate of increase to 0.1° C per decade, our cumulative emissions projections would need to be reduced by approximately 55 per cent through 2100 (or substantially more if one allows for other anthropogenic greenhouse gas emissions). Of course, translating global emissions into projected temperature changes is fraught with uncertainty regarding (i) climate sensitivity to atmospheric carbon concentrations, (ii) positive and negative feedback effects, and (iii) non-linearities inherent in the climate system. Nevertheless, we believe that this uncertainty only heightens the importance of global efforts to reduce emissions.

We believe that our analysis provides useful insights into the role that developed countries must play if we are to forestall global climate change. High-income countries are currently responsible for the lion's share of global emissions. At the same time, reducing these emissions without changing the carbon–GDP trajectories of developing nations will do relatively little to slow global carbon accumulation, insofar as our predictions imply substantial emissions growth among low- and lower-middle-income countries by the end of the next century. Given that per capita emissions in high-income countries are currently many times those in developing countries, and given that the ability to pay for reductions is so much lower in developing countries, we believe that our results highlight the importance of developed country leadership if countries at all income levels are to move away from the business-as-usual trajectories we examine in this paper.

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Appendix A: Cubic model estimation results

	Levels	*Logarithms*
Intercept	0.058216*	−0.161043*
	(0.0122592)	(0.0257165)
Linear term	0.125305*	0.599427*
	(0.01015517)	(0.0357043)
Quadratic term	−0.001202	0.182069*
	(0.0008449)	(0.0266553)
Cubic term	−0.00001453	−0.07909*
	(0.0000186)	(0.0081198)
R^2	0.8393	0.8874
Turning point	$32,716	$12,584

Notes: Standard errors in parentheses.
*Significant at the 5 per cent level of significance or higher.
Source: Authors' calculations.

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