Stationarity of Global Per Capita Carbon Dioxide Emissions: Implications for Global Warming Scenarios

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ABSTRACT

Annual global CO_2 emission forecasts at 2100 span 10 to 40 billion tonnes. Modeling work over the past decade has not narrowed this range nor provided much guidance about probabilities. We examine the time-series properties of historical per capita CO_2 emissions and conclude that per capita global emissions are stationary without trend, and have a constant mean of 1.14 tonnes per person with standard deviation of 0.02. With estimates of 21st century peak population levels in the 8-10 billion range, this implies that most emissions scenarios currently used for global warming forecasts are unrealistically high.

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ABSTRACT

Annual global CO_2 emission forecasts at 2100 span 10 to 40 billion tonnes. Modeling work over the past decade has not narrowed this range nor provided much guidance about probabilities. We examine the time-series properties of historical per capita CO_2 emissions and conclude that per capita global emissions are stationary without trend, and have a constant mean of 1.14 tonnes per person with standard deviation of 0.02. With estimates of 21st century peak population levels in the 8-10 billion range, this implies that most emissions scenarios currently used for global warming forecasts are unrealistically high.

1. Introduction

Concern about the buildup of carbon dioxide (CO_2) in the atmosphere, and its possible connection to climate change, has given rise to considerable interest in long-range projections of global CO_2 emissions. Current (2000) total global emissions are about 6.7 gigatonnes carbon equivalent (GtC), or just less than 1.1 tonnes per person, according to the Carbon Dioxide Information and Analysis Center at the Oak Ridge National Laboratory (CDIAC, Marland et al., 2003). Simulations from a suite of dynamic models done in a survey paper for the OECD (Dean and Hoeller, 1992) in the early 1990s yielded a range of possible emission paths over the 21st century, with end-of-century peaks ranging from about 20 to 40 GtC. The OECD study also made mention of published studies with forecasts as low as 5 GtC and high as 60 GtC. The forecast range has narrowed little since then. Forecasts based on Hotelling resource depletion theory have yielded a possible lower end of zero (Chakravorty et al., 1997); several studies have suggested peak mid-century emissions in the neighborhood of 20 to 25 GtC (Webster et al., 2002; Schmalensee, 1998), and the range of forecast scenarios used in the 2001 Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report was roughly 4 to 38 GtC for 2100 (Watson et al., IPCC 2001).

The forty IPCC emission scenarios were developed in the *Special Report on Emissions Scenarios* ("SRES") by Nakicenovic et al. (2000) and are referred to herein as the SRES scenarios. Since these scenarios are used as inputs to IPCC climate change simulations they are highly influential on global warming predictions. This, in turn, has an impact on policy decisions (and media coverage) related to climate change, such as the push to implement the Kyoto Protocol. The wide range of these 40 SRES scenarios means that the range of global warming forecasts goes from relatively minor to potentially catastrophic in the IPCC Assessment Reports. The upper end of these forecasts has been the subject of intense media and policy interest, as well as focused criticism. For its Third Assessment Report, released in 2001, the IPCC used a qualitative "storyline" methodology in which future possible socioeconomic states of the world were narrated, and the required time-paths of consumption and output needed to reach the projected end-state were then inferred. The quality of economic analysis underpinning these storylines is difficult to gauge since they are not based on conventional growth theory. The SRES approach yielded a wide range of outcomes with (by decision) no guidance as to the relative likelihood of any of them. The IPCC scenarios have been criticized for, among other things, making international comparisons based on market exchange rates rather than purchasing power parities, which may bias emission estimates upward (Castles and Henderson, 2003; Nakicenovic et al., 2003). The IPCC has announced its intention to use the same set of SRES scenarios for its Fourth Assessment Report due in 2007.[1]

Use of more conventional economic methodology might not reduce the range of emissions scenarios by much. The large and persistent uncertainties from macroeconomic

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[1] IPCC (2003) Annex 5 outlines plans to develop new scenarios for the fifth Assessment Report, but not the fourth.

emission models reflect the influence of numerous key parameters for which there is little reliable empirical information. For instance, small changes in the assumed annual rate of "autonomous energy efficiency improvement" can halve (or double) peak emissions simply due to the effect of compounding over a century (Dean and Hoeller, 1992). Yet there is no agreed-upon measure of what is the most accurate value. Out-of-sample conjectures about substitution elasticities among fuel and factor types can also play a large role despite the absence of reliable empirical guidance. Modeling results are also sensitive to conjectures about the cost and feasibility of potential emissions-free backstop technologies that might become available decades from now, but these remain highly speculative (see Hoffert et al., 2002, for an overview).

The continuing wide range of emission forecasts has been a source of frustration for scientists and policymakers alike in trying to make sense of global warming projections. This paper proposes a simple method for assessing the probability of emission projections, which gets around the challenges of structural modeling by direct examination of the statistical properties of historical emissions data. The intuition is straightforward and makes use of a strong empirical regularity, which has been hitherto overlooked. Total global carbon dioxide emissions can be factored into two components: global per capita emissions and global population.[2] Population projections, at least to 2050, are reasonably well constrained and have exhibited a tendency in recent years to fall when compared to projections made in previous decades. In addition, global per capita CO_2 emissions have been remarkably stable over many decades at just over 1.1 tonnes

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[2] Data from the CDIAC include emissions from fossil fuel consumption and cement production. Data from SRES scenarios are based on projections of fossil fuel consumption, but cement production is included only in some cases depending on the model. SRES projections of CO_2 flux due to land use are not included in the comparisons in this paper. The slight discrepancy in definitions will tend to understate

per person (see Figure 1), a point that is, surprisingly, not discussed in the SRES Scenario Reports. After an increase in the 1950s and 1960s, average emissions peaked in the early 1970s and there is now a small, but insignificant downward trend. Examination of per capita CO_2 data has previously been made in Lanne and Liski (2004), who examined industrialized countries for evidence of structural breaks associated with the 1973 oil price shock, and Strazicich and List (2002) who were testing for convergence. Neither paper discussed the stationarity of average emissions as a means to evaluate the probability of IPCC scenarios. The stationarity and narrow width of the distribution of global per capita CO_2 emissions forms the basis of the probability calculations in this paper.[3]

In contrast to the global average, national per capita emissions vary considerably, from a low of about 0.02 tonnes per person in some African countries to a high of over 5.5 tonnes per person in the USA (a few small countries have even higher emissions). In addition, emissions within countries can change considerably over time. On a country-by-country basis, per capita emissions doubled, on average, within each country between 1970 and 2000. Many countries doubled or tripled their per capita emissions, while others experienced reductions of 75 percent or more.[4] Yet the global per capita hardly changed during this time. This suggests that variability in domestic per capita emissions in one country gets systematically offset by variability in other countries, which implies an equilibrating economic mechanism that acts to place quantitative bounds on global per capita emissions.

SRES scenario numbers, but since the main concern herein is that they are running too high this does not detract from our argument.

[3] Throughout, we measure global per capita (average) emissions by taking total world CO_2 emissions and dividing by total world population in each year.

[4] The 1996-2000 average of per capita emissions was compared to the average over 1968-1972 in a sample of 139 countries. The mean change was +118.6 percent, with a range of -86 to +2,556 percent.

Our analysis establishes that the global per capita CO_2 emissions rate is a stationary, trendless random variable with a constant mean of about 1.14 tonnes per person annually, a standard deviation of about 0.02, and a 95 percent confidence interval of 1.10 to 1.18 tonnes per person. Since the mean is neither drifting nor trending we can evaluate probabilities for each of the 40 SRES emissions scenarios based on where their implied global per capita emissions fit with respect to our confidence interval. The SRES scenarios provide projections for the year 2000, all of which fall well within the observed confidence interval. The SRES group predicted total fossil-fuel-based emissions of 6.9 GtC in 2000, while actual emissions were 6.4 GtC (Marland et al., 2004). The small overshooting was due to population over-estimates: the predicted per capita emissions rate averaged across scenarios was 1.13 tonnes per person.

The absence of trend or drift in the average permits evaluation of the scenario probabilities not only based on present behaviour, but also implied emissions over the next few decades. We confine our attention to the interval up to 2050, in part because there is little anyone can claim to know beyond that horizon and also because if scenarios are ruled out as improbable up to that point they would not be rehabilitated by their behaviour in the latter half of the century. As of 2020, 33 of the 40 scenarios imply per capita emissions outside the observed confidence interval (of which 30 are above it). The narrowness of the observed distribution is a feature of the data; it is not imposed by our analysis. Even if we expand the confidence interval to a more generous plus or minus five standard deviations, only 14 scenarios (out of 40) remain within the interval as of 2020. As of 2050, 39 of 40 scenarios are outside the 2-sigma range confidence interval and 33 are outside the five-sigma confidence interval. The spread of the SRES forecasts is exceedingly large. As of 2020, almost half of the SRES scenarios (18/40) have

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per capita emissions ten or more standard deviations above the observed average and as of 2050 over 70 percent are at least this distance above the mean. Thus, we conclude that most of the scenarios currently being used for IPCC emissions predictions are simply implausible when evaluated against historical data.

Key to this argument is establishing that global per capita emissions are a stationary series with a constant mean and well-defined variance. In what follows, we demonstrate that the post-1950 global time series rejects a unit root specification in favour of a trend stationary process with two structural breaks (at 1968 and 1981). In addition, we find that the trend following the second break is small, negative, and statistically insignificant. We then empirically examine individual emissions series in a sub-sample of 121 countries and in all but 26 we reject the unit root model in favour of a trend stationary specification. From a theoretical perspective, if the 121-country average is stationary then the remaining 26 nonstationary countries are cointegrated (although the 26 non-rejections may also reflect the test power—see discussion below). Indeed, we find that the 121-country average per capita emissions series is trend stationary with a structural break in 1978.[5] We can thus use moments estimated from the observed historical data to draw reasonable inferences about likely behaviour over the next few decades.

The majority of the SRES scenarios imply that global per capita CO_2 emissions are strongly trending upwards. Since current data show no such behaviour, to justify continued usage of this ensemble of scenarios the IPCC needs to make a case that the global economy is now undergoing, or will shortly undergo, a structural break that will quickly change

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[5] Economic interpretations of the break points are not necessary for the main argument and we are reluctant to engage in post-hoc rationalizations of them.

characteristics of the observed global emissions time series into either a random walk with positive drift or an upward deterministic trend. Yet the two structural breaks that we identify in the post-1950 global average act to reduce the trend, first from positive and significant to positive and insignificant, and then to negative and insignificant. To validate the top end of the SRES emissions scenarios the situation would have to change to a new positive trend that is about twice as steep as the most rapid trend segment observed in the post-1950 interval. In addition, this new steeper trend would have to be sustained for 50 years without interruption. This is a steep burden to meet, to say the least. In the absence of a compelling argument for a new structural break, the current data imply that the only plausible IPCC scenarios are clustered near the lowest end of the range with combined average total global emissions of about 10.1 GtC in 2050.

2. Time Series Characteristics of the Global Emissions Series

We collect historical annual per capita emissions data for the interval 1950 to 2000 (the full interval available as of January 2004) for the world as a whole and for 121 individual countries with continuous data. These data are all from the Carbon Dioxide Information and Analysis Center ("CDIAC" hereafter; Marland et al., 2003). The main difference between the 121-country group average and the global (world) average is the treatment of Russia and the USSR. Because of the break-up of the former Soviet Union there is not a continuous record of emissions from East Germany and the former Soviet countries past 1990. Thus, the 121-country group does not include East Germany or Russia and the other former Soviet countries, whereas they are all included in the global average. Nevertheless, the results are very similar between the 121-country average and the global average: neither exhibits evidence of a unit root or an upward trend after 1981. For the probability calculations in Section 4 we use the global average results.

We now wish to empirically determine if per capita CO_2 emissions are stationary or nonstationary. Following the seminal paper by Perron (1989), it is now well known that failure to allow for an existing structural break leads to bias against rejecting a false unit root null hypothesis. To provide a remedy, Perron (1989) suggested allowing for one known, or "exogenous," structural break in the augmented Dickey-Fuller (ADF, hereafter) unit root test. Following Perron (1989), Zivot and Andrews (1992, ZA hereafter), among others, suggested determining the break point "endogenously" from the data. The ZA test selects the break point where the t-statistic that tests the unit root null is minimized. A potential problem common to the ZA and other similar ADF-type endogenous break unit root tests is that they derive their critical values while assuming no break(s) under the null. Nunes, Newbold, and Kuan (1997) show that this assumption leads to size distortions in the presence of a unit root with break. Lee and Strazicich (2001) further investigate this issue and discover that the ADF-type endogenous break tests tend to select the break where bias in estimation of the unit root test coefficient is the greatest. As a result, when using these tests researchers might conclude that a time series is trend stationary with breaks when in fact the series is nonstationary with break(s). In this regard, a "spurious rejection" of the unit root null hypothesis may result. To avoid these problems, we utilize the endogenous two-break Lagrange multiplier (LM) unit root test derived in Lee and Strazicich (2003b). In contrast to previously developed endogenous break unit root tests, size properties of the minimum LM test are unaffected by breaks under the null. Thus, test results using the LM test are clearer, since rejection of the null unambiguously implies a trend stationary series.

Implementation of the two-break minimum LM unit root can be described as follows. According to the LM (score) principle, a unit root test statistic can be obtained from the following regression:

$$\Delta y_t = \delta'\Delta Z_t + \phi \tilde{S}_{t-1} + \Sigma \gamma_i \Delta\tilde{S}_{t-i} + \varepsilon_t, \qquad (1)$$

where $\tilde{S}_t$ is a de-trended series such that $\tilde{S}_t = y_t - \tilde{\psi}_x - Z_t\tilde{\delta}$, t = 2,..,T. $\tilde{\delta}$ is a vector of coefficients in the regression of Δy_t on ΔZ_t and $\tilde{\psi}_x = y_1 - Z_1\tilde{\delta}$, where Z_t is defined below; y_1 and Z_1 are the first observations of y_t and Z_t, respectively, and Δ is the difference operator. ε_t is the contemporaneous error term and is assumed independent and identically distributed with zero mean and finite variance. Z_t is a vector of exogenous variables defined by the data generating process. The LM test with two changes in level and trend is described by $Z_t = [1, t, D_{1t}, D_{2t}, DT_{1t}^*, DT_{2t}^*]'$, where $D_{jt} = 1$ for $t \geq T_{Bj} + 1$, j = 1, 2, and zero otherwise; $DT_{jt}^* = t - T_{Bj}$ for $t \geq T_{Bj} + 1$, j = 1,2, and zero otherwise; T_{Bj} stands for the time period of the breaks. Note that the test regression (1) involves ΔZ_t instead of Z_t so that $\Delta Z_t = [1, B_{1t}, B_{2t}, D_{1t}, D_{2t}]'$, where $B_{jt} = \Delta D_{jt}$ and $D_{jt} = \Delta DT_{jt}^*$, j = 1, 2. To correct for serial correlation, we include augmented terms $\Delta\tilde{S}_{t-i}$, i = 1,..,k as necessary.[6] Under the unit root null hypothesis $\phi = 0$ in equation (1), the test statistic can be defined as follows:

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[6] At each combination of break points $\lambda = (\lambda_1, \lambda_2)'$ in the time interval [.1T, .9T] (to eliminate end points), where T is the sample size, we determine k by following the "general to specific" procedure suggested by Perron (1989). We begin with a maximum number of lagged first-differenced terms k = 8 and examine the last term to see if it is significantly different from zero at the 10% level (critical value in an asymptotic normal distribution is 1.645). If insignificant, the maximum lagged term is dropped and the model re-estimated with k = 7 terms. The procedure is repeated until either the maximum term is found or k = 0, at which point the procedure stops. This technique has been shown to perform well as compared to other data-dependent procedures to select the number of augmented terms in unit root tests (Ng and Perron, 1995).

$$\tilde{\tau} = \text{t-statistic for the null hypothesis } \phi = 0. \quad (2)$$

To endogenously determine the location of two breaks ($\lambda_j = T_{Bj}/T$, j=1, 2), the LM unit root test uses a grid search as follows:

$$LM_\tau = \underset{\lambda}{\text{Inf}}\, \tilde{\tau}(\lambda). \quad (3)$$

The combination of two break points is determined where the unit root t-test statistic is the most negative and, thus, least favorable to the unit root null hypothesis. As demonstrated in Lee and Strazicich (2003a, 2003b), critical values for the model with level and trend break(s) depend (somewhat) on the location of the breaks (λ_j). Therefore, we use critical values that correspond to the location of the breaks.

After identifying two breaks in level and trend for each country we examine the significance of each break at the 10% level in an asymptotic normal distribution (i.e., critical value is 1.645). If two break years are not significant, we repeat the testing procedure using the one-break LM unit root test of Lee and Strazicich (2003a).[7] If no break is statistically significant at the 10% level in the one break test, we utilize the conventional (no break) ADF test. In this manner we also endogenously determine the number of structural breaks for each country.[8]

The two-break LM test results for the global average are displayed in the first line of Table 1 labeled "WORLD." The global average CO_2 emissions per capita series rejects the unit root at the 10 percent significance level, with structural breaks in 1968 and 1981. Given our

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[7] The one-break minimum LM unit root test has similar properties to the two-break minimum LM test.

[8] Gauss codes for the one- and two-break minimum LM unit root test are available on the web site http://www.cba.ua.edu/~jlee/gauss.

finding that global per capita emissions are stationary after controlling for structural breaks we estimated a simple OLS regression on the three identified intercepts (D) and trends (T). We utilize White's robust standard errors to correct for possible heteroskedasticity. In addition, we include an AR(1) term to correct for serial correlation.[9] The estimated coefficients can be used to examine more carefully the size and significance of the different intercepts and trends. The estimated equation is identified as follows (t-statistics in parentheses):

Regression of Global Average Per Capita CO_2 Emissions on Structural Breaks 1950-2000

$$\underset{(17.73)}{0.605D51} + \underset{(31.37)}{1.077D69} + \underset{(53.23)}{1.140D82} + \underset{(8.87)}{0.022T51} + \underset{(1.55)}{0.009T69} - \underset{(-0.76)}{0.001T82} \qquad (4)$$

Adjusted R-squared = 0.9804 S.E.E = 0.0228 D.W. = 1.7078

The coefficients in (4) estimate three intercepts and trends in global per capita CO_2 emissions corresponding to the three time spans identified by the structural breaks (i.e., 1951-1968, 1969-1981, and 1982-2000). While there is a small increase in the intercept of per capita emissions following each break (i.e., after 1968 and 1981), the trend slope is not significantly different from zero after 1968 (at the 10% level). While we do not attempt to interpret the timing of the breaks, Lanne and Liski (2004) estimate structural breaks in long time series of per capita CO_2 in 16 industrialized nations and conclude that none could be readily identified with well-known oil price shocks. This may be because CO_2 emissions are more heavily influenced by solid fuel consumption (coal, etc.) than by liquid petroleum use, but whatever the explanation it is not

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[9] A general to specific procedure similar to that described in footnote 7 was utilized to determine the correct number of AR terms.

necessary to rationalize the dating of endogenous breaks in order to derive implications from our findings.

In summary, the above empirical findings indicate that global per capita emissions have evolved into a trendless series centered on a stationary mean. The estimated 1969-1981 mean (D69) and standard deviation is 1.077 and 0.034, respectively, while the estimated 1982-2000 mean (D82) and standard deviation is 1.140 and 0.021, respectively. For the inferences below we use the post-1981 mean and standard deviation. To compare the actual global average emissions data with the values fitted from regression (4) we display both series in Figure 1. Visual examination supports our empirical findings, as the fitted values are closely aligned with the identified breaks.

3. Examination of 121 Countries

We now turn to our unit root test results for the 121 individual countries for which we were able to obtain consistent time series on per capita CO_2 emissions from 1950-2000. In Table 1, a bold-faced entry indicates that the unit root hypothesis could not be rejected (at the 10% level). This finding of nonstationarity was observed for 26 countries. However, in 22 of these countries the test statistic nearly rejects the unit root (at the 10% level). Given the relatively low power of unit root tests in general, we might consider that all of the 121 per capita emission series are stationary. To consider this possibility, we also test the 121-country average emissions series (total emissions divided by total population for these 121 countries) using the two-break LM unit root test. Since only one significant structural break was identified, we repeated our test procedure using the one-break LM unit root test. The endogenous one-break LM test results are displayed in the top row of Table 1 as “121 Average.” As with the global average series, the unit root null hypothesis is rejected (at the 10% level). Given that the 121 country average series is stationary after allowing for one structural break, we perform an OLS regression on intercepts and trends similar to (4). The results are as follows:

Regression of 121-Country Average Per Capita CO_2 Emissions on Structural Breaks 1950-2000

$$\underset{(9.90)}{0.623D52} + \underset{(29.99)}{1.089D79} + \underset{(4.82)}{0.015T52} - \underset{(-0.34)}{0.001T79} \tag{5}$$

Adjusted R-squared = 0.9820   S.E.E = 0.019   D.W. = 1.7086

The coefficients in (5) estimate two intercepts and trends in the average per capita CO_2 emissions of the 121 countries in Table 1. The coefficients correspond to the time spans identified by the structural breaks (i.e., 1951-1978 and 1979-2000).[10] While there is a small increase in the mean of per capita emissions after 1978, the post-1978 trend slope is slightly negative but not significantly different from zero (at the 10% level). Again, to compare the actual 121-country average emissions data with the values fitted from our regression in (5) we display both series in Figure 2. Visual examination again supports our empirical findings, as the fitted values are closely aligned with the identified breaks.

Since the 121-country average emissions series is stationary, we can infer that if the 26 countries identified in Table 1 are indeed nonstationary then a cointegrating relationship exists such that shocks to per capita emissions in one or more of the 26 countries is offset by opposing movements in other countries. Theoretically, if 95 of the 121 country series are I(0) (i.e., stationary in levels) and the remaining 26 countries are I(1) (i.e., stationary after differencing),

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[10] The regression in (5) uses White's heteroskedasticity-consistent standard errors and includes an AR(1) and AR(2) term to correct for serial correlation. The number of AR terms was determined with the general to specific procedure described for (4).

but the 121 country average is I(0), then the 26 nonstationary series must be cointegrated. Practically speaking, this could arise, for example, through the energy market. If increased emissions in one country reflect increased energy consumption, this could cause upward pressure on energy prices and induce lower emissions in other countries. On the other hand, as previously noted, the inability to reject the unit root null hypothesis for 26 of the 121 countries might be due to insufficient power and per capita emissions may indeed be stationary in all countries.

To examine the time paths of country emissions in more detail, we performed OLS regressions of per capita emissions on intercepts and trends for the 95 stationary series identified by the LM test results in Table 1.[11] The methodology followed is the same as when estimating equations (4) and (5). Table 2 shows the estimated trend coefficients for the individual countries in the time period following the most recent structural break. Overall, 46 (48%) of the 95 countries that reject the unit root (at the 10% level) have positive and significant trends in their per capita emissions, while 18 (19%) have negative and significant trends. The remaining 31 (33%) countries have no significant trend. Thus over half (52%) of the countries have (recent) trend slopes that are either negative or not significantly different from zero.

To summarize, national per capita CO_2 emissions are primarily stationary, except possibly for a subgroup of 26 countries which, if nonstationary, must be cointegrated. The time series of global per capita CO_2 emissions rejects the unit root and is well represented by a stationary model with two structural breaks, with a post-1981 trend slope that is negative and insignificant. Given these findings, we conclude that post-1981 global per capita CO_2 emissions

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[11] Regressions were not reported for the 26 countries that could not reject the unit root in Table 1, as regression results from these time series may be unreliable.

can be well described by a stationary mean of 1.14 tonnes per person with a standard deviation of 0.02, implying a 2-sigma confidence interval of 1.10 to 1.18 annual tonnes per capita.

4. Evaluating the Probability of Carbon Dioxide Emission Scenarios

In this section we ask what can be said about the probability of future emissions scenarios if the global average per capita emissions level is a constant. The forty SRES scenarios are summarized in Table 3. As of 2000, the observed distribution of per capita emissions overlaps with the histogram of the SRES scenarios (Figure 3), which indeed are more clustered and slightly lower than the observed distribution.

But Figure 4 shows that after 2000 the match between the SRES distribution and the observed data breaks down. The observed distribution in Figure 4 is the same as in Figure 3, i.e. $N(1.14, 0.02^2)$ but the axes are rescaled to accommodate the histograms of the SRES emissions rates in 2020 and 2050. As of 2020 the SRES distribution has spilled dramatically out to the right, and the dispersion carries on through 2050. A ten standard deviation departure above the mean would imply 1.34 tonnes per person annually. Figure 4 shows that by 2050 the spread has continued well past this, with some scenarios going past 2.74 tonnes or 80 standard deviations above the mean.

Table 4 shows the probabilities attached to each of the 40 SRES scenarios, evaluated by comparing the implied per capita emissions in 2020 and 2050 to $N(1.14, 0.02^2)$. We have highlighted in italics the 14 scenarios that are within five standard deviations of the mean as of 2020, and in bold the 7 scenarios that are in the same proximity as of 2050. This range is quite wide in probability terms, and would permit the mean to drift upward by one standard deviation per decade for the first half of the 21st century. Any scenarios outside this range can likely be set aside as too improbable to merit close consideration.

For the seven scenarios that are plausible as of 2050, the total emissions projected as of 2050 average to 10.1 GtC, with a range of 9.11 to 11.23 GtC. Most population projections predict declining numbers of people after 2050, which will serve to reduce global CO_2 emissions through the remainder of the century.

If a trend were to re-appear in the data starting at 2000, a worst-case scenario by historical standards would have per capita emissions rising by about 0.02 tonnes per capita per year (see equation 4). If this persisted for 50 years, emissions would rise from 1.14 to 2.14 tonnes per capita. If this were taken as the upper limit of emissions, it would still rule out 8 of the 40 SRES scenarios. If the trend were only to reach the 1968-1980 magnitude, but continue for 50 years, emissions per capita would rise to 1.59 tonnes per capita, leaving 17 of 40 beyond the maximum. To validate the highest SRES scenario, we would need to observe an annual increase in emissions per capita of just under 0.04 tonnes per person every year for the next 50 years, roughly double the trend observed during the 1950-1968 time period.

4. Conclusions

The SRES emissions scenarios used by the IPCC are very influential on discussions of the global warming issue. But because they span a very wide range, as do emissions projections generated by economic modelers over the past decade, they provide little guidance about probable future emissions. We showed that, despite considerable variability in per capita CO_2 emission levels within and among countries, the global per capita CO_2 emissions are extremely stable. In particular, global per capita emissions are stationary and trendless, perhaps reflecting the role of international energy markets in constraining total fossil fuel consumption. The current mean of 1.14 tonnes per person is neither drifting nor trending upwards, despite worldwide growth in per capita income and consumption. This suggests that the probability of realizing projections of long-range global emissions can be evaluated by the proximity of their implied per capita emissions to the current mean. Even allowing for a more generous 5 standard-deviation departure from the mean over the next 50 years disqualifies 33 of the 40 IPCC emissions scenarios. Those remaining have an overall average of 10.1 billion tonnes of annual fossil fuel-based CO_2 emissions, suggesting the most likely emissions trajectory is at the low end of the ensemble used in the IPCC projections of global warming.

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TABLE 1. LM Unit Root Tests of Per Capita CO_2 Emissions for the Global Average and 121 Countries, 1950-2000

Country	t-statistic	breaks	Country	t-statistic	breaks	Country	t-statistic	breaks
WORLD	-5.39c	68, 81	121 Average	-4.31c	78			
Afghanistan	-7.06a	68, 90	**Guinea Bissau**	**-3.95**	72	Pap.NewGuinea	-7.04a	70, 82
Albania	-6.88a	75, 89	**Guyana**	**-5.24**	73, 86	Paraguay	-6.99a	77, 92
Algeria	-5.54b	70, 82	Haiti	-4.41c	91	Peru	-6.21b	71, 86
Angola	-6.24b	71, 93	**Honduras**	**-4.05**	80	**Philippines**	**-4.71**	71, 82
Argentina	**-4.97**	83	Hong Kong	-7.79a	68, 84	Poland	-6.74a	74, 88
Australia	-5.52c	77, 90	Hungary	-5.53c	74, 88	Portugal	-8.74a	71, 87
Austria	-5.69b	69, 82	Iceland	-6.46a	67, 80	**Qatar**	**-4.95**	62, 89
Bahamas	-7.88a	69, 88	India	-6.22b	76, 94	Rep.Cameroon	-7.21a	78, 88
Bahrain	-6.09ba	71, 75	Indonesia	5.75b	68, 90	Romania	-8.14a	74, 88
Barbados	-7.58a	61, 90	Iraq	-7.22a	79, 84	St. Lucia	-7.53a	68, 92
Belgium	-5.40c	70, 81	Ireland	-3.39c		Samoa	-8.52a	74, 80
Belize	**-1.47**		Iran	-5.62c	71, 86	SaoTomePrinc.	-5.61c	69, 82
Bolivia	-7.43a	77	Israel	-5.61c	73, 90	**Saudi Arabia**	**-4.53**	70, 87
Brazil	-5.49c	71, 85	**Italy**	**-4.24**	77, 88	Seychelles	-4.20c	69
Brunei	-8.95a	68, 80	Jamaica	-6.16b	70, 83	Sierra Leone	-7.70a	68, 81
Bulgaria	**-5.28**	74, 94	Japan	-6.87a	67, 80	SolomonIslands	-4.61b	77
Canada	**-4.27**	62, 74	Jordan	-7.76a	79, 88	South Africa	-7.81a	77, 88
Cape Verde	**-2.69**	60	**Kenya**	**-4.43**	65, 89	**Spain**	**-4.26**	69, 88
Chile	-5.97b	69, 86	Korea N.	-6.13b	77, 86	Sri Lanka	-5.84b	68, 82
China	-9.05a	64, 93	**Korea S.**	**-1.21**		St. Vincent	-4.97b	83
Columbia	-6.66a	68, 90	Kuwait	-6.66a	62, 76	**Sudan**	**-4.91**	68, 90
Costa Rica	**-4.84**	77, 92	Lebanon	-5.56a	90	Suriname	-5.58c	73, 88
Cuba	-5.67b	73, 88	Liberia	-5.46c	67, 83	Sweden	-5.59c	66, 80
Cyprus	-5.85b	69, 72	Libya	-10.26a	65, 76	Switzerland	-6.07b	60, 69
Denmark	-5.57c	67, 90	Luxembourg	-5.48c	66, 81	**Syria**	**-4.16**	77
Djibouti	-5.99b	66, 80	Madagascar	-6.25b	70, 84	Taiwan	-6.04b	74, 85
Dominica	-6.27b	74, 95	Malta	-4.85b	88	Thailand	-9.26a	79, 93
Dominican Rep	-5.51c	71, 86	Mauritius	-5.42c	73, 88	Togo	-8.32a	95
Ecuador	-5.47c	77, 88	Mexico	-6.48a	68, 78	Tonga	-5.94b	64, 88
Egypt	-6.34a	65	Mongolia	-8.99a	83	Trinidad Tobago	-5.97b	75, 86
El Salvador	-5.65c	79, 91	Morocco	-6.87a	71, 82	Tunisia	-4.36c	77
Equat. Guinea	-7.23a	95	Mozambique	-5.71c	79, 92	**Turkey**	**-5.10**	70, 92
Fiji	-5.67c	62, 83	Myanmar	-7.20a	66, 85	**Uganda**	**-5.13**	65, 83
Finland	**-4.02**	70	Nepal	-7.69a	70, 87	United ArabEm	-9.09a	67, 79
France	-5.82b	74, 84	**Netherlands**	**-4.06**	70	United Kingdom	-5.09a	74
Gambia, The	-4.75b	76	New Zealand	-6.72a	76, 85	**United States**	**-4.21**	62, 80
Germany	**-5.48**	68, 89	Nicaragua	-6.97a	74, 89	Uruguay	-5.35b	81, 90
Ghana	-7.39a	69, 88	**Nigeria**	**-5.20**	70, 87	Vanuatu	-6.58a	61, 68
Greece	-5.65b	69, 89	Norway	-8.94a	80, 88	**Venezuela**	**-4.55**	60, 93
Grenada	-7.47a	78, 84	Panama	-5.75b	77, 80	Zaire	-6.22b	69, 81
Guatemala	-4.52b	85, 95						

Notes: The dependent variable is the level of annual per capita co_2 emissions in country i. t-statistic tests the null hypothesis of a unit root. All unit root tests include intercept(s) and trend(s). Breaks denote the structural break years that were identified by the one- or two-break LM unit root test (the 1900 prefix is omitted to conserve space). A blank space denotes no breaks were significant at the 10% level. In the case of no significant breaks, the results were obtained using the conventional ADF test. a, b, and c denote significance at the 1%, 5%, and 10% levels, respectively. Critical values for the one- and two-break minimum LM test come from Lee and Strazicich (2003a, 2003b).

TABLE 2. OLS Coefficient of Final Trend Break in Per Capita CO_2 Emissions

Country	trend	break
Afghanistan	-0.003b	90
Albania	-0.029	89
Algeria	0.002	82
Angola	-0.010	93
Argentina		83
Australia	0.100a	90
Austria	0.011a	82
Bahamas	-0.109	88
Bahrain	0.063a	75
Barbados	-0.021	90
Belgium	-0.024c	81
Belize		
Bolivia	0.003	77
Brazil	0.005c	85
Brunei	0.125a	80
Bulgaria		94
Canada		74
Cape Verde		60
Chile	0.047a	86
China	0.004	93
Columbia	-0.013a	90
Costa Rica		92
Cuba	-0.014b	88
Cyprus	0.046a	72
Denmark	-0.101a	90
Djibouti	-0.003a	80
Dominica	0.032a	95
Dominican Rep	0.028a	86
Ecuador	0.006	88
Egypt	0.026c	65
El Salvador	0.014a	91
Equat. Guinea	-0.003	95
Fiji	0.002b	83
Finland		70
France	-0.014	84
Gambia, The	-0.0004	76
Germany		89
Ghana	0.003a	88
Greece	0.051a	89
Grenada	0.027a	84
Guatemala	0.017	95
Guinea Bissau		72
Guyana		86
Haiti	0.002	91
Honduras		80
Hong Kong	0.007	84
Hungary	-0.040a	88
Iceland	0.010a	80
India	0.005	94
Indonesia	0.009b	90
Iraq	0.012a	84
Ireland	0.042a	
Iran	0.039a	86
Israel	0.103a	90
Italy		88
Jamaica	0.039a	83
Japan	0.022b	80
Jordan	0.012	88
Kenya		89
Korea N.	-0.003	86
Korea S.		
Kuwait	0.082b	76
Lebanon	0.036b	90
Liberia	-0.005a	83
Libya	0.010	76
Luxembourg	-0.096a	81
Madagascar	0.0009a	84
Malta	0.083a	88
Mauritius	0.031a	88
Mexico	0.010a	78
Mongolia	-0.012	83
Morocco	0.007a	82
Mozambique	0.001	92
Myanmar	0.001	85
Nepal	0.002a	87
Netherlands		70
New Zealand	0.025a	85
Nicaragua	0.004b	89
Nigeria		87
Norway	0.102	88
Panama	0.013b	80
Pap.NewGuinea	-0.002b	82
Paraguay	0.001	92
Peru	0.005	86
Philippines		82
Poland	-0.048a	88
Portugal	0.050a	87
Qatar		89
Rep.Cameroon	-0.006	88
Romania	-0.144a	88
St. Lucia	0.030b	92
Samoa	0.002a	80
SaoTomePrinc.	0.002a	82
Saudi Arabia		87
Seychelles	0.020a	69
Sierra Leone	0.0001	81
SolomonIslands	-0.0003	77
South Africa	-0.027c	88
Spain		88
Sri Lanka	0.003b	82
St. Vincent	0.015a	83
Sudan		90
Suriname	0.0004	88
Sweden	-0.035a	80
Switzerland	-0.010a	69
Syria		77
Taiwan	0.099a	85
Thailand	0.179a	93
Togo	0.010	95
Tonga	0.012a	88
Trinidad Tobago	0.112a	86
Tunisia	0.008a	77
Turkey		92
Uganda		83
United ArabEm	0.051	79
United Kingdom	-0.016a	74
United States		80
Uruguay	0.010	90
Vanuatu	-0.002a	68
Venezuela		93
Zaire	-0.001a	81

Notes: The dependent variable is the level of annual per capita co_2 emissions in country i. The above results are from regression on means and trends identified using the LM test results in Table 1. Break denotes the most recent structural break year identified by the one- or two-break LM unit root test (the 1900 prefix is omitted to conserve space). Trend is the t-statistic of the estimated trend slope coefficient following the most final structural break. The t-statistic tests the null hypothesis that the trend slope coefficient following the recent structural break is insignificant from zero. A blank space denotes no breaks were significant at the 10% level. In the case of no significant breaks, the results were obtained using the conventional ADF test (with intercept and trend). a, b, and c denote significance at the 1%, 5%, and 10% levels, respectively.

TABLE 3: Forty SRES Scenarios and Implied Per Capita Emissions at 2000, 2020, and 2050

		2000	2020			2050		
	Name of Scenario	CO_2/capita (tons/person)	Population (millions)	Total CO_2 (GtC)	CO_2/capita (tonnes)	Population (millions)	Total CO_2 (GtC)	CO_2/capita (tonnes)
1	A1B-AIM	1.1280	7,493	12.12	1.6175	8,704	16.01	1.8394
2	A1B-ASF	1.1280	7,537	14.67	1.9464	8,704	25.72	2.9550
3	A1B-IMAGE	1.1271	7,618	11.10	1.4571	8,708	18.70	2.1475
4	A1B-MARIA	1.1280	7,617	8.69	1.1409	8,704	12.66	1.4545
5	A1B-MESSAGE	1.1280	7,617	10.56	1.3864	8,704	16.47	1.8922
6	A1B-MiniCAM	1.1311	7,618	10.74	1.4098	8,703	18.18	2.0889
7	A1C-AIM	1.1280	7,493	14.34	1.9138	8,704	26.79	3.0779
8	A1C-MESSAGE	1.1280	7,617	10.97	1.4402	8,704	20.64	2.3713
9	A1C-MiniCAM	1.1311	7,618	10.99	1.4426	8,703	24.45	2.8094
10	A1G-AIM	1.1280	7,493	13.09	1.7470	8,704	25.58	2.9389
11	A1G-MESSAGE	1.1280	7,617	10.66	1.3995	8,704	21.45	2.4644
12	A1FI-MiniCAM	1.1311	7,618	11.19	1.4689	8,703	23.10	2.6543
13	A1T-AIM	1.1280	7,493	9.79	1.3066	8,704	11.43	1.3132
14	A1T-MESSAGE	1.1280	7,617	10.00	1.3129	8,704	12.29	1.4120
15	A1T-MARIA	1.1280	7,617	8.41	1.1041	8,704	10.80	1.2408
16	A1v1-MiniCAM	1.1311	7,618	9.81	1.2877	8,703	15.80	1.8155
17	A1v2-MiniCAM	1.1591	7,228	9.91	1.3711	8,393	15.39	1.8337
18	A2-AIM	1.1252	8,198	11.29	1.3772	11,287	16.60	1.4707
19	A2-ASF	1.1183	8,206	11.01	1.3417	11,296	16.49	1.4598
20	A2G-IMAGE	1.1183	8,225	9.07	1.1027	11,298	18.17	1.6082
21	A2-MESSAGE	1.1183	8,206	10.32	1.2576	11,296	15.11	1.3376
22	A2-MiniCAM	1.1115	8,192	9.40	1.1475	11,296	15.24	1.3492
23	A2-A1-MiniCAM	1.1487	7,558	7.89	1.0439	9,723	10.46	1.0758
24	B1-AIM	1.1394	7,426	10.05	1.3534	8,631	12.59	1.4587
25	B1-ASF	1.1280	7,537	13.22	1.7540	8,704	17.50	2.0106
26	B1-IMAGE	1.1271	7,618	10.00	1.3127	8,708	11.70	1.3436
27	B1-MARIA	1.1280	7,617	7.80	1.0240	8,704	9.11	1.0466
28	B1-MESSAGE	1.1280	7,617	9.19	1.2065	8,704	9.24	1.0616
29	B1-MiniCAM	1.1311	7,618	8.23	1.0803	8,703	9.30	1.0686
30	B1T-MESSAGE	1.1280	7,617	9.11	1.1960	8,704	8.48	0.9743
31	B1High-MESSAGE	1.1280	7,617	8.99	1.1803	8,704	10.11	1.1615
32	B1High-MiniCAM	1.1311	7,618	9.15	1.2011	8,703	11.93	1.3708
33	B2-AIM	1.1328	7,612	10.21	1.3413	9,367	14.96	1.5971
34	B2-ASF	1.1328	7,650	11.48	1.5007	9,367	15.42	1.6462
35	B2-IMAGE	1.1328	7,869	8.47	1.0764	9,875	11.23	1.1372
36	B2-MARIA	1.1328	7,672	8.85	1.1535	9,367	12.74	1.3601
37	B2-MESSAGE	1.1328	7,672	9.02	1.1757	9,367	11.23	1.1989
38	B2-MiniCAM	1.1225	7,880	9.11	1.1561	9,874	12.73	1.2892
39	B2C-MARIA	1.1328	7,672	9.56	1.2461	9,367	14.28	1.5245
40	B2High-MiniCAM	1.1225	7,880	9.92	1.2589	9,874	16.44	1.6650

Notes: Also shown for 2020 and 2050 is the total projected population and total projected emissions.

TABLE 4. Probability of Observing Projected Per Capita Emissions, or Higher, as of 2020 and 2050, for each of the 40 SRES Scenarios

		2020			2050		
	Name of Scenario	CO_2/capita (tonnes)	Z-score	Prob(Z)	CO_2/capita (tonnes)	Z-score	Prob(Z)
1	A1B-AIM	1.6175	23.87	0.0000	1.8390	34.95	0.0000
2	A1B-ASF	1.9464	40.32	0.0000	2.9550	90.75	0.0000
3	A1B-IMAGE	1.4571	15.86	0.0000	2.1470	50.35	0.0000
4	*A1B-MARIA*	*1.1409*	*0.05*	*0.4821*	*1.4550*	*15.75*	*0.0000*
5	A1B-MESSAGE	1.3864	12.32	0.0000	1.8920	37.60	0.0000
6	A1B-MiniCAM	1.4098	13.49	0.0000	2.0890	47.45	0.0000
7	A1C-AIM	1.9138	38.69	0.0000	3.0780	96.90	0.0000
8	A1C-MESSAGE	1.4402	15.01	0.0000	2.3710	61.55	0.0000
9	A1C-MiniCAM	1.4426	15.13	0.0000	2.8090	83.45	0.0000
10	A1G-AIM	1.7470	30.35	0.0000	2.9390	89.95	0.0000
11	A1G-MESSAGE	1.3995	12.98	0.0000	2.4640	66.20	0.0000
12	A1FI-MiniCAM	1.4689	16.44	0.0000	2.6540	75.70	0.0000
13	A1T-AIM	1.3066	8.33	0.0000	1.3130	8.65	0.0000
14	A1T-MESSAGE	1.3129	8.64	0.0000	1.4120	13.60	0.0000
15	*A1T-MARIA*	*1.1041*	*-1.80*	*0.9637*	*1.2410*	*5.05*	*0.0000*
16	A1v1-MiniCAM	1.2877	7.39	0.0000	1.8150	33.75	0.0000
17	A1v2-MiniCAM	1.3711	11.55	0.0000	1.8340	34.70	0.0000
18	A2-AIM	1.3772	11.86	0.0000	1.4710	16.55	0.0000
19	A2-ASF	1.3417	10.08	0.0000	1.4600	16.00	0.0000
20	*A2G-IMAGE*	*1.1027*	*-1.87*	*0.9689*	*1.6080*	*23.40*	*0.0000*
21	A2-MESSAGE	1.2576	5.88	0.0000	1.3380	9.90	0.0000
22	*A2-MiniCAM*	*1.1475*	*0.38*	*0.3538*	*1.3490*	*10.45*	*0.0000*
23	***A2-A1-MiniCAM***	***1.0439***	***-4.80***	***1.0000***	***1.0760***	***-3.20***	***0.9993***
24	B1-AIM	1.3534	10.67	0.0000	1.4590	15.95	0.0000
25	B1-ASF	1.7540	30.70	0.0000	2.0110	43.55	0.0000
26	B1-IMAGE	1.3127	8.64	0.0000	1.3440	10.20	0.0000
27	**B1-MARIA**	**1.0240**	**-5.80**	**1.0000**	**1.0470**	**-4.65**	**1.0000**
28	***B1-MESSAGE***	***1.2065***	***3.33***	***0.0004***	***1.0620***	***-3.90***	***1.0000***
29	***B1-MiniCAM***	***1.0803***	***-2.99***	***0.9986***	***1.0690***	***-3.55***	***0.9998***
30	*B1T-MESSAGE*	*1.1960*	*2.80*	*0.0026*	*0.9740*	*-8.30*	*1.0000*
31	***B1High-MESSAGE***	***1.1803***	***2.01***	***0.0220***	***1.1620***	***1.10***	***0.1357***
32	*B1High-MiniCAM*	*1.2011*	*3.05*	*0.0011*	*1.3710*	*11.55*	*0.0000*
33	B2-AIM	1.3413	10.07	0.0000	1.5970	22.85	0.0000
34	B2-ASF	1.5007	18.03	0.0000	1.6460	25.30	0.0000
35	***B2-IMAGE***	***1.0764***	***-3.18***	***0.9993***	***1.1370***	***-0.15***	***0.5596***
36	*B2-MARIA*	*1.1535*	*0.67*	*0.2498*	*1.3600*	*11.00*	*0.0000*
37	***B2-MESSAGE***	***1.1757***	***1.78***	***0.0371***	***1.1990***	***2.95***	***0.0016***
38	*B2-MiniCAM*	*1.1561*	*0.81*	*0.2104*	*1.2890*	*7.45*	*0.0000*
39	B2C-MARIA	1.2461	5.30	0.0000	1.5250	19.25	0.0000
40	B2High-MiniCAM	1.2589	5.95	0.0000	1.6650	26.25	0.0000

Notes: Z-score: number of standard deviations above or below the observed mean of 1.14 tonnes. Prob(Z): probability of observing SRES emissions or higher, evaluated using $N(1.14, 0.02^2)$. Rows in *italics* show the 2020 outcome within 5 standard deviations of the observed mean. Rows in **bold** show the same for 2050.

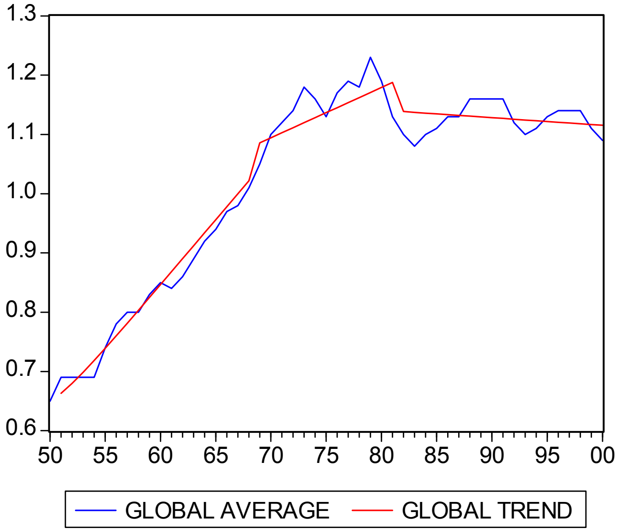

Figure 1. Global Per Capita CO_2 Emissions Data from 1950-2000, and least squares regression on two level and trend breaks.

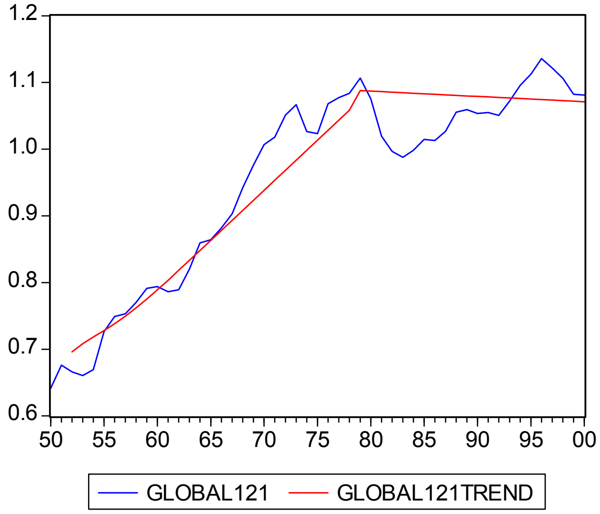

Figure 2. Average Per Capita CO_2 Emissions Data for 121 sample countries from 1950-2000, and least squares regression on one level and trend break.

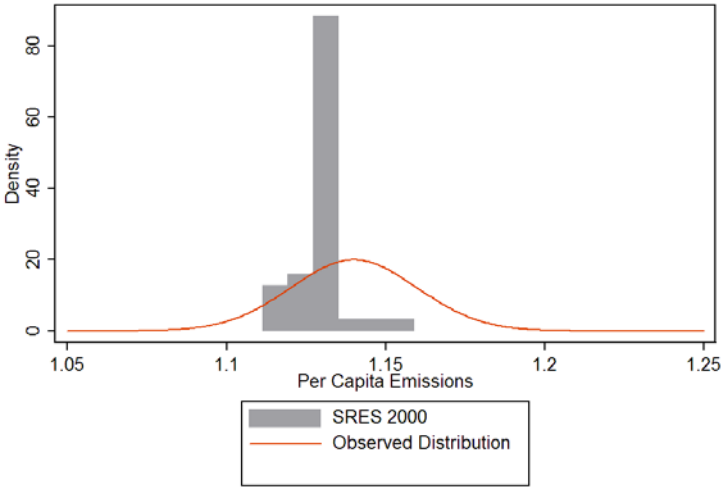

Figure 3. Histogram of implied CO_2 per capita emissions as of year 2000 in 40 SRES scenarios, compared to the observed distribution in global data ($N(1.14, 0.02^2)$).

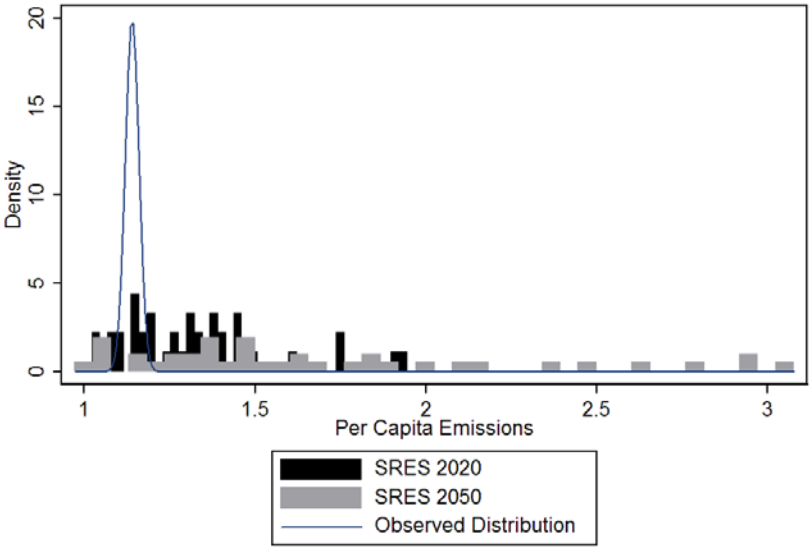

Figure 4. Histograms of implied CO_2 per capita emissions as of 2020 (black) and 2050 (grey) in 40 SRES scenarios, compared to the observed distribution in global data (*N*(1.14, 0.02^2)).