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# Divergence in State-Level Per Capita Carbon Dioxide Emissions

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## Abstract

Decisionmakers considering policies to mitigate climate change will benefit from information about current and future distributions of carbon dioxide (CO<sub>2</sub>) emissions. Examining the emissions dynamics of advanced economies that have experienced income convergence could provide insights about how distributions of country-level emissions may evolve over time if country-level incomes eventually undergo some convergence. This paper addresses the question of whether income convergence is sufficient for per capita CO<sub>2</sub> emissions convergence by focusing on a set of advanced economies, the U.S. states. I undertake a variety of cross-sectional and stochastic convergence tests with two novel measures of 1960–1999 state-level CO<sub>2</sub> emissions per capita—production (pre-electricity trade) CO<sub>2</sub> and consumption (post-electricity trade) CO<sub>2</sub>—and with income per capita. Although incomes continue to converge, I find stark divergence in production CO<sub>2</sub> per capita and no evidence of convergence for consumption CO<sub>2</sub> per capita. Forecasts of future distributions show little convergence in emissions.

**Key Words:** Markov chain transition matrix, sigma convergence, stochastic convergence, emissions distributions

**JEL Classification Numbers:** O40, Q54, Q56

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## Divergence in State-Level Per Capita Carbon Dioxide Emissions

Joseph E. Aldy\*

### Introduction

Understanding the geographic distribution of pollution can inform policymakers of the need for and the impacts of environmental policies. Assessing the distribution of air pollutant concentrations has shown whether pollution abatement has been progressive or regressive (Asch and Seneca 1978). The changes in ozone concentrations in attainment and nonattainment areas illustrate how some emissions-intensive industrial production grew faster in those areas with a lower regulatory burden (Henderson 1996). Recent research has explored the question of whether pollution distributions converge in a comparable fashion as income and may be considered a part of the economic growth process (List 1999; Brock and Taylor 2004).

The relationship between economic growth and pollution has received considerable attention in the context of carbon dioxide (CO<sub>2</sub>) emissions. Several studies have focused on per capita CO<sub>2</sub> emissions and assessed how they vary with per capita income by estimating reduced-form environmental Kuznets curves (Holtz-Eakin and Selden 1995; Schmalensee et al. 1998). Although it has been suggested that an inverted-U environmental Kuznets curve is sufficient for emissions convergence, Aldy (2006) shows that this is not the case for the transition to the steady state from any per capita emissions starting points among rich and poor economies.

More explicit tests of whether distributions of per capita CO<sub>2</sub> emissions have been converging using various tools from the empirical economic growth literature have yielded mixed results. For large international samples including developed and developing countries, Nguyen Van (2005) finds no convergence in per capita CO<sub>2</sub>, and Aldy (2006) reports some evidence of historical divergence and forecasts continued divergence over the next several decades. In contrast, for the countries of the Organisation for Economic Co-operation and

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Development (OECD), several papers report convergence in per capita CO<sub>2</sub> (Strazicich and List 2003; Brock and Taylor 2004; Nguyen Van 2005; and Aldy 2006).

The lack of emissions convergence among the broader, global set of countries may reflect the lack of convergence in incomes. The results for OECD countries suggest that as countries converge in per capita incomes, their per capita emissions of CO<sub>2</sub> also converge. This paper addresses this question by focusing on the distributional dynamics of income and emissions for another set of advanced economies, the U.S. states. By focusing on the states, with per capita incomes converging over the past century, I can explicitly assess whether per capita carbon dioxide emissions converge as a by-product of economic convergence.

A novel aspect of this analysis is that I evaluate the effects of emissions-intensive trade on the distributional dynamics of per capita emissions. I have constructed two state-level CO<sub>2</sub> data sets for the 1960–1999 period from a state energy consumption data set. The first data set is the standard measure of an economy’s CO<sub>2</sub> emissions, or a “production” measure, since it is based on where the emissions are produced. The second data set accounts for interstate electricity trade and adjusts a state’s CO<sub>2</sub> emissions up if it is a net importer of electricity and down if it is a net exporter. This post-trade, or “consumption,” measure of emissions better reflects the location of consumption of one major carbon-intensive good, electricity.<sup>1</sup>

This paper follows in the spirit of Barro and Sala-i-Martin (1992) on incomes, Asch and Seneca (1978) on particulate matter concentrations, and List (1999) on nitrogen oxide and sulfur dioxide emissions by focusing on distributions at the state level. It complements the country-level analyses on convergence in per capita carbon dioxide emissions by addressing another set of economies. It extends the literature by employing a broader set of tools for testing for convergence, and unlike most other papers, it presents forecasts of future emissions distributions as well.<sup>2</sup> By explicitly accounting for the effect of trade in electricity on state-level emissions, this paper provides additional insights on the nature of emissions distributional dynamics. I have also undertaken tests of income convergence to contextualize the emissions results.

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<sup>1</sup> Ideally, a complete consumption measure of carbon dioxide would also reflect the emissions intensity in all traded goods and services. Unfortunately, such interstate trade data are not collected.

<sup>2</sup> The forecasting of future distributions has received attention only in the companion paper by Aldy (2006) on country-level emissions distributions.

In contrast to the work on OECD countries, I find a striking *divergence* in state-level production CO<sub>2</sub> per capita over the 1960–1999 period. I find no evidence of convergence or divergence for state-level CO<sub>2</sub> per capita after accounting for the role of electricity trade, but I do find income convergence among the states. The lack of convergence in the historical CO<sub>2</sub> data is also evident in forecasts of future distributions based on Markov chain transition matrix analysis. The states' long-run steady-state distributions have thick tails and are less compact than current distributions. Forecasts of future dispersion measures reveal very little convergence relative to current distributions. The next section describes the construction of the state-level CO<sub>2</sub> emissions data set. The third section presents the states' historical analyses. The fourth section focuses on forecasting future emissions distributions. The final section concludes and offers suggestions for further research.

### States' Emissions and Income Data

I have constructed state-level emissions estimates based on fossil fuel combustion data for the 1960–1999 period. The Energy Information Administration (EIA 2001b) has compiled state-level energy consumption by fuel type and sector for this period. I converted energy consumption to CO<sub>2</sub> emissions using national sector- and fuel-specific emissions factors provided by EIA (2001a, Appendix B).<sup>3</sup> A total of 51 fuel-sector measures allowed for precise matches of fuel-sector emissions factors to sector-specific fuel consumption. Refer to Lutter (2000), Marland et al. (2003), and Blasing et al. (2004) for similar applications of this approach.

I undertook two checks to assess the plausibility of constructing state-level CO<sub>2</sub> emissions in this manner. First, I constructed national estimates from the state-level CO<sub>2</sub> emissions values and compared these with the Marland et al. (2003) and EIA (2001a) estimates for national emissions. Over 1960–1999, my constructed annual national values differ, on average, 1.9 percent from the Marland et al. estimates (1.6 percent standard deviation). The maximum annual differential between the data sets is 6.0 percent. A comparison with EIA (2001a) national CO<sub>2</sub> emissions estimates yields an average difference of 2.0 percent with a standard deviation of 0.92 percent. The maximum annual differential between the two data sets is 4.8 percent. To provide context for these comparisons, a comparison of the EIA and Marland et

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<sup>3</sup> All statistical analyses presented in this paper exclude Alaska, Hawaii, and Washington, DC.

al. national data sets arrives at similar magnitude differences: an average difference of 1.7 percent (1.0 percent standard deviation) with a maximum annual difference of 4.5 percent.

Second, I compared my data set with a state-level CO<sub>2</sub> emissions data set constructed and published after I began this research project. The Blasing et al. (2004) data set is constructed from the same source file as my data set (EIA 2001b), so the comparison can assess only differences in the methods used in constructing emissions from fossil fuel consumption. The dispersion (variance) in per capita emissions measures estimated from both data sets follows virtually identical paths over the 40-year period. The estimated interquartile ranges are very similar and follow the same trends over time as well. My constructed data set and the Blasing et al. data set yield very similar quantitative results and the same qualitative conclusions about the distributional dynamics for state-level carbon dioxide emissions over the 1960–1999 period.<sup>4</sup>

My constructed carbon dioxide data set represents emissions associated with producing all goods and services in a given state, so we can also denote them *production* CO<sub>2</sub> emissions. The standard measure of CO<sub>2</sub> emissions, this is comparable to the national measures used to develop greenhouse gas commitments under the Kyoto Protocol. In the presence of interstate trade, the emissions intensity of a state's production may differ from the intensity of this state's consumption. Some states may specialize in carbon-intensive production and export a substantial share of this output, while others may specialize in carbon-lean production for export.

To illustrate the potential role of trade in measuring carbon dioxide, a second emissions data set was constructed to account for interstate electricity trade. To construct this post-electricity trade CO<sub>2</sub> data set, I started with the production CO<sub>2</sub> data set. Then, I calculated the annual average carbon intensity of each state's electricity sector. For a state that is a net exporter of electricity in a given year, the carbon emissions associated with the exported electricity (reflecting the state's average electricity carbon intensity) are deducted from that state's total emissions for that year. For a net importer, that state's emissions are augmented based on the average carbon intensity of electricity imports.<sup>5</sup> Since this modified measure reflects post-trade

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<sup>4</sup> Additional details comparing the two data sets are available from the author upon request.

<sup>5</sup> This average intensity of imports is a national average; it reflects the average intensity of electricity generation for all states that export electricity in that year. Although the carbon intensity of the marginal power source for electricity would be preferable, it is difficult to determine what constitutes the marginal source in each state.

emissions and attempts to approximate for *consumption* emissions, as opposed to the production or standard measure of emissions, I refer to it as consumption CO<sub>2</sub> throughout this analysis.<sup>6</sup>

The income variable used in these analyses is the state personal income series of the Bureau of Economic Analysis (BEA 2000).<sup>7</sup> This series has been used in environmental Kuznets curve and economic growth papers (e.g., Aldy 2005; Barro and Sala-i-Martin 1992). BEA also provides the annual state population data used to construct all per capita estimates.

## Evaluation of Historical Convergence

To determine whether state-level per capita CO<sub>2</sub> emissions have been converging, I have adapted two common concepts of convergence from the empirical growth literature. First, I evaluated the emissions distributions to ascertain whether states that have low per capita emissions “catch up” to high per capita emissions states. This cross-sectional convergence could be evident through a reduction in the cross-sectional dispersion and compression in the emissions distribution. Second, I investigated whether differences in per capita emissions are persistent, thereby reflecting the permanence of shocks to per capita emissions. I employ time series tests for unit roots to assess for stochastic convergence. My analysis focuses on the production and consumption CO<sub>2</sub> measures, although I also present evidence of income convergence.

## Methods

Three types of analysis are used to assess cross-sectional convergence. First, I estimate the annual standard deviation of the natural logarithm of per capita CO<sub>2</sub> emissions for both production and consumption measures and for per capita income. This measure of dispersion, referred to as  $\sigma$ -convergence, has been used extensively in the economic growth literature but has received very little attention in emissions convergence research. If dispersion declines over time, then per capita emissions are converging in a  $\sigma$ -sense (Barro and Sala-i-Martin 1992).

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<sup>6</sup> If states that export electricity are disproportionately importers of energy-intensive goods, then this consumption measure could yield misleading results about the role of trade. To investigate this proposition, I evaluated petroleum and coal products; paper; primary metals; stone, glass, and clay; and chemicals—the five most energy-intensive two-digit SIC manufacturing industries according to the Energy Information Administration. There is little correlation between concentration in an energy-intensive industry (i.e., the state’s share of income from economic activity in this industry relative to the national average) and electricity exports: the correlation coefficients range from –0.18 to 0.06. This does not support the notion that states substitute the production of electricity with the production of other emissions-intensive goods.

<sup>7</sup> These values were converted to constant-year (1999) dollars based on the national CPI-Urban deflator.

Second, I present estimated kernel densities of per capita emissions and per capita income for 1960 and 1999 to illustrate emissions trends. Characterizing the complete distributions over time can further illuminate intradistributional dynamics that may not be captured by a single parameter characterizing the variance of the cross section ( $\sigma$ -convergence). Depicting distributions for production CO<sub>2</sub>, consumption CO<sub>2</sub>, and income can also illustrate the similarities and differences in the convergence of these measures over time. For these illustrations, a state's per capita emissions are expressed as the ratio of its emissions per capita to the national average for that year (i.e., relative emissions per capita [RE<sub>it</sub>] and relative income per capita [RY<sub>it</sub>]).<sup>8</sup> Normalizing a state's emissions against the national average allows us to discern state-specific movements from national growth or trends in emissions.

To estimate the densities, I have used the Epanechnikov kernel and Silverman's (1986) bandwidth choice rule. This yields a kernel density estimator function of

$$(1) \text{pdf}(RE_0) = (Nh)^{-1} \sum_{i=1}^N K\left(\frac{RE_i - RE_0}{h}\right)$$

$$\text{where } K = \frac{3(1 - 0.2RE^2)}{4\sqrt{5}} \text{ if } |RE| < \sqrt{5}, \text{ and } 0 \text{ otherwise,}$$

$$h = \frac{0.9 \left( \min \left\{ \hat{\sigma}, \frac{IQR^{75-25}}{1.349} \right\} \right)}{\sqrt{5}}, \text{ and}$$

$N$  is the number of states (sample size for these analyses),  $\hat{\sigma}$  represents the sample standard deviation, and  $IQR^{75-25}$  is the 75–25 interquartile range for the sample. The Epanechnikov kernel minimizes the mean integrated square error more efficiently than other kernel functions, and the Silverman bandwidth choice rule is commonly used in density estimation.

Third, to complement the estimated kernel densities, I estimate various percentiles in the emissions distributions and test whether the spread in a given interpercentile range differs statistically over various periods. I estimate the 20th and 80th percentiles and associated 80–20

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<sup>8</sup> All references to relative emissions, RE, in the equations in this paper also hold for the analogous relative income measure, RY.

interquartile ranges (IQRs) for the emissions per capita relative to the national average for these three-year periods: 1960–1962, 1969–1971, 1979–1981, 1989–1991, and 1997–1999.<sup>9</sup>

I use least absolute deviations estimators to construct these percentiles and IQRs. Let  $\theta_0$  be the estimated relative measure (RE or RY) at the percentile of interest. Then the least absolute deviations estimator of  $\theta_0$  solves

$$(2) \min_{\theta \in \Theta} N^{-1} \sum_{i=1}^N |RE_i - \theta| w_i$$

where  $w_i = 2q$  if  $RE_i - \theta_0 > 0$  and  $2(1-q)$  otherwise,  $\mathbf{1}$  is a vector of ones, and  $q$  is the quantile of interest. For example, in estimating the 80th percentile,  $q = 0.8$ , the positive residuals are weighted by 1.6, and the negative residuals by 0.4. The estimator for the IQR fits models that are the differences of the two estimated quantiles. The estimated variance-covariance matrices are based on bootstrapping with 1,000 replications.

Those estimates allow for an explicit evaluation of whether the spread in distribution changes over time in a statistically meaningful way through tests comparing the estimated magnitudes of the IQRs. The results also show whether changes in the interquartile spread reflect changes at the bottom of the distribution, at the top, or at both ends. I examine the null hypotheses that the 80–20 IQRs for the three-year periods around 1970, 1980, 1990, and 1998 are no different from that for the 1960–1962 period:

$$(3) H_0^i : \text{IQR}_{1960} = \text{IQR}_i \text{ for } i = 1970, 1980, 1990, 1998$$

A decrease in IQRs since the 1960–1962 period and a rejection of the null suggests that the tails of the distribution have moved closer over time, indicating convergence; an increase in IQRs over time and a rejection of the null suggests divergence. I jointly estimate the IQRs for each pair under consideration and evaluate these hypotheses with a Wald test.

To assess stochastic convergence, I test for whether a unit root characterizes the time series of relative emissions per capita. If per capita emissions are converging in a stochastic sense, then shocks to emissions are temporary and the data are stationary over time. If a unit root characterizes the emissions time series, however, then shocks are permanent and emissions are

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<sup>9</sup> I have made similar estimates based on one-year samples (1960, 1970, 1980, 1990, and 1999), which yield very similar point estimates but larger estimated standard errors. I have estimated the 75–25 and 90–10 ranges, and these results are available from the author upon request.

not converging. Carlino and Mills (1993) used tests for unit roots to evaluate income convergence among U.S. regions and found evidence of income convergence. In the emissions context, List (1999) conducted such tests for assessing regional convergence in per capita emissions of nitrogen oxides (NO<sub>x</sub>) and sulfur dioxide (SO<sub>2</sub>), and Strazicich and List (2003) applied a panel-based unit root test to OECD countries for per capita CO<sub>2</sub> emissions.

I have employed the exact panel-based unit root test developed by Im et al. (2003) to determine whether the states' emissions and incomes are converging in a stochastic sense. The first step of the test requires state-specific augmented Dickey-Fuller tests. To construct the Dickey-Fuller test statistic, I have estimated on a state-by-state basis the following specification:

$$(4) \Delta RE_t = \alpha_0 + \alpha_1 time + \delta RE_{t-1} + \sum_{p=1}^P \beta_p \Delta RE_{t-p} + \varepsilon_t$$

where  $\Delta RE_t$  is the first difference of relative emissions per capita,  $RE_t - RE_{t-1}$ ,  $time$  is a time trend, and  $P$  is the lag length. The augmented Dickey-Fuller statistic is the t-statistic testing  $\delta = 0$ , denoted by  $t_\delta^i$ . An analogous relative income specification is also estimated for the relative income per capita unit root tests. The lag length, which is allowed to vary from one to five, is chosen on a state-by-state basis using the Akaike Information Criterion. The Im et al. test statistic is constructed by averaging the state-specific augmented Dickey-Fuller statistics:

$$(5) \bar{t}_{NT} = N^{-1} \sum_{i=1}^N t_\delta^i .$$

Im et al. showed that this test is more powerful than individual augmented Dickey-Fuller tests in rejecting the null hypothesis that unit roots characterize every time series under consideration. They also estimated sample critical values via simulation for evaluating the panel-based test statistic that will be used to assess the two carbon dioxide measures and the income measure.

### ***Historical Evaluation of Emissions and Income Convergence***

Figure 1 illustrates quite starkly a divergence in states' production emissions per capita over the 1960–1999 period. This trend is all the more striking considering that per capita incomes among the states continue to converge (following a century-plus trend; see Barro and Sala-i-Martin 1992). The dispersion in consumption CO<sub>2</sub> also increases with time but to a much lesser extent than the production emissions series. The increase in the dispersion coefficient for production CO<sub>2</sub> was more than double the increase in the consumption measure. This suggests

that trade in electricity, which has increased in total and as a share of electricity generated over time, may be responsible for part of the divergence in per capita emissions.

The smaller variance in incomes relative to emissions in Figure 1 is also evident in Figures 2 and 3. In 1960, the relative income per capita distribution was more compact than either of the emissions distributions. With little interstate electricity trade in 1960, the two emissions per capita distributions are nearly identical. In 1999, the income distribution has become even more compact while the emissions distributions have both increased their spread, especially with thicker upper tails of the distribution. The consumption density peaks closer to one, while the top of the distribution has increased, but less so than the production distribution.

In 1960, only two states had production emissions per capita that were less than half the national average, and no states had such emissions more than twice the national average. By 1999, nine states were at least a factor of two away from the national average. Following a similar trend, only one state had consumption emissions per capita less than half the national average in 1960, and none had such emissions at least twice the national average. In 1999, six states had consumption CO<sub>2</sub> emissions that were at least a factor of two away from the national average.

Table 1 presents the estimated 20th and 80th percentiles of the relative emissions per capita and relative income per capita distributions. A state at the 20th percentile of the production emissions distribution has experienced modest variations in its relative emissions per capita between 0.59 and 0.68 times the national average for 1960–1999. In contrast, a state at the 80th percentile has experienced growth in its production emissions per capita from 1.28 times the national average in 1960 to about 1.47 times the national average in 1999. This resulted in a widening in the 80–20 interquantile range for production emissions from 0.57 in 1970 to 0.93 in 1990 before decreasing to 0.84 in 1999. The larger spread in the 80–20 range for 1990 (1999) is statistically distinct from the 1960 interquantile range at the 5 percent(10-percent) level.

Although the production CO<sub>2</sub> distributions experience an increasing spread in their 80–20 interquantile ranges over time, the consumption CO<sub>2</sub> estimated 80–20 interquantile ranges are quite stable over time. The 20th and 80th percentile estimates experience only very modest changes over the 1960–1999 period: the 20th percentile estimates range from 0.65 to 0.68, and the 80th percentile estimates range from 1.19 to 1.26. These estimates result in an 80–20 range that experiences very little variation over the period, from 0.53 to 0.58, and the 1990 and 1999 ranges are virtually identical to the 1960 range. The constancy in the 80–20 spreads over time while the sample variance has increased (Figure 1) suggests that the very extremes of the

distribution (beyond the 80–20 range) may be moving apart over time. Estimates of the 90–10 spreads were not sufficiently precise to confirm statistically this conjecture.

Consistent with Figures 1–3, incomes have experienced a decreasing spread in their 80–20 IQRs over the 1960–1999 period. The 20th percentile experienced modest growth in relative per capita income while the 80th percentile has seen virtually no change. The estimated 80–20 IQRs have declined from 0.33 in 1960 to 0.24–0.26 over 1980–1999. The smaller IQRs in 1980 and 1990 are statistically different from the 1960 spread at the 10 percent level. These statistical analyses of the relative emissions per capita and relative income per capita distributions show that production CO<sub>2</sub> emissions have been diverging, the distribution of consumption emissions has not changed much, and the relative income distribution has been converging.

The wedge between consumption CO<sub>2</sub> and production CO<sub>2</sub> may reflect the effects of local air quality regulation and economic trade. Henderson (1996) has shown that concentrations of regulated air pollutants have decreased in areas failing to meet national ambient air quality standards (nonattainment areas) but increased in those complying with these standards (attainment areas). Since nonattainment areas are generally more densely populated than attainment areas, this shift in emissions-intensive economic activity has relocated production to more sparsely populated areas. Given the correlation between CO<sub>2</sub> emissions and regulated air pollutants, higher CO<sub>2</sub> emissions in sparsely populated areas coupled with lower CO<sub>2</sub> emissions in densely populated areas could explain this divergence in per capita emissions. With minimal barriers to interstate trade, relocating emissions-intensive production to other states should not substantially affect a state's consumption. The low population density of the highest per capita CO<sub>2</sub> states,<sup>10</sup> the increasing role of emissions-intensive interstate electricity trade,<sup>11</sup> and the high correlations between CO<sub>2</sub> and sulfur dioxide and nitrogen oxides emissions<sup>12</sup> suggest that this mechanism could explain at least part of the emissions divergence.

An evaluation of stochastic convergence for the states reveals little evidence of convergence for relative production CO<sub>2</sub> emissions. The Im et al. (2003) test statistic for the production measure is –2.16 (Table 2), which cannot justify rejecting the null hypothesis that the

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<sup>10</sup> The five states with the highest per capita CO<sub>2</sub> in 1999 had a population density less than 20 percent of the national average.

<sup>11</sup> Interstate electricity trade has been increasing over the past 40+ years. Nearly one-quarter of all electricity-related CO<sub>2</sub> emissions in 1999 for the 26 net exporting states was associated with electricity exports.

<sup>12</sup> The primary source of all three pollutants is the combustion of fossil fuels.

states' time series are characterized by a unit root. Shocks to relative production emissions appear to be persistent, and the states are not converging in a stochastic sense.

In contrast, the Im et al. test results for the relative consumption measure and income do show evidence of stochastic convergence. The consumption CO<sub>2</sub> test statistic of  $-2.41$  is statistically significant at the 5 percent level, and the income test statistic of  $-2.35$  is significant at the 10 percent level. Both statistics suggest rejecting the null hypotheses that unit roots characterize the consumption CO<sub>2</sub> and income time series.

For the U.S. states, despite income convergence, I find a consistent trend toward divergence in production emissions. In contrast, consumption emissions show little cross-sectional evidence of divergence but some evidence of stochastic convergence. The wedge between production CO<sub>2</sub> and consumption CO<sub>2</sub> appears to yield very different distributional dynamics. The next section explores whether such historical trends may continue.

## Markov Chain Transition Matrix Forecasts

### Methods

The transition matrix framework is a nonparametric method frequently used in the economic growth literature to evaluate the dynamics of income distributions (Quah 1993; Kremer et al. 2001). Quah (1993) applied the transition matrix framework to evaluate the distribution of relative per capita incomes. Following Quah, this framework maps today's distribution ( $F_t$ ) of relative per capita emissions (or income) into tomorrow's distribution ( $F_{t+1}$ ):

$$(6) F_{t+1}(RE) = M \cdot F_t(RE)$$

Consistent with Quah and Kremer et al., I assume that the mapping operator,  $M$ , follows a first-order Markov process with time-invariant transition probabilities. Iterating (6)  $T$  times yields:

$$(7) F_{t+T}(RE) = M^T \cdot F_t(RE)$$

If  $F_{t+T} = F_{t+T-1}$  for some  $T$ , then this expression can illustrate the long-run steady-state (ergodic) distribution of relative per capita CO<sub>2</sub> emissions.

Similar to Quah and Kremer et al., I have discretized the relative emissions and relative income data in the following five categories: <50 percent national average, 50 percent–75 percent national average, 75 percent–100 percent national average, 100 percent–200 percent national average, and >200 percent national average. I calculated the one-year transitions from

one category to another to construct the transition matrices presented in Tables 3 through 5. The transition probabilities in these tables represent the mapping operator that is applied to the distribution in the last year of the data sets to estimate the future steady-state (ergodic) distributions.

This approach does not impose much structure on the data, other than in the construction of the discrete categories and the first-order Markov assumption. It is intended to characterize the patterns in the distributional dynamics. Although it may characterize future distributions, this analysis does not provide enough information to explain *why* the emissions (or income) distribution evolves as it does. The representation of the distributional dynamics in the transition matrices may be sensitive to the choice of time period to consider (see Aldy 2006 for an example with country-level data). Transitions in the 1960s may be significantly different from transitions in later periods. To assess this issue, I compare ergodic distributions derived from transition matrices based on 1960–1999, 1970–1999, 1980–1999, and 1990–1999. Finally, this approach cannot incorporate significant changes from past experience in policies or technologies (e.g., new CO<sub>2</sub> regulations, breakthroughs in renewable energy) in forecasting future distributions.

### ***Estimated Transition Matrices***

Table 3 presents the transition matrix for production CO<sub>2</sub> over 1960–1999 and the estimated ergodic distribution. For example, a state in the lowest category (per capita emissions <50 percent national average) has an 88 percent probability of remaining in that category next year and a 12 percent probability of moving up one category (to 50 percent–75 percent national average). If that state does move up to the next category, then in the following year, it will have a 5 percent probability of moving up to the third category, a 2.8 percent probability of returning to the lowest category, and a 92 percent probability of remaining in the second category. The triple-diagonal condition noted in the income convergence literature holds here: transition probabilities off the three main diagonals are zero, implying that states do not experience very substantial changes in their per capita emissions relative to the national average. The steady-state (ergodic) distribution based on these transition probabilities suggests little long-term convergence in relative production CO<sub>2</sub> per capita. The estimated ergodic distribution is slightly more (less) compact than the 1999 (1960) distribution of emissions.

Tables 4 and 5 present the transition matrices for relative consumption CO<sub>2</sub> per capita and relative income per capita. The consumption CO<sub>2</sub> transition probabilities also follow the triple diagonal condition. The consumption CO<sub>2</sub> probabilities show that a state's relative consumption emissions is more likely than its relative production emissions to move up from the

lowest category (0.21 versus 0.12) and more likely to move down from the highest category (0.067 versus 0.050). This yields a slightly more compact steady-state (ergodic) distribution than the steady-state production CO<sub>2</sub> distribution, although this distribution does not substantially differ from the current consumption CO<sub>2</sub> distribution.

Table 5 shows that the relative income per capita transitions likewise follow the triple diagonal condition, although there are no observations in the two extreme categories. The very high probabilities along the main diagonal suggest a high degree of persistence in states' relative income per capita. The steady-state income distribution is markedly more compact than either of the emissions distributions presented at the bottom of Tables 3 and 4.

The evolution of the production CO<sub>2</sub> distribution over 1960–1999 is evident in the estimated ergodic distributions with shorter panels (Table 6). Constructing transition matrices from shorter panels yields less compact distributions.<sup>13</sup> The ergodic distribution from the 1990–1999 transition matrix has thicker tails than the 1999 distribution, suggesting that emissions may continue to diverge if the more recent dynamics better explain future distributions.

## Conclusions

The recent literature on the national-level distributions of per capita CO<sub>2</sub> emissions shows that emissions convergence is evident among the OECD countries—a group of nations that have also experienced economic convergence. Analyses with data sets including developed and developing countries show no evidence of emissions or income convergence. By focusing on the U.S. states, a group of advanced economies that have been converging in economic terms for more than a century, this paper provides several empirical tests of the notion implicit in the OECD analyses that per capita CO<sub>2</sub> emissions converge as per capita incomes converge.

In contrast to the OECD results, I find that the U.S. states' per capita CO<sub>2</sub> emissions have been diverging over the 1960–1999 period. This standard, or production, measure of CO<sub>2</sub> emissions per capita has shown a substantially increasing dispersion (variance) over the period. The estimated kernel densities show much thicker tails over time for production CO<sub>2</sub>. The estimated 80–20 interquantile ranges have increased since the 1960s, and the 1990s have 80–20 spreads that are statistically larger than the 1960s spreads. The hypothesis that production CO<sub>2</sub>

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<sup>13</sup> Aldy (2006) obtained similar results with a sample of 88 countries with transition matrices based on panels varying from 1960–2000 to 1990–2000.

emissions are characterized by persistent shocks cannot be rejected, precluding stochastic convergence. Forecasts of the production emissions distributions using a Markov transition matrix suggests virtually no convergence in the steady-state distribution of per capita emissions relative to current emissions, and some continued divergence based on shorter-length panels.

Although production CO<sub>2</sub> emissions have diverged as state per capita incomes continue to converge, accounting for interstate electricity trade reveals substantially different emissions dynamics. States' consumption CO<sub>2</sub> emissions per capita have experienced a less pronounced increase in their dispersion, but this appears to be driven by states at the extremes of the distribution, since the estimated 80–20 interquantile ranges have remained effectively constant over the 40-year period. Moreover, the consumption CO<sub>2</sub> measure does appear to be converging in a stochastic sense. Consumption CO<sub>2</sub> emissions per capita are more compressed in historical distributions and in the forecast steady-state distributions, but both measures of emissions have much less compressed distributions than for per capita income.

The different distributional dynamics between production emissions and consumption emissions reflect the effect of increasing interstate electricity trade over time. Future research could explore whether this trade effect is evident for other emissions-intensive goods. The characteristics of net exporters and net importers of electricity suggest that air quality regulations could be driving some of the trend in electricity trade. Additional research could explore more explicitly the possible connection between air quality rules and the CO<sub>2</sub> emissions distribution.

As decisionmakers continue to debate policies to mitigate climate change, they will benefit from information about future distributions of CO<sub>2</sub> emissions. Focusing on the emissions dynamics of a set of advanced economies that have experienced income convergence could provide insights about how distributions of country-level emissions may evolve over time if country-level incomes eventually undergo some convergence. The disconnect between income convergence and emissions convergence for the U.S. states suggests caution about the design of future policies. Some have proposed that rights to the atmosphere should be allocated on a per capita basis (see Bodansky 2004 for a survey of climate policy proposals, including those advocating for such a per capita allocation rule). This analysis suggests that such a rule could involve very substantial resource transfers (either through a tradable permit program or through the relocation of emissions-intensive industries) even *if* economies converge because income convergence does not appear to be sufficient for emissions convergence. Further understanding of the role of trade in the production of emissions-intensive goods—and the distribution of the production and consumption of these goods—can inform policymakers about the potential distribution of the burden of emissions mitigation policies.

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Figures and Tables

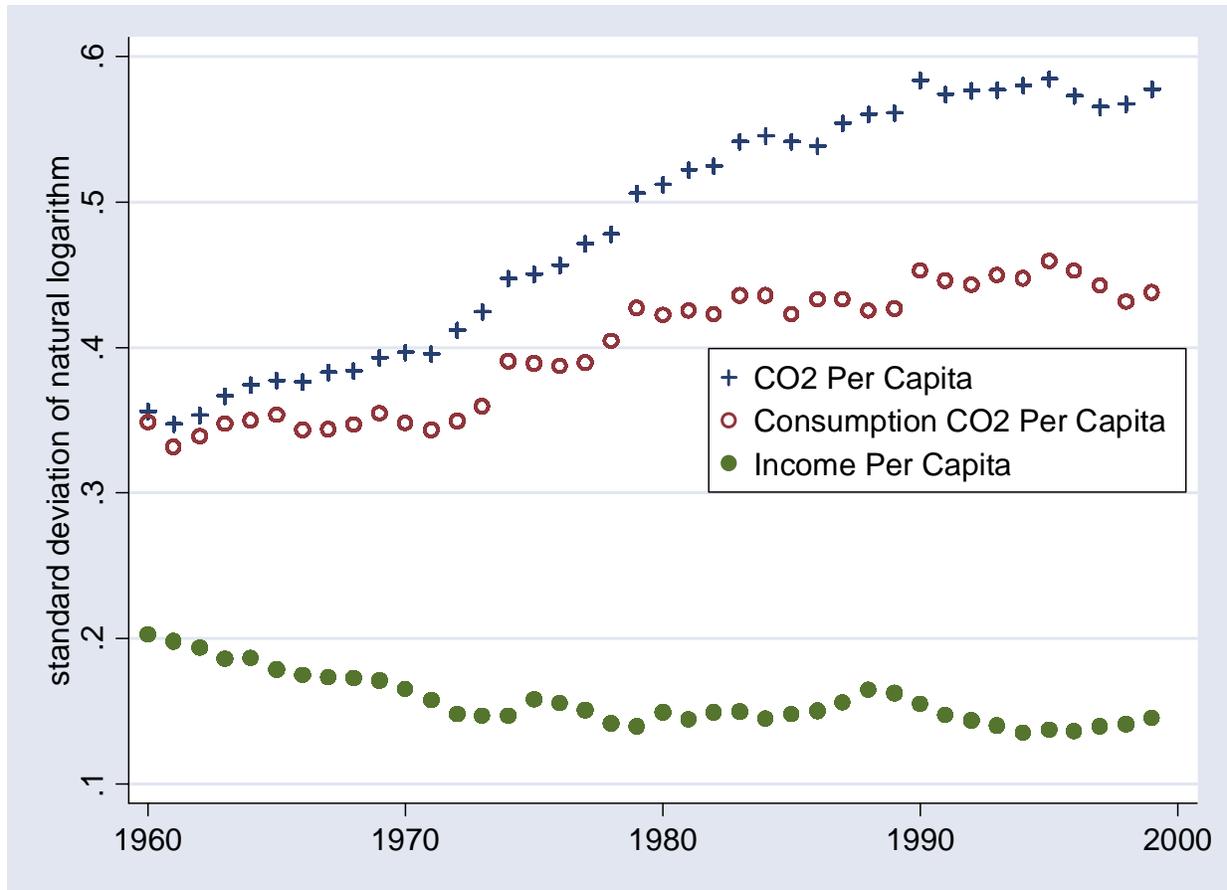
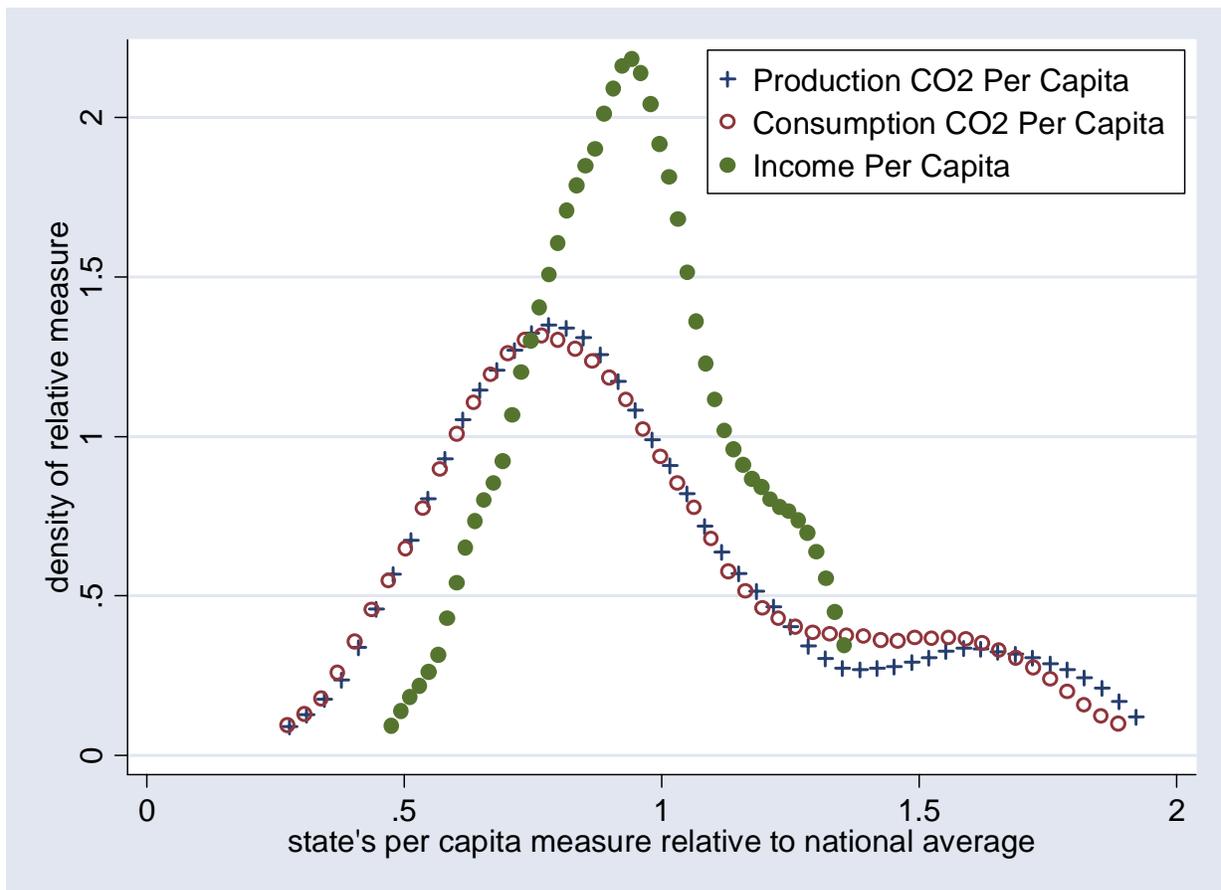


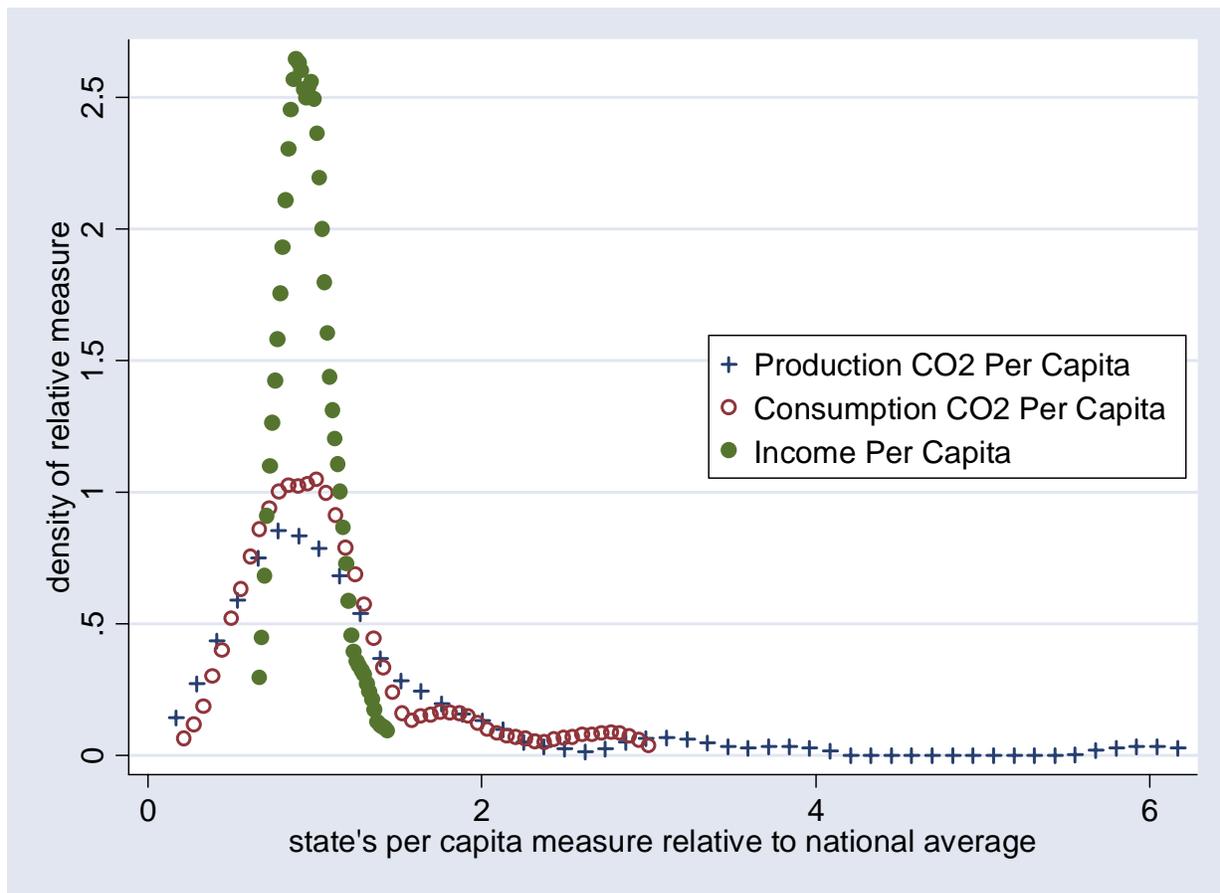
Figure 1. Dispersion in Per Capita CO<sub>2</sub> Emissions and Income, 1960–1999

Notes: Represents the standard deviation of the natural logarithm of CO<sub>2</sub> emissions per capita and the standard deviation of the natural logarithm of income per capita. CO<sub>2</sub> emissions data are constructed by author from energy consumption data in EIA (2001a), and income per capita data are from BEA (2000).



**Figure 2. Estimated Kernel Densities for Relative Production CO<sub>2</sub> Per Capita, Consumption CO<sub>2</sub> Per Capita, and Income Per Capita, 1960**

Notes: Kernel densities for all three measures (relative production CO<sub>2</sub> per capita, consumption CO<sub>2</sub> per capita, and income per capita) are estimated using the Epanechnikov kernel function and the Silverman (1986) bandwidth choice rule. CO<sub>2</sub> emissions data are constructed by author from energy consumption data in EIA (2001a), and income per capita data are from BEA (2000).



**Figure 3. Estimated Kernel Densities for Relative Production CO<sub>2</sub> Per Capita, Consumption CO<sub>2</sub> Per Capita, and Income Per Capita, 1999**

Notes: Kernel densities for all three measures (relative production CO<sub>2</sub> per capita, consumption CO<sub>2</sub> per capita, and income per capita) are estimated using the Epanechnikov kernel function and the Silverman (1986) bandwidth choice rule. CO<sub>2</sub> emissions data are constructed by author from energy consumption data in EIA (2001a), and income per capita data are from BEA (2000).

**Table 1. Estimated 20th and 80th Percentiles and 80–20 Interquantile Ranges of States' Relative CO<sub>2</sub> Per Capita and Relative Income Per Capita Distributions, 1960-1999**

Percentile of distribution	1960–1962		1961–1971		1979–1981		1989–1991		1997–1999	
	20th	80th	20th	80th	20th	80th	20th	80th	20th	80th
Production CO <sub>2</sub> per capita (relative to national average)	0.68 (0.021)	1.28 (0.11)	0.68 (0.026)	1.25 (0.093)	0.66 (0.042)	1.34 (0.071)	0.59 (0.042)	1.52 (0.11)	0.63 (0.045)	1.47 (0.12)
Production CO <sub>2</sub> interquantile range	0.60 (0.074)		0.57 (0.086)		0.67 (0.073)		0.93 (0.11)**		0.84 (0.13)*	
Consumption CO <sub>2</sub> per capita (relative to national average)	0.67 (0.016)	1.26 (0.083)	0.68 (0.037)	1.21 (0.059)	0.65 (0.045)	1.19 (0.054)	0.68 (0.047)	1.26 (0.095)	0.68 (0.049)	1.24 (0.095)
Consumption CO <sub>2</sub> interquantile range	0.58 (0.090)		0.53 (0.053)		0.54 (0.077)		0.58 (0.064)		0.57 (0.064)	
Income per capita (relative to national average)	0.75 (0.024)	1.07 (0.039)	0.79 (0.014)	1.07 (0.029)	0.83 (0.0085)	1.06 (0.018)	0.81 (0.011)	1.06 (0.020)	0.82 (0.012)	1.08 (0.013)
Income interquantile range	0.33 (0.042)		0.27 (0.039)		0.24 (0.019)*		0.25 (0.017)*		0.26 (0.016)	

Notes: Bootstrapped standard errors based on 1,000 replications presented in parentheses. \*, \*\* indicates that a Wald test comparing the estimated interquantile ranges for the 1960 period and other periods rejects the null that the ranges are identical at the 10 percent and 5 percent levels, respectively.

**Table 2. Im et al. (2003) Panel-Based Unit Root Tests**

<i>Measure</i>	<i>Im et al. (2003) Test Statistic</i>
Relative production CO <sub>2</sub> per capita	-2.16
Relative consumption CO <sub>2</sub> per capita	-2.41**
Relative income per capita	-2.35*

Notes: Test statistics constructed from 48 state-specific, 40-year time series augmented Dickey-Fuller tests (with trend). The lag structure was chosen on a state-by-state basis using the Akaike information criterion. Im et al. (2003) present exact critical values for N=50, T=40 panels for panel-based test statistics: 10 percent: -2.32; 5 percent: -2.36; 1 percent: -2.44 (Table 2, 61–62). \*, \*\* denote statistical significance at 10 percent and 5 percent levels, respectively.

**Table 3. Estimates of Transition Matrix and Ergodic Distribution, States' Relative Production CO<sub>2</sub> Emissions Per Capita, 1960–1999**

<i>Upper Endpoint (Ratio of State CO<sub>2</sub> Emissions per Capita to U.S. CO<sub>2</sub> Emissions per Capita)</i>						
<i>Upper Endpoint</i>	<i>0.50</i>	<i>0.75</i>	<i>1.00</i>	<i>2.00</i>	<i>∞</i>	
0.50	0.88	0.12	0	0	0	
0.75	0.028	0.92	0.054	0	0	
1.00	0	0.048	0.91	0.043	0	
2.00	0	0	0.046	0.95	0.003	
∞	0	0	0	0.050	0.95	
Ergodic	0.07	0.29	0.32	0.30	0.02	

Notes: Constructed by author with CO<sub>2</sub> emissions data constructed from energy consumption data in EIA (2001a).

**Table 4. Estimates of Transition Matrix and Ergodic Distribution,  
States' Relative Consumption CO<sub>2</sub> Emissions Per Capita, 1960–1999**

<i>Upper Endpoint (Ratio of State CO<sub>2</sub> Emissions per Capita to U.S. CO<sub>2</sub> Emissions per Capita)</i>						
<i>Upper Endpoint</i>	<i>0.50</i>	<i>0.75</i>	<i>1.00</i>	<i>2.00</i>	<i>∞</i>	
0.50	0.79	0.21	0	0	0	
0.75	0.036	0.91	0.054	0	0	
1.00	0	0.041	0.94	0.024	0	
2.00	0	0.0015	0.034	0.96	0.0029	
∞	0	0	0	0.067	0.93	
Ergodic	0.052	0.30	0.39	0.26	0.012	

Notes: Constructed by author with CO<sub>2</sub> emissions data constructed from energy consumption data in EIA (2001a).

**Table 5. Estimates of Transition Matrix and Ergodic Distribution,  
States' Relative Income Per Capita, 1960–1999**

<i>Upper Endpoint (Ratio of State Income per Capita to U.S. Income per Capita)</i>						
<i>Upper Endpoint</i>	<i>0.50</i>	<i>0.75</i>	<i>1.00</i>	<i>2.00</i>	$\infty$	
0.50	0	0	0	0	0	0
0.75	0	0.92	0.078	0	0	0
1.00	0	0.015	0.96	0.027	0	0
2.00	0	0	0.044	0.96	0	0
$\infty$	0	0	0	0	0	0
Ergodic	0	0.10	0.55	0.34	0	0

Notes: Constructed by author with income data from BEA (2000).

**Table 6. Estimated Ergodic Distributions Based on Various Time Periods,  
States' Production CO<sub>2</sub> Emissions Per Capita**

<i>Time Period</i>	<i>Upper Endpoint (Ratio of State CO<sub>2</sub> Emissions per Capita to U.S. CO<sub>2</sub> Emissions per Capita)</i>				
	<i>0.50</i>	<i>0.75</i>	<i>1.00</i>	<i>2.00</i>	$\infty$
1960–1999	0.07	0.29	0.32	0.30	0.02
1970–1999	0.07	0.26	0.33	0.31	0.03
1980–1999	0.12	0.26	0.27	0.31	0.04
1990–1999	0.11	0.22	0.24	0.34	0.10

Note: Constructed by author with CO<sub>2</sub> emissions data constructed from energy consumption data in EIA (2001a).