Divergence in State-Level Per Capita Carbon Dioxide Emissions

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ABSTRACT. *This paper addresses the question of whether income convergence is sufficient for per capita carbon dioxide (CO_2) 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 to 1999 state-level CO_2 emissions per capita: production (pre-electricity trade) CO_2 and consumption (post-electricity trade) CO_2, and with income per capita. Although incomes continue to converge, I find stark divergence in production CO_2 per capita and no evidence of convergence for consumption CO_2 per capita. Forecasts of future distributions show little convergence in emissions.* (JEL Q54, Q56)

I. 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 non-attainment 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).

This relationship between economic growth and pollution has received considerable attention in the context of carbon dioxide (CO_2) emissions. Several studies have focused on per capita CO_2 emissions and assessed how they vary with per capita income by estimating reduced-form environmental Kuznets curves (Holtz-Eakin and Selden 1995; Schmalensee, Stoker, and Judson 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_2 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_2, 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 Cooperation and Development (OECD), several papers report convergence in per capita CO_2 (Strazicich and List 2003; Brock and Taylor 2004; Nguyen Van 2005; Aldy 2006).

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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_2 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 CO_2 emissions converge as a by-product of economic convergence.

The distribution of per capita CO_2 emissions may have important implications for the design of climate change policy even though the climatic impact of CO_2 emissions do not vary by the location of emissions sources. Governments and non-governmental organizations have advocated for allocating CO_2 emission rights on a per capita basis. For example, Bodansky (2004) identified 10 international climate change policy proposals that would distribute emissions rights on a per capita basis. Several respondents to a recent solicitation of views by the U.S. Senate Committee on Energy and Natural Resources (2006) advocated for a domestic CO_2 emissions trading program based on a per capita permit allocation.

To illustrate the potential impacts of a per capita emissions allocation, consider a hypothetical U.S. policy. Suppose that the United States proceeded with the Kyoto Protocol and decided to allocate its emissions rights to the states either through a per capita allocation (based on each state's share of 1999 U.S. population) or a historical proportional allocation (or "grandfathering," based on each state's share of 1999 U.S. CO_2 emissions). These two allocation schemes would differ significantly: the average state would receive an allocation under the per capita scheme that differs by 40% from the grandfathering allocation. Since CO_2 emissions rights prices could range from tens to hundreds of dollars per ton of carbon, tens of billions of dollars in annual rents would be at stake with this hypothetical allocation.

If per capita emissions converge over time, then the difference between a per capita allocation and a historical proportional allocation would decrease. This would reduce the magnitude of rents at stake and limit the potential for political dispute over the allocation of emissions rights. In contrast, if per capita emissions diverge over time, this could complicate efforts to achieve an agreement on climate change policies, in both national and international contexts. Those with low per capita emissions may not be inclined to take on emissions commitments while those with high per capita emissions may not be inclined to agree to any policies premised on per capita emissions allocations. The U.S. states can effectively serve as a laboratory of economies at advanced stages of development. If they do not experience emissions convergence even as their incomes converge, then that may raise questions about what should be expected for national-level emissions distributions in the future even if incomes do experience some convergence among developed and developing countries. This analysis about the distributional dynamics of emissions can inform policymakers working on U.S. and international policies.

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_2 data sets for the 1960–1999 time period from a state energy consumption data set. The first data set is the standard measure of an economy's CO_2 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_2 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 reflects the location of consumption of one major carbon-intensive good, electricity.[1] This consumption measure of CO_2 is the carbon analog to the standard measure of end-use energy consumption.

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 state-level distributions. It complements the country-level analyses on emissions convergence by addressing another set of economies. It employs a broader set of tools for convergence testing and, unlike most other papers; it presents forecasts of future emissions distributions.[2] By accounting for the effect of trade in electricity on state-level emissions, this paper provides additional insights into emissions distributional dynamics. I have also undertaken tests of income convergence to provide context for the emissions results.

In contrast to the work on OECD countries, I find a striking *divergence* in state-level production CO_2 per capita over the 1960–1999 time period. I find no evidence of convergence or divergence for state-level CO_2 per capita after accounting for electricity trade, but I find income convergence. This paper provides the first assessment of emissions convergence that includes an explicit investigation of the cause of the emissions divergence with its focus on interstate electricity trade. The divergence in the historical CO_2 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 CO_2 emissions data set. Section 3 presents the states historical analyses. Section 4 focuses on forecasting future emissions distributions. The final section concludes with policy implications and ideas for further research.

II. 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_2 emissions using national sector- and fuel-specific emissions factors provided by EIA (2001a, Appendix B).[3] A total of 51 fuel-sector measures allowed for precise matches of fuel-sector emissions factors to sector-specific fuel consumption. This measure assigns all fossil fuel combustion-related CO_2 emissions to the state in which the fossil fuels are burned. It includes all fuels used in transportation, all fuels used in buildings, all energy used in industrial activities, and electricity-related emissions based on the location of power generation. Refer to Lutter (2000) and Blasing, Broniak, and Marland (2004) for similar applications of this approach.

I undertook two checks to assess the plausibility of constructing state-level CO_2 emissions in this manner. First, I constructed national estimates from the state-level CO_2 values and compared these with the Marland, Boden, and Andres (2003) and EIA (2001a) estimates for national emissions. Over 1960–1999, my constructed annual national values differ on average 1.9% from the Marland, Boden, and Andres estimates (1.6% standard deviation). A comparison with EIA (2001a) national CO_2 estimates yields an average difference of 2.0% (0.92% standard deviation). To provide context for these comparisons, a comparison of the EIA and Marland,

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[1] Ideally, a complete consumption measure of CO_2 would also reflect the emissions intensity in all traded goods and services. Unfortunately, such interstate trade data are not collected.

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

[3] All statistical analyses presented in this paper exclude Alaska, Hawaii, and Washington, D.C.

Boden, and Andres data sets arrives at similar differences: an average difference of 1.7% (1.0% standard deviation).

Second, I compared my data set with a state-level CO_2 emissions data set constructed and published after I began this research project. The Blasing, Broniak, and Marland (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 follow virtually identical paths over the 40-year period. The estimated interquantile ranges are very similar and follow the same trends over time as well. My constructed data set and the Blasing, Broniak, and Marland data set yield very similar quantitative results and the same qualitative conclusions about the distributional dynamics for state-level CO_2 emissions over the 1960–1999 time period.[4]

My constructed CO_2 data set represents emissions associated with producing all goods and services in a given state, so we can also denote them *production* CO_2 emissions. This standard measure of CO_2 emissions is comparable to the national measures used to develop emissions commitments under the Kyoto Protocol. In the presence of interstate trade, the emissions intensity of a state's production may differ from its consumption intensity. 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 CO_2, a second emissions data set was constructed to account for interstate electricity trade. To construct this post-electricity trade CO_2 data set, I started with the production CO_2 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.[5] Since this modified measure reflects post-trade emissions and attempts to approximate for *consumption* emissions, I refer to it as consumption CO_2 throughout this analysis.[6] As in the standard or production measure, consumption emissions account for all fossil fuel-related CO_2 emissions, but it differs by assigning utility sector emissions based on the location of electricity consumption, not generation. It is the carbon equivalent to the standard measure of end-use energy consumption used in the energy literature.

The income variable used in these analyses is the state personal income series of the Bureau of Economic Analysis (BEA 2000).[7] 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.

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[4] Additional details comparing the two data sets are available from the author upon request.

[5] 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.

[6] 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.

[7] These values were converted to year-1999 dollars based on the national CPI-Urban deflator.

III. EVALUATION OF HISTORICAL CONVERGENCE

To determine whether state-level per capita CO_2 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_2 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_2 emissions for both production and consumption measures and for per capita income. This measure of dispersion, referred to as σ-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 σ-sense (Barro and Sala-i-Martin 1992).

Second, I present estimated cross-sectional kernel densities of per capita emissions and per capita income for 1960, 1980, 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 (σ-convergence). Depicting distributions for production CO_2, consumption CO_2, 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_{it}] and relative income per capita [RY_{it}]).[8] 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 an estimator of the probability density function at RE_0 of

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

$$K = \frac{3(1 - 0.2RE_i^2)}{4\sqrt{5}},$$

$$\text{if } |RE_i| < \sqrt{5}, \text{ and 0 otherwise;}$$

$$h = 0.9\left(\min\left\{\hat{\sigma}, \frac{IQR^{75-25}}{1.349}\right\}\right)\Big/\sqrt{5}. \qquad [1]$$

N is the number of states (sample size for these analyses), $\hat{\sigma}$ represents the sample standard deviation, IQR^{75-25} is the 75–25 interquartile range for the sample, and the density function is evaluated at each of the N different observations denoted by RE_0. 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 interquantile

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[8] All references to relative emissions, *RE*, in the equations in this paper also hold for the analogous relative income measure, *RY*.

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.[9]

I use least absolute deviations estimators to construct these percentiles and IQRs. Let θ_0 be the estimated relative measure (*RE* or *RY*) at the percentile of interest. Then the least absolute deviations estimator of θ_0 solves

$$\min_{\theta \in \Theta} N^{-1} \sum_{i=1}^{N} |RE_i - \theta_0| w_i,$$

$$\text{where } w_i = 2q \text{ if } RE_i - \theta_0 > 0 \text{ and } 2(1-q) \text{ otherwise.} \quad [2]$$

The quantile of interest is represented by q. 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 interquantile 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:

$$H_0^i : \mathrm{IQR}_{1960} = \mathrm{IQR}_i \text{ for } i = 1970, 1980, 1990, 1998. \quad [3]$$

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 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_x) and sulfur dioxide (SO_2), and Heil and Selden (1999) and Strazicich and List (2003) have applied panel-based unit root tests of country-level convergence of per capita CO_2 emissions.

I have employed the exact panel-based unit root test developed by Im, Pesaran, and Shin (2003) to determine whether the states' emissions and income are converging in a stochastic sense. Although an assumption of independence across state-specific series underlying the Im, Pesaran, and Shin test may not make it robust to cross-state correlated shocks, I have employed it as a means of comparison with Heil and Selden (1999) and Strazicich and List (2003), both of which used it. 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:

$$\Delta RE_t = \alpha_0 + \alpha_1 time + \delta RE_{t-1} + \sum_{p=1}^{p} \beta_p \Delta RE_{t-p} + \varepsilon_t, \quad [4]$$

where ΔRE_t is the first difference of relative emissions per capita, $RE_t - RE_{t-1}$, *time* is

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[9] 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.

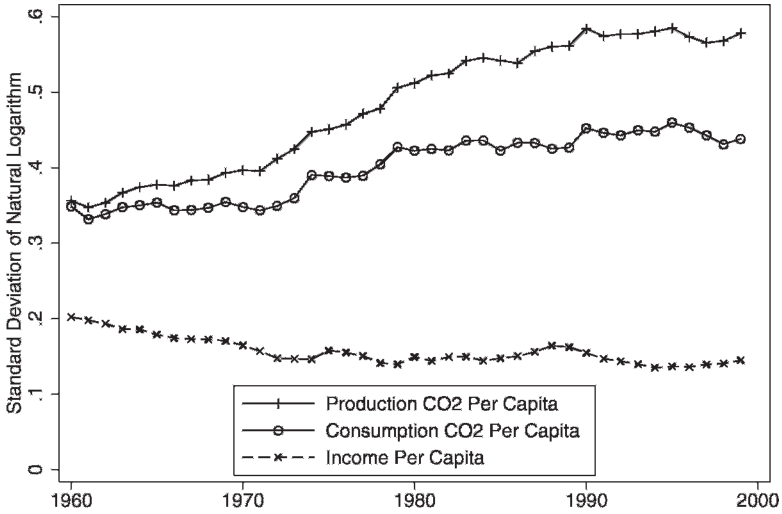

FIGURE 1

Dispersion in Per Capita CO_2 Emissions and Income, 1960–1999

Notes: Represents the standard deviation of the natural logarithm of CO_2 emissions per capita and the standard deviation of the natural logarithm of income per capita. CO_2 emissions data are constructed by author from energy consumption data in EIA (2001a), and income per capita data are from BEA (2000).

a time trend, and P is the lag length. The augmented Dickey-Fuller statistic is the t-statistic testing $\delta = 0$, denoted by t^i_δ. 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, Pesaran, and Shin test statistic is constructed by averaging the state-specific augmented Dickey-Fuller statistics:

$$\bar{t}_{NT} = N^{-1} \sum_{i=1}^{N} t^i_\delta. \qquad [5]$$

Im, Pesaran, and Shin 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 CO_2 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 time 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_2 also increases with time, but to a much lesser extent than the production emissions series. The increase in the dispersion coefficient for production CO_2 was more than double the increase in the consumption measure. This suggests that trade in electricity, which has increased in total and as

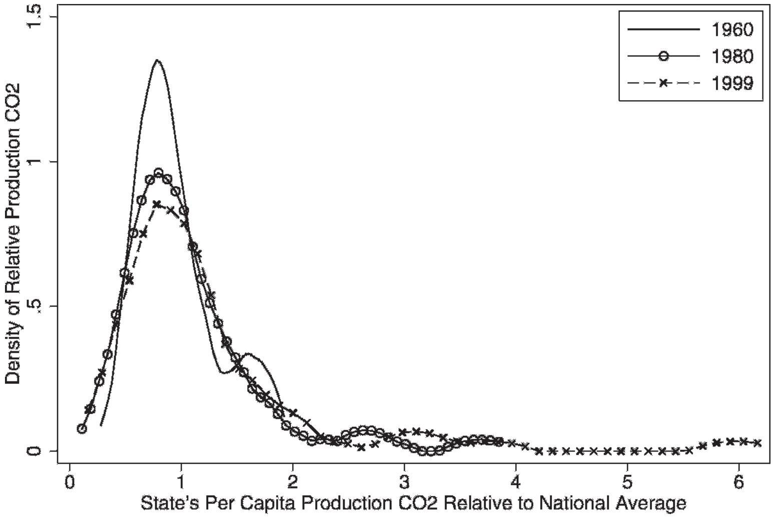

FIGURE 2
ESTIMATED KERNEL DENSITIES FOR RELATIVE PRODUCTION CO_2 PER CAPITA, 1960, 1980, 1999

NOTES: KERNEL DENSITIES FOR RELATIVE PRODUCTION CO_2 PER CAPITA ARE ESTIMATED USING THE EPANECHNIKOV KERNEL FUNCTION AND THE SILVERMAN (1986) BANDWIDTH CHOICE RULE. THE CO_2 EMISSIONS DATA ARE CONSTRUCTED BY AUTHOR FROM ENERGY CONSUMPTION DATA IN EIA (2001A).

a share of electricity generated over time, may be responsible for part of the divergence in per capita emissions.

Figure 2 shows how the entire relative production emissions distribution has become less compact from 1960 through 1980 to 1999. 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. The peak in the distribution does not change much over the 1960–1999 time period, but the upper tail of the distribution does increase substantially over time.

Figure 3 displays the consumption emissions distributions for 1960, 1980, and 1999. With little interstate electricity trade in 1960, the two emissions per capita distributions in Figures 2 and 3 are nearly identical. In 1960, 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_2 emissions that were at least a factor of two away from the national average. The consumption density peaks closer to one in 1999 than in earlier periods, and the upper end of the distribution has increased, but less so than the production distribution.

Figure 4 illustrates the much tighter income distribution over the 1960–1999 time period and the convergence over time. The smaller variance in incomes relative to emissions in Figure 1 is also evident in comparing Figures 2–4. In 1960, the relative income per capita distribution was more compact than either of the emissions distributions. In 1999, the income distribution has become even more compact while the emissions distributions have both increased their spreads.

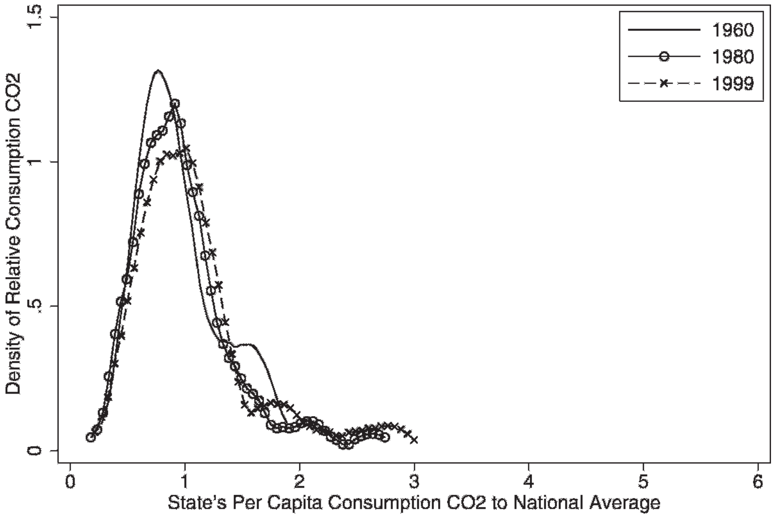

FIGURE 3

Estimated Kernel Densities for Relative Consumption CO_2 Per Capita, 1960, 1980, 1999

Notes: Kernel densities for relative consumption CO_2 per capita are estimated using the Epanechnikov kernel function and the Silverman (1986) bandwidth choice rule. The CO_2 emissions data are constructed by author from energy consumption data in EIA (2001a).

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 CO_2 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 CO_2 per capita from 1.28 times to 1.47 times the national average over 1960–1999. The 80–20 IQR for production CO_2 increased 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 IQR at the 5% (10%) level.

Although the production CO_2 distributions experience an increasing spread in their 80–20 IQRs over time, the consumption CO_2 estimated 80–20 IQRs are quite stable over time. The 20th and 80th percentile estimates experience modest changes over time: the 20th percentile estimates range from 0.65 to 0.68 and the 80th percentile estimates range from 1.19 to 1.26. Little variation in the 80–20 range occurs 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 and 4, 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

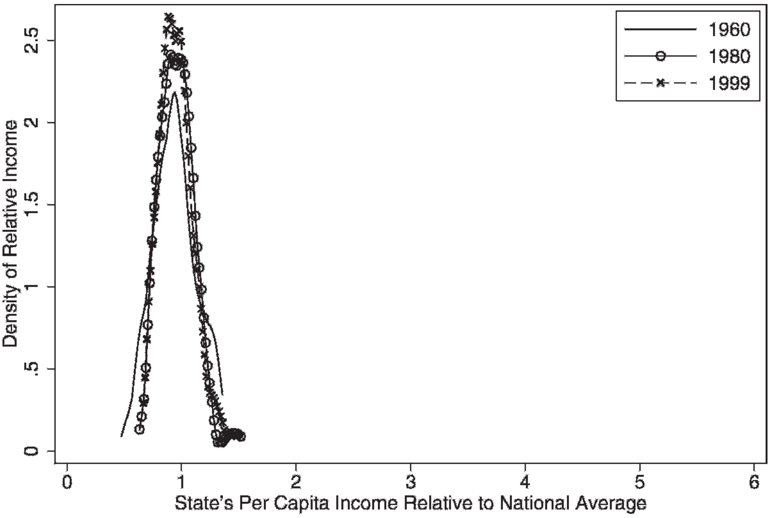

FIGURE 4

Estimated Kernel Densities for Relative Income Per Capita, 1960, 1980, 1999

Notes: Kernel densities for relative income per capita are estimated using the Epanechnikov kernel function and the Silverman (1986) bandwidth choice rule. The income per capita data are from BEA (2000).

spread at the 10% level. These statistical analyses of the relative emissions per capita and relative income per capita distributions show that production CO_2 emissions have been diverging, the distribution of consumption emissions has not changed much, and the relative incomes have been converging.[10]

The wedge between consumption CO_2 and production CO_2 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 (non-attainment areas) but increased in those complying with these standards (attainment areas). Since non-attainment 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_2 emissions and regulated air pollutants, higher CO_2 emissions in sparsely populated areas coupled with lower CO_2 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_2

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[10] To provide additional context for these results, I have analyzed the dispersion in BTU per capita and the dispersion in carbon-energy ratios in the transportation, industrial, residential, and commercial sectors. I find that industrial BTU per capita has been diverging over the 1960–1999 period, but transportation energy use per capita has experienced no change in its dispersion, and residential and commercial buildings sectors have experienced some convergence. The variance in the carbon intensity of energy has increased in transportation, industrial, and commercial sectors and remained fairly constant for the residential sector over this 40-year period. This suggests that the decreasing variance in BTU per capita has been offset by increasing variance in the carbon intensity of energy consumption and this underlies the lack of convergence in consumption CO_2, the carbon analog to these end-use energy consumption measures. Further details are available from the author upon request and in Aldy (2007).

TABLE 1

ESTIMATED 20TH, 80TH PERCENTILES, AND 80–20 INTERQUANTILE RANGE, OF STATES' RELATIVE CO_2 PER CAPITA AND RELATIVE INCOME PER CAPITA DISTRIBUTIONS, 1960–1999

	1960–1962		1961–1971		1979–1981		1989–1991		1997–1999	
Percentile of distribution	20th	80th	20th	80th	20th	80th	20th	80th	20th	80th
Production CO_2 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_2 interquantile range	0.60 (0.074)		0.57 (0.086)		0.67 (0.073)		0.93 (0.11)**		0.84 (0.13)*	
Consumption CO_2 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_2 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% and 5% levels, respectively.

TABLE 2

Im, Pesaran, and Shin (2003) Panel-Based Unit Root Tests

Measure	Im, Pesaran, and Shin (2003) Test Statistic
Relative production CO_2 per capita	−2.16
Relative consumption CO_2 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, Pesaran, and Shin (2003) present exact critical values for $N = 50$, $T = 40$ panels for panel-based test statistics: 10%: −2.32; 5%: −2.36; 1%: −2.44 (Table 2, pp. 61–62).

*, ** denote statistical significance at 10% and 5% levels, respectively.

states, the increasing role of emissions-intensive interstate electricity trade,[11] and the high correlations between CO_2 and sulfur dioxide and nitrogen oxides emissions[12] 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_2 emissions. The Im, Pesaran, and Shin (2003) test statistic for the production measure is −2.16 (Table 2), which cannot justify rejecting the null hypothesis that the 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, Pesaran, and Shin test results for relative consumption CO_2 and income show evidence of stochastic convergence. The consumption CO_2 test statistic of −2.41 is statistically significant at the 5% level and the income test statistic of −2.35 is significant at the 10% level. Both statistics suggest rejecting the null hypotheses that unit roots characterize these measures.

For the U.S. states, despite income convergence, I find a consistent trend towards divergence in production CO_2. In contrast, consumption CO_2 shows little cross-sectional evidence of divergence but some evidence of stochastic convergence. The wedge between production CO_2 and consumption CO_2 appears to yield very different distributional dynamics. The next section explores whether such historical trends may continue.

IV. 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, Onatski, and Stock 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}):

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

Consistent with Quah and Kremer, Onatski, and Stock, I assume that the mapping operator, M, follows a first-order Markov process with time-invariant transition probabilities. Iterating [6] T times yields

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

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_2.

Similar to Quah and Kremer, Onatski, and Stock, I have discretized the relative emissions and relative income data in the following five categories: < 50% national average, 50%–75% national average, 75%–100% national average, 100%–200% national average, and > 200% national average. I

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[11] Interstate electricity trade has been increasing over the past 40+ years. Nearly one-quarter of all electricity-related CO_2 emissions in 1999 for the 26 net exporting states were associated with electricity exports.

[12] The primary source of all three pollutants is the combustion of fossil fuels.

TABLE 3

ESTIMATES OF TRANSITION MATRIX AND ERGODIC DISTRIBUTION, STATES RELATIVE PRODUCTION CO_2 EMISSIONS PER CAPITA, 1960–1999

	Upper Endpoint (Ratio of State CO_2 Emissions Per Capita to U.S. CO_2 Emissions Per Capita)				
Upper Endpoint	0.50	0.75	1.00	2.00	∞
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

Note: Constructed by author with CO_2 emissions data constructed from energy consumption data in EIA (2001a).

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 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_2 regulations, renewable energy innovations) in forecasting future distributions.

Estimated Transition Matrices

Table 3 presents the transition matrix for production CO_2 over 1960–1999 and the estimated ergodic distribution. For example, a state in the lowest category (per capita emissions < 50% national average) has an 88% probability of remaining in that category next year and a 12% probability of moving up one category (to 50%–75% national average). If that state does move up to the next category, then in the following year, it will have a 5.4% probability of moving up to the third category, a 2.8% probability of returning to the lowest category, and a 92% probability of

TABLE 4

ESTIMATES OF TRANSITION MATRIX AND ERGODIC DISTRIBUTION, STATES RELATIVE CONSUMPTION CO_2 EMISSIONS PER CAPITA, 1960–1999

	Upper Endpoint (Ratio of State CO_2 Emissions Per Capita to U.S. CO_2 Emissions Per Capita)				
Upper Endpoint	0.50	0.75	1.00	2.00	∞
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

Note: Constructed by author with CO_2 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

	Upper Endpoint (Ratio of State Income Per Capita to U.S. Income Per Capita)				
Upper Endpoint	0.50	0.75	1.00	2.00	∞
0.50	0	0	0	0	0
0.75	0	0.92	0.078	0	0
1.00	0	0.015	0.96	0.027	0
2.00	0	0	0.044	0.96	0
∞	0	0	0	0	0
Ergodic	0	0.10	0.55	0.34	0

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

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 large changes in their emissions relative to the national average. The steady-state distribution based on these transition probabilities suggests little long-term convergence in relative production CO_2 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_2 per capita and relative income per capita. The consumption CO_2 transition probabilities also follow the triple diagonal condition. The consumption CO_2 probabilities show 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_2 distribution, although this distribution does not substantially differ from the current consumption CO_2 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_2 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.[13] The ergodic distri-

TABLE 6

Estimated Ergodic Distributions Based on Various Time Periods, States Production CO_2 Emissions Per Capita

	Upper Endpoint (Ratio of State CO_2 Emissions Per Capita to U.S. CO_2 Emissions per Capita)				
Time Period	0.50	0.75	1.00	2.00	∞
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_2 emissions data constructed from energy consumption data in EIA (2001a).

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

bution 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.

V. CONCLUSIONS

Recent papers have found CO_2 emissions convergence among 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 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_2 emissions converge as per capita incomes converge.

In contrast to the OECD results, I find that the U.S. states' per capita CO_2 emissions have been diverging over the 1960–1999 period. Dispersion (variance) has increased substantially for this standard, or production, measure of per capita CO_2 over the period. The estimated kernel densities show much thicker tails over time for production CO_2. 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_2 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 continued divergence based on shorter-length panels.

Although production CO_2 emissions have diverged as per capita incomes converge, accounting for interstate electricity trade reveals substantially different emissions dynamics. States' consumption CO_2 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. The consumption CO_2 measure does appear to be converging in a stochastic sense. Consumption CO_2 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 and consumption emissions reflect the effect of increasing interstate electricity trade. Future research could explore whether this trade effect is evident for other emissions-intensive goods. The characteristics of net exporters and importers of electricity suggest that air quality regulations could be driving some of the trend in electricity trade. Future research could explore more explicitly the relationship between air quality rules and the CO_2 emissions distribution.

As decisionmakers continue to debate policies to mitigate climate change, they will benefit from information about future distributions of CO_2 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 states suggests caution about the design of future policies. Some have proposed that emissions rights should be allocated on a per capita basis. This analysis suggests that such a rule could involve very substantial resource transfers (either through a tradable permit program or the relocation of emissions-intensive industries), even *if* economies converge because income convergence is not sufficient for emissions convergence.

This analysis provides the first exploration for the cause of the distributional dynamics by focusing on the role of interstate electricity trade. 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. Specifically, the role of electricity trade could play a more significant role over time with the economic and energy sector integration in the European Union. With previous EU climate change policy decisions reflecting, at least in part, per capita CO_2 emissions, such as the so-called EU "bubble" reallocation of the Kyoto Protocol commitments (Ringius 1999), an assessment of the effect of trade in emissions-intensive goods and services could benefit European policymakers in the future.

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