Convergence of per capita carbon dioxide emissions in urban China: A spatio-temporal perspective

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Abstract

Carbon dioxide (CO2)-emission dynamics are critical to inter-governmental climate negotiations. Previous studies have noted a gradual equalization of per capita CO2 emissions across developed countries; that is, CO2 emissions converge across developed countries. However, they have ignored the effects of spatio-temporal dynamics on such convergence. In this paper, we address this gap in understanding the regional convergence of CO2 emissions by considering the spatio-temporal dynamics underlying the data. An empirical analysis of CO2 emissions in urban China based on our spatio-temporal model shows that overall, per capita CO2 emissions in these areas increased and converged from 1985 to 2008. The proposed convergence model provides greater explanatory power than its conventional counterpart due to the specification of spatio-temporal dependency. Our results reveal the dynamics of spatial effects in the convergence model, thus identifying the role of spatial effects in a disaggregated manner. The convergence rate increases when considering its spatio-temporal dependency. This 'catching-up' in the convergence of CO2 emissions indicates an increasing trend in such emissions in China, although the Chinese government has taken many measures to reduce CO2 emissions. These results should motivate policy makers to reflect on whether current policies actually reduce carbon emissions.

Introduction

In the past two decades, global warming has become an increasing concern for policy makers. According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007), there is a greater than 90% chance that the average global temperature increase over the last century was primarily caused by human activities. As centers of human activity, urban areas drive economic growth, material consumption and energy demand and are the largest emitters of carbon dioxide (CO2) (Rosenzweig, Solecki, & Hammer, 2011). Cities are estimated to contribute 75–80% of all fuel emissions (Satterthwaite, 2008), particularly in developing countries, where population and wealth are concentrated within urban areas (IEA, 2008). However, city governments can play an active role in mitigating climate change by developing sustainable energy systems to meet the increasing demands of economic growth while reducing major greenhouse gases (GHGs; i.e., CO2 emissions) (Hillmer-Pegram, Howe, Greenberg, & Yarnal, 2012). Urban areas undoubtedly play a pivotal role in carbon emissions and mitigation.

Fairness and regional equity have attracted considerable attention from applied geographical researchers (Li & Wei, 2010) and from GHG negotiators and policy makers (Cazorla & Toman, 2001; Meyer, 2000). Per capita CO2 emissions are assumed to gradually approach equal levels across countries over the long term (convergence) (Baumol, 1986). One important implication of this convergence assumption is that regions with lower initial per capita CO2 emissions will experience more rapid emissions growth, eventually catching up to regions with higher per capita emissions. The recent ‘Contraction and Convergence’ proposal of the Global Commons Institute (GCI) aims to allocate commitments among countries as a way of mitigating GHG emissions (GCI, 2008). This approach substantially compresses the reduction of global CO2 emissions (contraction) while gradually equalizing the per capita CO2 emissions across counties (convergence). The majority of projection models currently guiding policy makers in the formulation of emissions-abatement strategies to combat global warming assume this convergence in emissions (McKibbin & Stegman, 2005). Thus, the question of whether a convergence trend exists among regions has far-reaching implications for both national and regional policy makers in the formulation of carbon targets.

In addition to motivating policy makers, convergence has also captured the attention of theorists (Brock & Taylor, 2004; Harvey & Braun, 1996; Ordás Criado, Valente, & Stengos, 2011) and empirical
scholars (Aldy, 2006; Strazicich & List, 2003) in the field of carbon mitigation since the late 1990s. The theoretical literature has always focused on developing theoretical models to understand space-time, place and the environment for a better world based on equity (Harvey & Braun, 1996). Brock and Taylor (2004) amended the Solow model, the core model of modern macroeconomics, to obtain the ‘Green Solow model’ by incorporating abatement technologies to provide a cohesive theoretical explanation of the relationship between per capita pollution and income. The Green Solow model confirms the conditional convergence of per capita pollution across 22 countries belonging to the Organization for Economic Cooperation and Development (OECD) from 1960 to 1998. Motivated by Brock and Taylor (2004), Ordás Criado et al. (2011) developed a neoclassical growth model with endogenous emissions reduction based on two assumptions: that pollution growth rates are (i) positively related to output growth (scale effect) and (ii) negatively related to emissions levels (defensive effect). This growth model was reduced to a convergence equation and was empirically tested for two regulated air pollutants (sulfur and nitrogen oxides) across 25 OECD countries from 1980 to 2005, yielding significant convergence. These two growth models have provided new levels of theoretical sophistication in explaining emissions growth.

However, empirical studies rather than theoretical explanations generally drive the debate in the GHG-mitigation literature (Islam, 2003; Jobert, Karanfil, & Tykhonenko, 2010). Strazicich and List (2003) were the first to analyze CO2-emissions convergence in detail. These authors used both cross-sectional regression tests and panel unit root tests to show strong evidence of convergence in CO2 emissions across 21 developed countries from 1960 to 1997. Nguyen Van (2005) examined CO2-emissions convergence across an expanded global sample of 100 countries. Using a non-parametric approach, they detected divergence across the full data set and convergence across the developed countries from 1966 to 1996. Aldy (2006) obtained similar results, confirming the convergence hypothesis across 23 OECD countries while detecting divergence across 88 countries in a worldwide sample from 1960 to 2000. Later, Aldy (2007) found no evidence of convergence in per capita production and consumption-based CO2 emissions across the United States from 1960 to 1999. Clearly, despite the numerous recent studies on convergence, no consensus has been reached.

Moreover, the theoretical and empirical convergence literature has largely ignored the spatio-temporal dependence of the data, with a few exceptions (Abreu, De Groot, & Florax, 2005; Egger & Pfaffermayr, 2006; Rey & Janikas, 2005). Spatial effects can invalidate the inferential basis of traditional econometric methods because they violate the key assumption of observational independence. From a geographical perspective, spatial effects can arise in a number of ways including technology spillovers, labor and non-labor migration, commodity flows and a host of other spatial interaction types capable of tying the fortunes of neighboring economies together (Rey & Janikas, 2005). A typical example of a spatial convergence study on regional income inequality can be found in Rey and Montouri (1999). Their spatial economic specification identifies strong evidence of the misspecification of the standard convergence model due to ignoring spatial dependencies. The presence of spatial error autocorrelation also complicates the transitional dynamics of the overall convergence process. Furthermore, a key limitation of the majority of empirical analyses of spatial convergence — whether formed by cross-sectional, time-series or panel data — has been the assumption that each sampled entity maintains a single spatial role over time (Abreu et al., 2005; Badger, Muller, & Tonelli, 2004; Bode & Rey, 2006; Ertur, Le Gallo, & Baumont, 2006). The inherently dynamic nature of spatial properties makes it necessary to incorporate the spatio-temporal dynamic components of spatial convergence.

Numerous analyses of carbon-emissions convergence at various scales and using different approaches have yielded mixed results. Recent studies on spatial convergence in economic growth have also omitted the temporal dynamics of spatial dependence. Few studies have incorporated a spatio-temporal perspective on the convergence of environmental outputs, despite the close connection between economic growth and environmental outputs. Our goal is to extend the research on the regional convergence of CO2 emissions by considering the spatio-temporal dynamics of this phenomenon. We address this research gap in the following ways. First, in contrast to previous studies analyzing CO2-emissions convergence using standard models, we extend the model to incorporate temporal dynamics and spatial dependence, the effects of which have not yet been reported. Second, and more importantly in the context of spatio-temporal specification, we describe the dynamics of spatio-temporal dependence using period-specific spatial coefficients. Thus, we identify the variation in the spatial patterns of CO2 emissions over time and across regions using these period-specific spatial coefficients. We also discuss the policy implications for CO2-emissions mitigation based on the emissions dynamics.

Our results suggest that spatio-temporal specification improves the explanatory power of the convergence model. Per capita CO2 emissions from urban areas converged significantly from 1985 to 2008, with a slightly increasing spatial clustering across provinces. Our findings also indicate that the convergence rate increases when spatio-temporal specification is considered.

The remainder of this paper is organized as follows. Section 2 specifies our convergence model incorporating spatio-temporal dynamics. Section 3 describes the research area and the properties of the data. Section 4 provides the empirical results of our spatio-temporal convergence analysis. Section 5 discusses the uncertainty in this study and its related implications, and Section 6 concludes the paper.

Convergence model with spatio-temporal specification

Spatial dependence

Here, we present the spatial weights matrix on which the subsequent analyses rely. The specification of the spatial weights matrix is an important issue in applied spatial geography (Anselin, Gallo, & Jaeyt, 2008). We begin by choosing a simple contiguity weights matrix, assuming that Hainan Island connects to Guangdong Province. However, CO2-emissions growth is positively related to economic growth (Raufach et al., 2007). Thus, we modify the simple contiguity weights matrix by accounting for the economic weights of neighboring provinces:

\[ w_{ij} = \begin{cases} \frac{\text{GDP}_j}{\sum_{k=1}^{K} \text{GDP}_j} & \text{for contiguous provinces} \\ 0 & \text{otherwise} \end{cases} \]  

where \( w_{ij} \) is the element of the spatial weights matrix \( W \) between provinces \( i \) and \( j \) and \( \text{GDP} \) represents the provincial average per capita GDP. This approach differentiates the contribution of each neighboring province, allowing for larger spatial effects from provinces with relatively higher per capita GDPs. The contiguity weights matrix and the economic weights matrix are applied simultaneously in the following analyses.

Spatial dependence can arise in many ways, including technology spillovers, labor migration, commodity flows and other spatial
interactions affecting the growth rates of neighboring regions. Generally, the spatial dependence \( I_t \) in period \( t \) is measured by the global Moran’s I statistic, which is expressed as:

\[
I_t = \frac{(n/S)}{\left( \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}x_i x_j / \sum_{i=1}^{n} x_i^2 \right) / \left( \sum_{i=1}^{n} x_i \right)^2} \quad \forall \; t = 1, 2, \ldots, T
\]  

(2)

where \( n \) is the number of provinces, \( X_t \) is the natural log of per capita CO₂ emissions \((f)\) from region \( i \) in year \( t \) and \( S \) is a scaling factor equal to the sum of all the elements of \( W \). The values of Moran’s I fall between \(-1.0\) and \(+1.0\). A value close to zero indicates the random distribution of per capita CO₂ emissions.

An emerging question is to what extent the global Moran’s I of non-stationary spatial dependence (‘club convergence’) deviates from the overall distribution. To address this issue, we use a deeper disaggregated analysis based on the Getis–Ord statistic \((G_*)\) (Ord & Getis, 1995) to detect local spatial dependence:

\[
G_{t,i}^* = \frac{S}{\left( \sum_{j=1}^{n} w_{ij}X_j - \bar{X}_t \sum_{j=1}^{n} w_{ij} \right)^2 / (n - 1)}
\]

(3)

where \( \bar{X}_t \) is the mean value of the natural log of per capita CO₂ emissions \((f)\) in year \( t \) and \( S \) is the standard deviation of \( X \). A positive \( G_*^* \) value for province \( i \) indicates a spatial cluster of high per capita emissions (hot-spot), whereas a negative value of this statistic indicates a spatial cluster of low per capita emissions (cold-spot).

Convergence model with spatial specification

Initial work on the convergence hypothesis (Barro & Sala-i-Martin, 1990) was based on neoclassical growth theory, and convergence was estimated using a growth-regression approach (Rey & Janikas, 2005):

\[
(1/T) \ln \left( \frac{f_{t_0}}{f_{t_0 + T}} \right) = \alpha + \beta \ln \left( f_{t_0} \right) + \epsilon_{t_0}
\]

(4)

This equation relates the per capita emissions growth rate over the period from \( t_0 \) to \( t_0 + T \) to an initial emissions level, \( f_{t_0} \). \( \alpha \) and \( \beta \) are the parameters to be estimated, and \( \epsilon \) is a stochastic error term. A statistically significant and negative \( \beta \) is expected to support the β-convergence hypothesis (Baumol, 1986).

Recent research has yielded increasing evidence that spatial dependence can affect the convergence rate. Spatial econometric models are useful tools for integrating spatial effects into convergence models (Abreu et al., 2005; Rey & Montouri, 1999). In particular, we consider two traditional spatial econometric models: the spatial lag model and the spatial error model. The former model includes spatially lagging per capita CO₂ emissions (dependent variable) on the right side of the regression, while the latter model posits that spatial dependence in a set of observed local characteristics makes the error terms auto-dependent across space (Anselin et al., 2008). The spatial econometric literature (Anselin et al., 2008; Elhorst, 2003) offers a wide variety of model specifications that we do not attempt to detail here. In all cases, a prior Lagrange Multiplier (LM) test is applied to ascertain whether a spatial lag model or a spatial error model is preferred, followed by the decision rule suggested by Anselin and Florax (1995). Here, the test statistic of the spatial lag model is significantly larger than that of the spatial error model; hence, the spatial lag model is strongly favored:

\[
G_{t_0 + T} = \frac{1}{T} \ln \left( \frac{f_{t_0 + T}}{f_{t_0}} \right) = \alpha + \beta \ln \left( f_{t_0} \right) + \rho \sum_{j=1}^{n} w_{ij} \ln \left( f_{t_0 + T} \right) + \epsilon_{t_0}
\]

(5)

where \( G_{t_0 + T} \) is the natural log of the annual average growth rate of per capita CO₂ emissions over the period from \( t_0 \) to \( t_0 + T \), \( \rho \) is the spatial autoregressive coefficient (with a constant value over the studied period) and all other terms are as previously defined. The Ordinary Least Squares (OLS) estimator applies to the spatial lag model and is thus invalidated due to the simultaneity introduced through the spatial lag. Instead, an alternative estimator based on the Maximum Likelihood (ML) principle is commonly applied in empirical studies (Rey & Montouri, 1999). Thus, an ML estimator is used here. We performed these estimates using MATLAB routines adapted from Elhorst (2010).

However, the inherent dynamics of spatial dependence, as generated by the dynamics of the socioeconomic connections between provinces over time, make it challenging to use the invariable spatial autoregressive coefficient (\( \rho \)) to describe the dynamic spatio-temporal effect (Aroca, Guo, & Hewings, 2006; Rey & Janikas, 2005). Hence, we construct an alternative convergence model using spatio-temporal specification to capture the spatio-temporal dynamics of the convergence process.

Convergence model with spatio-temporal specification

Temporal dynamics are initially introduced in a familiar way in fixed-effects models by allowing time-specific intercepts and/or slopes and in random-effects models by incorporating a random time component or factor (Anselin et al., 2008). However, these approaches do not allow the spatial dependence to be correlated across time periods. We outline an alternative specification based on Eq. (5) that is appropriate for describing spatio-temporal dependency:

\[
G_{t_0 + T} = \alpha + \beta \ln \left( f_{t_0} \right) + \rho_t W_N G_{t_0 + T} + \epsilon_{t_0}
\]

(6)

where \( \rho_t \) is the period-specific spatial autoregressive coefficient and \( W_N \) is the spatial weights matrix. This approach can be regarded as an extension of single cross-sections for \( T \) periods. In each period \( t = t_0, t_0 + 1, \ldots, t_0 + T \), the \( N \times 1 \) dependent vector \( G_{t_0 + T} \) can then be written in a reduced form:

\[
(I_N - \rho_t W_N) G_{t_0 + T} = \alpha + \beta \ln (F_{t_0}) + \epsilon_{t_0}
\]

(7)

Unlike that of Eq. (6), the LHS of Eq. (7) can be seen as a new dependent variable from which the effect of spatio-temporal autocorrelation has been eliminated.

As proven in spatial econometrics, the use of OLS in the presence of non-spherical errors yields a biased estimate of a parameter’s variance. Thus, we use an ML estimator for each \( \rho_t, t=t_0, t_0 + 1, \ldots, t_0 + T \), assuming a Gaussian distribution for the error term \( \epsilon_t \):

\[
L_T = \ln |I_N - \rho_t W_N| - (N/2) \ln \sigma^2 - (1/2) \sigma^2 / \epsilon^2
\]

where \( \sigma^2 = G_{t_0 + T} - \rho_t (I_T \otimes W_N) G_{t_0 + T} - \beta \ln F_{t_0} \)

(8)

Thereafter, the spatial autoregressive coefficient \( \rho_t \) is obtained by \( dL_T / d\rho_t = 0 \), as the solution to the usual first-order conditions

\footnote{Due to space limitations, the statistical results of the LM tests are not presented here but are available from the authors.}
(for technical details, see Anselin et al., 2008). Because the $F$ matrix in the convergence model covers only the initial level of explanatory variables, the fixed-effects approach may suffer from inefficient estimation. The spatio-temporal specification, therefore, utilizes the random-effects approach. We extended the MATLAB routines provided by Elhorst (2010) to allow the spatio-temporal specification procedure proposed in this paper.

Study area and data description

Here, we focus on the growth of CO2 emissions in urban China from 1985 to 2008. Before collecting data, we discussed whether to explicitly define the urban areas under study as spatial administrative units or as functional units. Generally, built-up areas would be most suitable for our research due to their established infrastructure and large buildings. Unfortunately, limited data are available for this category. Municipal districts, which are administrative units that typically cover built-up areas and their urban fringes, are an alternative scale for our research. Thus, we use municipal districts at or above the prefectural level (except for Tibet due to limited data) as the sample urban areas.

The National Bureau of Statistics of China (NBSC) (1986e2009b) publishes its national and provincial energy balance sheets annually. We use these reports to calculate provincial total energy consumption, from which we then estimate production-based total carbon emissions following the IPCC approach (IPCC, 2006). We assume that only fuel energy produces carbon emissions. Emissions from thermal power generation are allocated to the places where the electricity is consumed, and transportation emissions are allocated to the places where the fuel is sold to the end users. This approach is problematic because the NBSC does not report urban energy statistics together with provincial energy statistics. Therefore, we propose a top-down approach to downscale provincial emissions and allocate them among urban areas. We assume a linear relationship between fuel emissions and GDP at the provincial level. Thus, each urban area’s share of CO2 emissions is equal to the ratio of the urban GDP to the entire provincial GDP. This assumption may result in the slight overestimation of urban energy consumption because the carbon-use intensity of an urban area is expected to be slightly lower than the provincial average (Dhakal, 2009). However, urban dwellers emit approximately 2–2.5 times the fuel CO2 emissions of rural residents (Dodman, 2009), thus compensating for some of the overestimation that may occur under this assumption.

To obtain population statistics, we determine the total registered (hukou) population of each municipal district (urban area) in each prefecture-level city from the China City Statistical Yearbook (NBSC, 1986–2009a) and aggregate these data at the provincial level to match the scale of the provincial data. Thus, per capita CO2 emissions in urban areas are calculated on a provincial basis.

Fig. 1 provides a general overview of the growth of per capita CO2 emissions in urban China from 1985 to 2008. Overall, the per capita CO2 emissions of the urban areas in 30 provinces increased over time. During the study period, Hainan Province was the smallest emitter, while Xinjiang Province was the greatest emitter. The latter province produces energy-related carbon emissions in the middle of the overall range despite having a much smaller urban population compared to other regions. Notably, the per capita CO2 emissions from certain provinces included in the “Western China Development” program were initially small but increased relatively rapidly in 2008, suggesting that convergence ‘catches up’.

Fig. 2. Moran’s I for regional CO2 emissions in urban China from 1985 to 2008.

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2 Western China Development: a program launched by the Chinese central government to boost its less-developed western regions, which encompass 71.4% of the area of mainland China.
Empirical results

Spatio-temporal dynamics

We first calculate Moran’s I statistic (Eq. (2)) to detect the global spatial dependence of per capita emissions in urban China. Fig. 2 displays the trajectories of the spatial dependence of per capita CO₂ emissions in urban China from 1985 to 2008. All of the Moran’s I statistics are statistically significant at \( p = 0.05 \) over the studied period, providing strong evidence of spatial dependence.\(^3\) The

\(^3\) Due to space limitations, neither the \( z \)-scores of the Moran’s I statistic nor the \( p \)-values are reported here, but both are available from the authors.
trajectories are clearly opposite when applying different weights matrices. In particular, applying the contiguity weights matrix causes per capita CO2 emissions to spatially cluster from 1985 to 2001 and disperse from 2002 to 2004. In contrast, applying the economic weights matrix causes the spatial dependence of per capita CO2 emissions to increase slightly and the spatial relationships to cluster throughout the study period. In other words, the apparent spatial relationships of per capita CO2 emissions vary between the geographical and economic structures, and considering the economic weights enhances the spatial dependence of per capita CO2 emissions between neighboring provinces. Moreover, the fluctuations of both curves in Fig. 2 reflect the temporal dynamics of the spatial dependence of per capita CO2 emissions, which may weaken or strengthen the convergence of per capita CO2 emissions over time. However, the existence of the spatio-temporal dependence of per capita CO2 emissions over the study period violates the assumption of the OLS convergence-estimation model that the per capita CO2 emissions from each province are independent observations.

Fig. 3 provides a more disaggregated view of the spatial dependence of per capita CO2 emissions in urban China, showing the GI* statistics calculated using the contiguity weights matrix and the economic weights matrix in 1985 and 2008. Spatially, per capita CO2 emissions are much higher in northern and northwestern China than in southern and eastern China, which are the most affluent regions of the country (Fig. 3a and b). Moreover, the local spatial relationships vary across provinces, although the global Moran's I statistic indicates spatial clustering in both 1985 and 2008. Using the contiguity weights matrix, hot spots appear in northern and northwestern China, with a new hot spot emerging in southwestern China in 2008. This pattern implies the spatial clustering of high per capita CO2 emissions in these regions. The cold spots shift from the eastern coastal regions in 1985 to the central regions in 2008 (Fig. 3c and d). Using the economic weights matrix (Fig. 3e and f), both hot and cold spots appear in western China in 1985. In 2008, the economic weights matrix and the contiguity weights matrix yield similar patterns for the local spatial dependence of per capita CO2 emissions. We conclude that when analyzed with the spatial distribution of per capita GDP, the contiguity weights matrix reflects the geographical structure of the analyzed data, while the economic-weights matrix highlights the economic effects of neighboring regions with similar per capita GDPs. Considering the unusual nature of these weight matrices, both are used in the following analyses.

Convergence process with spatio-temporal specification

Fig. 4 provides a graphical analysis of the initial level and annual growth rate of per capita CO2 emissions from 1985 to 2008, together with an estimated linear regression model ($R^2 = 0.41$). The negative slope of the estimated trend line implies a convergence trend in CO2 emissions in urban China.

Table 1 presents the estimated results for the spatial (Eq. (5)) and spatio-temporal (Eq. (6)) specifications of CO2-emissions convergence in urban China from 1985 to 2008. We do not report the results of the spatial convergence model using the economic weights matrix because they are quite similar to those obtained using the contiguity weights matrix. The present results are consistent with those obtained from the conventional model (Eq. (4)), providing significant support for absolute convergence because the $\beta$ parameters are statistically significant and negative, with an acceptable overall model fit ($R^2$ greater than 0.60 for the spatio-temporal specification model). In particular, the range of the $\beta$ coefficient is narrow, with a smallest absolute value of 0.035 produced by the spatial convergence model and a largest absolute value of 0.044 produced by the spatio-temporal convergence model with the economic weights matrix. The corresponding convergence rates ($\theta$) for each case are also reported in Table 1. These results imply that considering the spatio-temporal dependence accelerates the convergence rate.

Fig. 5 shows the spatial dynamics yielded by each model over the study period. For both spatial weights matrices, the spatial autoregressive coefficients in Eq. (6) fluctuate strongly, with slightly increasing trends over the study period. Moreover, the range of the spatial autoregressive coefficients obtained with the economic weights matrix is much wider than that obtained with the contiguity weights matrix. As expected, the spatial autoregressive coefficient in Eq. (5) does not vary over the study period. However, it does not equal the mean value of the spatial autoregressive coefficients in Eq. (6) but rather has the relatively high value of 0.79.

### Table 1

<table>
<thead>
<tr>
<th>Convergence hypothesis estimates.</th>
<th>Spatial specification</th>
<th>Spatio-temporal specification</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Contiguity weights matrix</td>
<td>Contiguity weights matrix</td>
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<tr>
<td></td>
<td>Coefficient</td>
<td>$t$-stat.</td>
</tr>
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<td><strong>Const.</strong></td>
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<td>2.77</td>
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<td>$\beta$</td>
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<td>$-2.44$</td>
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<tr>
<td>$\theta$</td>
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<td>0.65</td>
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<tr>
<td>$\theta^*$</td>
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<td>$-321.32$</td>
</tr>
<tr>
<td>Likelihood</td>
<td>$-127.74$</td>
<td>$-321.32$</td>
</tr>
</tbody>
</table>

Notes: *Statistically significant at the 5% level. **Statistically significant at the 1% level. The convergence rate $\theta$ is obtained using $\theta = \ln(\beta + 1)/(-T)$, where $T$ is the number of years in the period.
The convergence estimate for urban China is uncertain for many reasons, but the greatest concern is the uncertainty of the data. Here, we use official data (energy consumption, population and GDP statistics) from the NSBC. Several scholars have questioned the reliability of these data, claiming politically motivated adjustments (Chan, 2010; Guan, Liu, Geng, Lindner, & Hubacek, 2012). Guan et al. (2012) have argued that the aggregated provincial energy value is 20% higher (3895 Mt standard coal equivalents) than the national energy consumption and that coal consumption accounts for 71% of this statistical discrepancy. Additionally, the de facto urban population is 1.3 times the number given by the household registration system (Hukou) (Chan, 2010). Thus, the uncertainty of per capita emissions is 10% according to the error-propagation law. Moreover, the performance-assessment function of GDP statistics inevitably introduces error into the data due to governmental pressure (Holz, 2004).

In addition to data uncertainty, methodological uncertainty arises from the assumption of a linear relationship between total fuel emissions and GDP in each province. To validate this assumption, we plot total fuel emissions against GDP for four provincial cities: Beijing, Tianjin, Shanghai and Chongqing (Fig. 6). The results show a strong, positive linear relationship between fuel emissions and GDP. Moreover, the goodness of fit ($R^2$) of the linear models is 0.89 for Beijing and Tianjin and 0.96 for Shanghai and Chongqing. Thus, the average error arising from the linearity assumption is approximately 7.5%.

In summary, the uncertainty of the convergence estimate is 17.5%, based on the quantitative sum of the uncertainties in the data and methodological assumptions. A sensitivity test to reveal the effects of this uncertainty on the convergence trend indicates the same convergence trends but different convergence rates.4

Implications of the convergence of per capita CO$_2$ emissions

The estimated convergence of per capita CO$_2$ emissions has several implications. First, the convergence model with spatio-temporal specification performs well in explaining the spatio-temporal variation in the growth of per capita CO$_2$ emissions. The results of the conventional convergence model (Fig. 4) are confirmed by the spatial convergence model and by the spatio-temporal convergence model with two different spatial weights matrices. As expected, the explanatory power increases as the temporal dynamics of spatial dependence are incorporated into the model: the spatio-temporal convergence model explains 67% of the variation, whereas the conventional convergence model explains only 41% of the variation. Given the dynamics of the Moran’s $I$ statistic, it is essential to consider the temporal dynamics in the regression model. More importantly, this is the first time that spatio-temporal effects have been specified in a convergence model, clearly demonstrating that spatio-temporal specification increases the explanatory power of the convergence model while revealing the dynamic spatial effects within the observed data.

Second, the results shown in Table 1 provide strong evidence of convergence in per capita CO$_2$ emissions in urban China from 1985 to 2008. This result is consistent with the empirical results described above showing convergence in the CO$_2$ emissions from developed countries (Jobert et al., 2010; McKibbin & Stegman, 2005; Ordás Criado et al., 2011; Strazicich & List, 2003). The estimated convergence rates lie between 0.04% and 0.77% (absolute and conditional convergence) in these empirical studies. Our results are generally consistent with these estimates. However, the spatio-temporal specification of the convergence model increases the convergence rate of per capita CO$_2$ emissions in urban China from 0.11% to 0.29%, suggesting that spatio-temporal dependence plays a significant role in the convergence process. This issue has been largely ignored in previous research. However, our conclusion differs from that of Rey and Montouri (1999), who found that the convergence rate of per capita income among states in the United States decreased slightly when spatial error specification was considered in the model. This difference suggests that the form of spatio-temporal dependence is related to the process of data generation.

The third implication follows from the properties of spatio-temporal dependence in the convergence model. The presence of significant spatial dependence in per capita CO$_2$ emissions can be considered to be the formal specification for the equilibrium outcome of spatial or social interaction processes, in which the value of per capita CO$_2$ emissions from one province is jointly determined with those of the neighboring provinces. The spatial or social interaction processes can be considered to result from technology diffusion or policy copying among regions. However, the causality is not clear. Nevertheless, modeling the complex neighborhood effects requires considerable attention to the choice of the weights matrix in a spatial model.

Finally, we examine the relationship between emissions convergence and industrial restructuring since 2000, when the Western Development policy was launched in China. Although the Western Development plan strongly emphasized environmental protection, and the migration of high energy-demand industries from eastern coastal China is officially forbidden, this type of migration does happen because local governments seek short-term rapid economic growth, resulting in the aforementioned ‘catching up’ of emissions convergence. For example, the shares of coal and electricity production in western China increased from 23% to 22%, respectively, in 1985 to 44% and 28%, respectively, in 2008. Moreover, 76% of China’s electricity is produced by coal-burning facilities, 53% of which are located in western China.5 This reliance on coal may be one reason why per capita CO$_2$ emissions in western China have increased slightly since 2000, as shown in Fig. 1. Thus,

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4 Due to space limitations, the results of the sensitivity test are not reported in the text but are available from the authors.

we encourage policy makers to pay attention to the ‘catching up’ of emissions convergence, which implies a tendency for CO2 emissions to increase on a per capita basis. Positive emissions-reduction policies are required to meet the established targets.

Conclusion

This paper extends the spatial convergence model to include a spatio-temporal effect specification and then examines whether CO2 emissions are converging across urban China. Our results identify a convergence trend in per capita CO2 emissions, corroborating previous findings on such emissions in developed countries. We also provide precise insight into the spatial distribution of CO2 emissions and new evidence for the role of spatio-temporal dependence in the analysis of urban CO2-emissions convergence.

Our confirmatory analysis is important because it provides the first detailed evidence for the dynamics of spatial dependence in CO2-emissions convergence in urban China. The results favor a spatial lag model, indicating that spatial or social interactions are involved in the process generating CO2-emissions data. We also show that spatio-temporal specification increases the explanatory power of the convergence model while accelerating the convergence rate of CO2 emissions in urban China. Furthermore, the specification of temporal dynamics in the spatial convergence model allows dynamic spatial effects in the estimated process, revealing the underlying dynamic properties of the geographical data. This type of specified convergence model will be useful in further studies of convergence issues because spatio-temporal dynamics are an important characteristic of geographical data.

Questions remain regarding empirical issues, such as whether emissions-reduction targets in China could be satisfied through a ‘catching up’ convergence trend. Because the average values of per capita emissions increase over time, we note a ‘catching up’ rather than a ‘slowing down’ convergence process, suggesting that the situation in urban China is worsening and that the economic gap and regional environmental policies simply urge high energy-demand industries to move from eastern to western China rather than shift them out of China. The emissions-reduction target is currently being challenged, and the outcome of this important issue will depend on the extent to which the relationship between industrial relocation, renewal and CO2-emissions reduction is balanced through the incorporation of stricter governmental policies that are not only adopted but also achieved.

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