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Hua Liao
Huai-Shu Cao

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Center for Energy and Environmental Policy Research
Beijing Institute of Technology
No.5 Zhongguancun South Street, Haidian District
Beijing 100081
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Yi-Ming Wei
Director of Center for Energy and Environmental Policy Research, Beijing Institute of Technology

For more information, please contact the office:

Address:
Director of Center for Energy and Environmental Policy Research
Beijing Institute of Technology
No.5 Zhongguancun South Street
Haidian District, Beijing 100081, P.R. China

Access:
Tel: +86-10-6891-8551
Fax: +86-10-6891-8651
Email: ceeper@vip.163.com
Website: http://ceep.bit.edu.cn/english/index.htm

How does carbon dioxide emission change with the economic development? Statistical experiences from 132 countries

Hua Liao[a, b, *], Huai-Shu Cao[a, b]

[a] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China;
[b] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China.

*** CORRESPONDING AUTHOR**
Hua Liao
Energy and Environmental Policy Research Center
School of Management and Economics
Beijing Institute of Technology
No. 5, Zhongguancun South Street,
Haidian District, Beijing 100081, China
Tel: +86-10-6891-8359
hliao@gmail.com, hliao@bit.edu.cn

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Abstract: Issues concerning what measures should be adopted to achieve a sustainable world with less carbon dioxide emission and in what magnitude should we reduce our emission have been on agenda in both international negotiations and countries' policy making aimed at coping with potential global climate change. These issues cannot be easily addressed unless comprehensive understanding about the countries' status quo as well as historical relationship between economic development and carbon dioxide emission are gained. In this paper, we examine the historical relationship between economic development and carbon dioxide emission; the *ex-ante* restrictions on function forms and the poorly handled robustness issues rife in economics literature are synthetically addressed. Evidence from recent four decades indicates that per capita carbon dioxide emission first significantly and monotonously increase at low income level and flattens after per capita income reaches at about 22,000$ (2005 constant price). We perform various robustness checks by employing different data sources, different model specifications and different econometric estimates. The captured development-emission relationship is robust. Our empirical results indicate factors such as urbanization, population density, trade, energy mix and economic environment etc. impact the absolute level of carbon dioxide emission not the overall income elasticity structure of carbon dioxide emission.

Keywords: Income elasticity; Carbon dioxide emission; Linear spline model; Environmental Kuznets curve

1. Introduction

While there is growing scientific evidences indicating anthropogenic factors have contributed to global warming in the past century and this trend, as projected, will continue in the current one (Solomon *et al*, 2007), international negotiations for the reduction of world's CO_2 emission are more or less at a standstill in terms of reaching binding agreements, and limited emission reduction measures have been taken by countries (Nordhaus, 2010). One of the main causes leading to this stagnancy is the uneven distribution of emission reduction volumes, its induced costs and implied economic welfare losses by emission reduction (Pan, 2008). Given the inseparable relationship between energy consumption, CO_2 emission and economic development, especially for countries in the process of industrialization, the problem of carbon emission has become a problem concerning each country's future development. For the sake of addressing issues concerning what measures should be adopted to achieve a sustainable world with less CO_2 emission and in what magnitude should we reduce our emission, the historical relationship between economic development and CO_2 emission should be well examined.

In literature, there are two major approaches modeling CO_2 emission, structural models and econometric models based on the Environmental Kuznets Curve (EKC) hypothesis.

The former approach sees the world or a specific region as an interactive system, and each component of the system is described with a set of equations, parameters of which are often unknown. The advantages of the structural models lie in that they provide a relatively complete description of the system being examined, and can allow researchers to perform various shock simulations and scenario analyses (Nordhaus, 2010). But models of this sort suffer from considerable criticism because of their lack of model transparency and robustness, and in practice they require massive detailed data sets for their components to be driven. The required data sets are often unavailable or not continuous in time dimension, and thus are usually fixed by the judgment of the researchers, calibration from available data sets or a combination of judgment and calibration (Schmalensee *et al*., 1998), which lead to significant difference and controversy in their simulation results even if the baseline scenarios proposed are the same (EMF, 2009).

In the second approach, econometric analyses with diversified geographic coverage and time intervals are performed. The econometric models are more concise, more transparent, and less data-intensive than large-scale structural models. Fixed single-equation model specifications, e.g. linear, quadratic or cubic polynomial, are widely adopted in these analysis; Holtz-Eakin and Selden (1995), Suri and Chapman (1998), AkbostancI *et al*. (2009), Tamazian and Rao (2010), Fodha and Zaghdoud (2010) and Sharma (2011) are among the many examples. He (2007) provided a earlier overview of these studies addressing the relationship between economic development and CO_2 eimssion, including their employed function forms and related empirical findings. And results of these studies differ considerably. While some problematic issues are properly addressed (see Stern (2010) for an example of estimating prevailing panel data models in the EKC literature), there are several remaining major criticisms of this branch of studies. First, data sets employed in these studies are often biased; observations showing a downward trend of the growth-emission relationship always come from world's richest countries or regions. Second, it seems that air pollutants like sulfur tend to have inverted-U relationship with income, but conclusions from studies testing the EKC hypothesis about the relationship between CO_2 and income differe. Third, these studies often adopt single fixed equation forms and cast an *ex-ante* constraint on the relationship between the variables. For comprehensive and profound reviews of EKC-based theory and empirical studies, see Stern (2004), Müller-Fürstenberger and Wagner (2007) and Carson (2010). Another branch of the studies performing econometric analysis employ non-parametric or semi-parametric methods to examine the emission-income relation using cross-sectional data sets covering different number of countries and different length of time intervals. Typical examples are Schmalensee *et al*. (1998), Taskin and Zaim (2000), Dijkgraaf and Herman (2001), Bertinelli and Strobl (2005), Azomahou *et al.* (2006), He and Richard (2010), Auffhammer and Steinhauser (2012). What in common this branch of studies have is that they do not impose *ex-ante* restrictions, at least not strict ones, on the employed models, but other important factors influencing CO_2 emission are either ignored or left poorly controlled even though some of them do include country or time fix effects in their panel data models. Still that in projection practices, since their purposes are to obtain appropriate projections of future emission, the investigation of the potential explanations of selected explanatory variables or model forms are weakened (see for example Auffhammer and Steinhauser, 2012). Thus while the estimated effects of the variables are useful in projection, they provide little information in terms of the causal relationship interested. And this is why these studies take such a different genre against studies devoted merely on the causal relationship. In addition, robustness check of their results is in short in some way.

In short, there are two main drawbacks rife in econometric analyses of the relationship between economic development and CO_2 emission, namely, the *ex-ante* restrictions on the model forms and the poorly handled robustness issue. In this study, we employed a piece-wise linear spline model similar with that of Schmalensee *et al.* (1998) to caputure the historical income-emission relationship. Data set used in this study covers 132 countries in recent 4 decades, *i.e.* from 1971 to 2009. And to gain robust results, we performed robustness checks on the influences of data source, model specification and estimation method on our results. The drawbacks mentioned above are synthetically handled.

The primary purpose of this study is to investigate how carbon dioxide emission has changed with economic development worldwide and address the two main drawbacks mentioned above synthetically to obtain robust results. We found that, as shown in Fig. 1, as economic progresses, per capita CO_2 emission first increases and then flattens, and the turning point is located where the GDP per capita reaches at about 22000$ (PPP, 2005 constant price). However, evidence from the historical data does not imply the stand of EKC for CO_2, because countries with the same level of economic development may still differ in other social-economic aspects that would influence CO2 emission in different ways. The effects of these relevant social-economic factors such as urbanization, population density, energy mix and economic environment that characterize a country's development status quo, on countries' per capita CO_2 emission were then examined. And in particular, since the problem of carbon leakage has drawn wide attention in recent years, we distinguished the effects of trade or export on per capita CO_2 emission in the current developed and developing countries.

<Fig. 1>

This paper is organized as follows. In Section 2, we describe the econometric model and data sets we employed. In Section 3, we present the empirical results and examine the robustness of the emission-income relationship we captured from several aspects, i.e. the influence of different data sources, different model specifications, and different estimation methods. And in

Section 4 we present our conclusions.

2. Model and data sets description

2.1 The linear spline model specification and control variables

As mentioned in Section 1, function forms rife in literature are linear, squared, and cubic polynomial functions of GDP. In the present paper, a more flexible model is employed to caputure the historical income-emission relationship.

The model we adopted can be described as:

$$\ln\left(c_{it}\right)=\gamma+\alpha_i+\beta_t+f[\ln\left(g_{it}\right)]+h[v_{1,it},v_{2,it},...]+\varepsilon_{it}, \qquad \varepsilon_{it}\sim N\left(0,1\right) \qquad (*)$$

where c_{it} and g_{it} represent per capita CO_2 emission and GDP per capita of country i in year t, α_i and β_t are country and time fixed effects respectively, f and h are some flexible function forms, v_k are some controlling variables we employed to examine the robustness of the income effects (these variables include social-economic development, trade, economic environment and institutional variables), and ε_{it} is normally distributed error term.

The component α_i and β_t absorb the unobservable effects driving CO_2 emission—the effects captured in α_i vary across different countries but don’t change over time, and the effects captured in β_t change over time but are the same for all the countries (Schmalensee *et al*., 1998). By this model setting, the omitted variable bias caused by some certain types of variables are omitted, *i.e.* variables depict country specific characters that don’t change over time and variables representing the global changes over time that are the same for all the countries. And we handle potential bias injected by factors that may vary both across countries and along time by including a wide range of variables in our model: urbanization, population density, trade (export), energy mix and economic environment. Urbanization and population density may influence CO_2 emission in two mechanisms that are contrary to each other. While they may provoke a leap in energy demand and thus increase emission, the opposite may happen since the process of urbanization can also lead to the improvement in the efficiency of public utilities (Poumanyvong and Kaneko, 2010). And economic environment, which may have correlation with distorted prices or countries' managerial efficiency in the both governments and firms, is simply measured by countries' Economic Freedom Index (EFI, see James *et al.*, 2012). The influences of these factors on CO_2 emission may take different patterns as well (see, for example, Kearsley and Riddel, 2010; Burke, 2011). Nevertheless, our focus is on estimating the income elasticity structure of CO_2 emission, therefore in this study they just serve as control variables and analysis of their effects on CO_2 emission are not comprehensively exploited.

To capture the income elasticity structure of CO_2 emission, we divided the income range into a considerable number of segments, and the function form of $f[\cdot]$ is specified as a piecewise linear function based on the segmentation and that of $h[\cdot]$ is merely a linear one. The piece-wise linear specification allows the income elasticity of CO_2 emission to change over time or along the progressing of per capita income. That means with different income level, the elasticity of CO_2 emission can be different. Thus, estimated income elasticity along the income range captured the evolution of CO_2 emission along the process of economic development.

While the linear specifications are not so convenient for the capture of so called inverted-U relation and although the quadratic or cubic models are easy to implement, less data-intensive and prove intuitive calculations of the "turning point", the main disadvantage of the linear, quadratic or cubic equation models lies in the fact that they place *ex-ante* restriction on the shape of the relationship curve of interest and there does not seem a convincing theoretical foundation for this specification, under which the interested relation is either “inverted-U” or “U” shaped. The spline model allows the income-emission curve to take a much wider range of shapes rather than being merely linear, quadratic or cubic; it is a spline-approximation of the underlying relationship. The piece-wise linear model is much more data-intensive and less precise (Suits *et al*., 1978; Ostro *et al*., 2006) than the polynomial ones; this is because a considerably lage number of “pieces” should be specified in order to approximate to the real relationship better and each ”piece” requires a considerably lage number of observations to be estimated with statistical significance. However, as will be described in Section 2.2, our data set covers 132 countries in recent 4 decades with over 4000 observations of the economic and CO2 emission data; we think it is qualified for the purpose of this study and can meet the data requirement of the piece-wise spline model.

2.2 **Data descriptions**

The data of per capita CO_2 emission is taken from IEA, and covers 132 countries with 4515 observations. There are 100 countries or regions whose data sets of CO_2 emission and per capita GDP are complete throughout the whole period 1971-2009. The data set of GDP is from the latest version of Penn World Table—PWT7.1 (Heston *et al*., 2012), and we also employed the GDP data provided by World Bank for the comparison of the results. And data sets of the v's , except that of *EFI*, are all from World Bank. Table 1 gives the definitions of variables and their descriptive statistics. And these definitions will be used throughout our analysis. As the purpose of this paper is to explore the long-run emission-income relationship exploiting international experiences, we include as many countries as possible in our study provided that the corresponding data sets are available.

<Table 1>

3. Empirical results and robustness check

3.1 Estimate Results

When estimating model (*), we first specified the model by dividing the income range into 15 segments by percentile such that each segment contains the same number of observations. And the corresponding 14 knots of the segmentation are 814, 1213, 1699, 2358, 3301, 4307, 5409, 6813, 8617, 11149, 15741, 20074, 25579, 33033 ($) respectively. $f[\cdot]$ is a piecewise linear function based on the segmentation. The country and time fixed effects are included in the model and other factors (the v 's) are temporarily left uncontrolled. Ordinary Least Square (OLS) estimates of income elasticity of each income segment are listed in Table 5, and a visualized display of this income effect structure is shown in Fig. 1. The result indicates that as per capita income increases, per capita CO_2 emission first increases at low income level and then slightly decreases, and the turning point is located where the GDP per capita reaches at about 22000$ (PPP, 2005 constant price). We find that the change of income elasticity after 22000$ is rather sharp. Before that point income elasticity ranges between 0.8~1.1, and -0.2~0 thereafter. This is mainly because of that observations from less developed countries, such as those of the Asia and Africa, are located at the left side of Fig. 1, and the right side observations are from rich west Europe and North America countries (Observations with GDP per capita greater than $22000 are all from high income countries. And in 2009, only 34 countries, about 77% of high income countries and 26% of all the countries covered in this paper, had GDP per capita greater than $22000. Total population of these countries accounts for only about 15% of global population.). And the coefficient of the last income segment is not statistically significant.

Therefore, this result does not necessarily sustain the so called EKC hypothesis, the turning point here is more like a critical point differentiating the two groups of countries, the less developed and the richer ones. Note that, $22000 is just a rough number. While partitioning the income range into 12, 15 or 20 segments, as we did in section 3, generates similar results and the "turning point" cannot be clearly formulated and accurately calculated as it is done in studies employing quadratic models.

Feasible Generalized Least Square (FGLS) estimates, which we employ to address the problems caused by potential autocorrelation and heterogeneity in the data and will be covered in detail in Section 3.2.3, of the base model including only income effect and country and time fixed effects are adopted for our final report of the income elasticity of CO_2 emission. The results are listed in Table 2. Coefficients in the highest 3 income segments are not statistically significant, not favorable to a downward trend. And coefficients of other segments fluctuate without a specific pattern, ranging from 0.306 to 0.759. This indicates a more complex income effect on CO_2 emission in countries with relatively lower per capita income.

<Table 2>

From these results, we extracted our general conclusions, which, after our robustness check, still stand. The rest of this section consists of our several robustness checks on the results above. If finally it is proved that these procedures cast little influence on the shape of the income elasticity curve presented above, we shall conclude that evidences from historical income and emission data are in favor of a first-rise-then-flat rather than an inverted-U income-emission relationship. And for most countries in the world, there is long way to go before they can both increase their per capita income and expect to emit relatively less CO_2.

3.2 Robustness Check

There are no particular economic model and week theoretical supports guiding the econometric specifications of the development-emission relationships (Harbaugh *et al*., 2002). And evidence supporting the stand of EKC hypothesis for carbon dioxide emission is “at best mixed”, and uncertainties originating from data source, model specifications, and estimation methods are seldom explored (Galeotti *et al*., 2006). Careful robustness check from these aspects is both necessary and practically feasible. In this sub-section, we perform robustness checks on the results above from three perspectives: data sources, model specifications and estimation methods.

3.2.1 Data sources

Estimates from Section 3.1 are based on the GDP data provided in PWT7.1 (Heston *et al*., 2012). PWT and World Bank are the most frequently adopted data sources of GDP or GDP per capita in literature, but the two data sets for GDP are not identical. To check whether our results are sensitive to data sources, we also fitted our models using the GDP data from World Bank. Due to the features of International Comparison Program (ICP) 2005 and different methodologies used by PWT and World Bank (see Heston *et al*., 2012), GDP per capita from the two sources may have considerable differences, although, in our case, the two GDP per capita series have a high correlation of 97.37%. The World Bank GDP data (PPP, 2005 constant price) is available since 1980; therefore we extended the GDP data before 1980 using economic growth rate data provided also by World Bank. And finally we got 4239 matched pairs (observations) of per capita carbon dioxide emission and World Bank GDP data. Differences of the two GDP series are demonstrated in Table 3. For 2009, the number of countries whose GDP per capita observations from the two data sources have a difference larger than 10% accounts for about 42% of all the countries covered in this study. And for the entire period 1971 to 2009, the average GDP per capita difference bewteen PWT.1 and World Bank is 13%.

<Table 3>

To check the sensitiveness of our conclusion to data sources, model specification here is exactly the same with that in Section 3.1, *i.e.* 15–segment piecewise linear function form with only country fixed effects, time fixed effects and income effect included. Estimates of income elasticity of each income segments under the two sources of GDP data set are shown in Fig. 2. We also performed the other two robustness checks on the two data sets, the details of which will be covered in the following part of this section, and the general conclusions do not change significantly. So in the rest of this paper only the results under the GDP data from PWT7.1 are displayed. For the estimate results under the two GDP data sets, while there are slight differences in income elasticity of each segment, the overall structure of income effect is basically the same, and so it is with the turning points.

<Fig. 2>

3.2.2 Model specifications

Model specification test in this study is twofold: functional form of $f[\cdot]$ and the inclusion of different covariates in our model.

First, rather than adopting the commonly used quadratic or cubic function forms, we tested whether the results are sensitive to the number of segments in the piecewise linear specification, and 12-, 15- and 20-segment models were adopted. And we also tested another alternative, which segments the income range into 15 intervals of equal interval width. Different number of income segments can allow different magnitude of flexibility for the income elasticity to change along the income range, and, intuitively, more segments more flexibility. To visually illustrate differences of the results, *i.e.* structure of the income effect, under the four model settings, we plotted their estimate results of income effect in Fig. 3 rather than list the coefficients of each income segments.

<Fig. 3>

Fig. 3 shows that under 12-, 15- and 20-segment models by percentile, estimate results of income effect are almost the same. The difference between the two 15-segment models (by percentile and equally spaced over the income range) is mainly caused by different observations captured in the last segment of each of the two models. The corresponding coefficients of the last income segment of the two model are neither significant, 0.797 (0.460)[3] for the equally-spaced model and -0.162 (0.083) for the model by percentile. Here 0.797 and -0.162 are the estimated coefficients, 0.460 and 0.083 in parentheses are the corresponding standard errors, and similarly hereinafter.

And the second part of specification test is one concerning if the results are fragile when other relevant factors are included in our model. While our main purpose is to check the robustness of the income effect, we also want to examine the impacts of these factors on carbon dioxide emission. So we estimated 6 models as listed in Table 4.

<Table 4>

OLS estimates of the included factors and income effects are listed in the corresponding columns of Table 5, from which several conclusions can be derived. What we are interested in are the robustness of emission-income relationship and other factors' impacts on carbon dioxide emission.

Comparison across estimate results of income effects derived from different models suggests that while levels of contribution of income effects to per capita CO_2 emission differ from model to model, differences between the structure of income effect derived from any model and from those of the others are nearly some parallel shift (This can be more intuitively seen in Fig. 4). That is to say, under different model specifications in terms of the inclusion of additional covariates, income elasticity of each income segment does not differ tremendously so that the overall structure of income effect, or the shape of the plots in Fig. 4, stays basically the same. We bootstrapped the coefficients of each income segments under all our model specifications. And according to the results, differences between coefficients of the same income segment across different model specifications, say coefficients of the first income segments from M1 and M2, tend to be significant. However, throughout this paper our emphasis is laid on the overall shape of the income effect. These results of bootstrapping and tests are available upon request.

<Fig. 4>

Table 5 also provides estimates of other potential influence factors' effects on carbon dioxide emission. Direct implications of these estimates concern whether they drive up or pull down a country's per capita CO_2 emission level. First, the coefficients of urbanization rate and population density (log) are 1.357 (0.118) and 0.741 (0.0396) respectively. It means that, on average, if the urbanization rate of a country increases by 10 percent points, its per capita CO_2 emission will increase by 14.53%; and if its population density is 10% denser than another country, with other conditions unchanged, its per capita CO_2 emission will be 7.69% higher. These two covariates are both endogenous variables in an economic system, so if the purpose of study is to study the whole contribution of economic development to carbon dioxide emission rather construct an optimal projection model, they should not be not included in the model (see Holtz-Eakin and Selden (1995)). The result for urbanization is consistent with that of Poumanyvong and Kaneko (2010). Second, we got relatively similar conclusions for the impacts of trade and export. That is, averagely speaking, developing countries raise their per capita CO_2 emission through trade or export, and if their trade dependence increases by 10 percent points, its per capita CO_2 emission will be lifted up by about 2.05%, and 3.01% for export of goods and services. Further, the interaction between trade or export and high-income countries has a negative influence on per capita CO_2 emission, meaning that, through trade (export), this country group tends to lower their per capita emissions. As for energy mix, a 0.1 ton/ktoe lower in carbon intensity is generally accompanied by a 6.51% lower per capita CO_2 emission. This is merely the average effect of energy mix. For a more thorough examination of this issue, see Burke (2011). It suggests an inverted-U shape between CO_2 intensity of energy use and GDP per capita, which implies that this factor may have inverse effects on CO_2, depending on whether a country falls in the high-income range or the lower one. And finally, we can see from Table 5 that the more economic freedom a country achieves, the less carbon it emits. This covariate is represented by economic freedom index (EFI) issued by Fraser Institute, and the index before 2000 is available every 5 years. We modified the original data in two ways in order to include this variable in our model: obtain additional data by linear interpolation and perform a panel data analysis on a 5-year basis. Under the two treatments, the estimate of income effect is basically the same with that of Model-1 described in Table 4 (for detailed estimate results see Model-6a and Model-6b in Table 5 respectively). Countries with more economic freedom tend to function more efficiently.

We analyzed the relationship between economic freedom (represented EFI) and efficiency (represented by CO_2 intensity). We estimated a two-way fixed model of the two factors, with CO_2 intensity being the dependent variable, and the coefficient of EFI is about -0.043 (0.0124) and statistically significant. For earlier studies that analyzed the effect of economic freedom on CO_2 emission, Koop (1998) found that more economic freedom is accompanied by higher efficiency, and Carlsson and Lundström (2001) concluded that economic freedom tends to hamper CO_2 emission.

We can see from the results above that while factors such as urbanization, population density, energy mix, trade and economic environment may influence the absolute level of per capita CO_2 emission by different magnitudes, they do cast little impact on the income elasticity structure or the shape of the elasticity curve, meaning that increase in per capita income seems to lift per capita emission undoubtedly though with different increment in each income level. The implication is that, while economic development will continue to drive up CO_2 emission, these factors may potentially contribute to reduce or lift up the absolute level of per capita CO_2 emission.

3.2.3 Estimation methods

Our last robustness check concerns the impact of alternative estimation method on the estimate results.

There are many studies performing stationary test on the data in order to access preferable data properties, but their results are sometimes mixed (Lee and Lee, 2009; Romero-Ávila, 2008); and further the construction of the alternative hypothesis is controversial in terms of the assumptions made about the data sets, and also there exist ambiguities concerning the optimal interpretation of the results (Pesaran, 2012). Considering the complications in the unit-test practice, we simply conduct our last robustness check by loosening the default assumptions made by OLS estimation in two ways, namely 1) allowing the error structure of the model to be heteroskedastic and 2) within each panel of the data sets, there may exist an global AR (1) autocorrelation. And this was done by employing a FGLS estimation of the same panel-data models as listed in Table 4. Another estimation method, GMM, may bring considerable improvements of the estimates under certain circumstances (see Wooldridge, 2001). GMM estimator requires specified moment conditions, which typically stems from assumptions of or constraints casted by the theoretical economic models, to be implemented. In our case, the empirical model is a reduced one, and we did not specify additional theoretical assumptions or constraints on our model. And we believe the most important and relevant constraint thus lies in the assumed property of the data, which we handled by comparing OLS and FGLS estimates. The estimate results are again visually compared with those derived from OLS estimation in Fig. 5, and detailed results are listed in corresponding columns of Table 5.

<Fig. 5>

The conclusions we can derive here are basically similar with as have been presented earlier in this section. That is, under different estimation methods, OLS and FGLS specifically, the income structure we are interested in stays roughly the same in our 6 models. After allowing for heteroskedasticity and autocorrelation, the income effect on CO_2 emission for the high-income segments either stay almost the same or become relatively flat and smooth. But this does not overthrow the general conclusion we propose in the beginning of this paper.

<Table 5>

4. Conclusions

Issues concerning what measures should be adopted to achieve a sustainable world with less CO_2 emission and in what magnitudes should we reduce our emission have been on agenda in both international negotiations and countries' policy making aimed at coping with potential global climate change. These issues cannot be easily addressed unless comprehensive understanding about the countries' status quo as well as historical relationship between economic development and CO_2 emission are gained. In addressing what is the relationship between economic development and CO_2 emission, earlier studies gave differed answers (see review by Stern (2004) and Carson (2010)), and some major drawbacks make the answers doubtful. In this paper, employing the CO_2 emission and economic development panel data sets of 132 countries in the time period 1971-2009 and a flexible econometric model, we investigated the historical relationship of economic development and CO_2 emission as well as its robustness from three aspects: data sources, model specifications and estimation methods. And several conclusions and some implications can be derived from our empirical resulting.

At first, for the emission–income relationship, we find a flattening trend in high income segments, which starts from per capita income of about 22000 dollars (PPP, 2005 constant price), after per capita CO_2 emission monotonously increases with the increase of per capita income. Economic development will continue to drive CO_2 emission though the marginal increment, according to the elasticity curve we capture, becomes smaller along the income range. In fact, according to the PWT per capita GDP data, currently most of the world's countries are located at the increasing part of the income elasticity curve, e.g. the "BRIC", Mexico, etc.; and located in the flattening segments are richer countries like UK, USA, Australia, etc. Secondly, different data sources, as well as different model specifications and different estimation methods, does not change the results substantially, only that when estimated by different methods (OLS and FGLS), and allowing for heteroskedasticity and autocorrelation, the resulted income effect becomes more flat in the high-income segments. And again, our results do not support the inverted-U shape relationship between CO_2 emission and economic development; we would rather describe the trend in the high income segments as a trend of saturation (see Fig. 6).

<Fig. 6>

In the process of robustness check, we examined the influences of some other relevant factors on per capita CO_2 emission. First, countries with higher level of urbanization and denser population tend to emit more carbon dioxide. Second, on average, countries raise their per capita emissions through trade or export, but the high-income countries do the opposite. Finally, countries with more economic freedom emit less CO_2 in a per capita sense. Factors such as urbanization, population density, trade (export), energy mix and economic environment influence the absolute level of per capita CO_2 emission, but not the income elasticity structure.

Implications of these results are that for countries to achieve both economic development and relatively dully lower per capita CO_2 emission, the effects of these factors in reduction must offset the income effect. And in the future, massive CO_2 will be emitted by the current developing countries until they achieve considerably high per capita income if they all follow similar growth modes with the developed world. That, if transitions of development modes or economical green technologies are not to be available, is not encouraging for future emission reduction. This is because each country will consider their development scenarios in both international negotiations and domestic emission reduction policy making, and in addition inertia in all aspects of the countries will contribute to considerably large amount of CO_2 emission (see the example for energy infrastructure by Davis *et al*. (2010)). Therefore from a historical view, and considering the financial and technological advantages in developed countries, these countries' political influence in the world and expected leadership in CO_2 emission reduction actions from the developing countries (Pan, 2009), reduction in terms of absolute level of CO_2 emission in the current developed countries make sense and is more consistent with the historical pattern of economic development; the poorer countries still need considerable emission volumes to survive from their economic backwardness.

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Figures

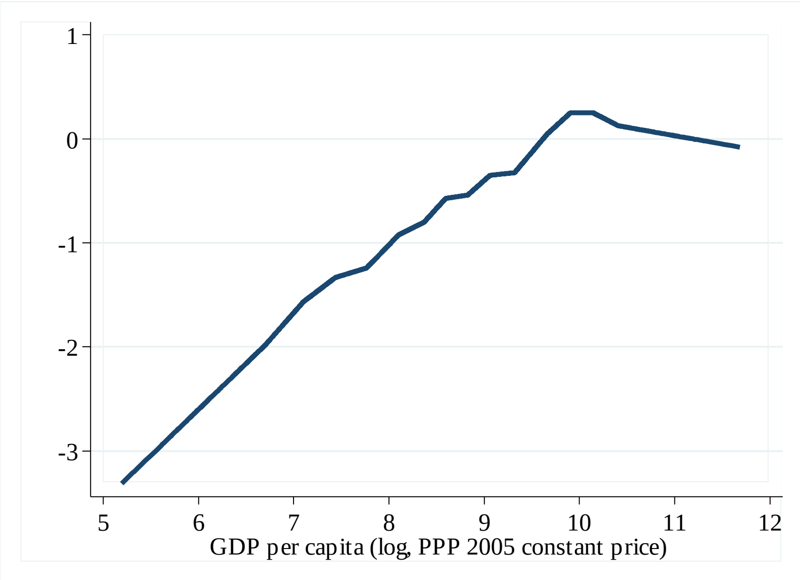

Fig. 1. Estimated structure of income effect on CO_2 emission. *Note:* Values on the vertical axis, namely CO_2 emission per capita, are computed using income effect in our model specification, in which country and time fixed effects are also included.

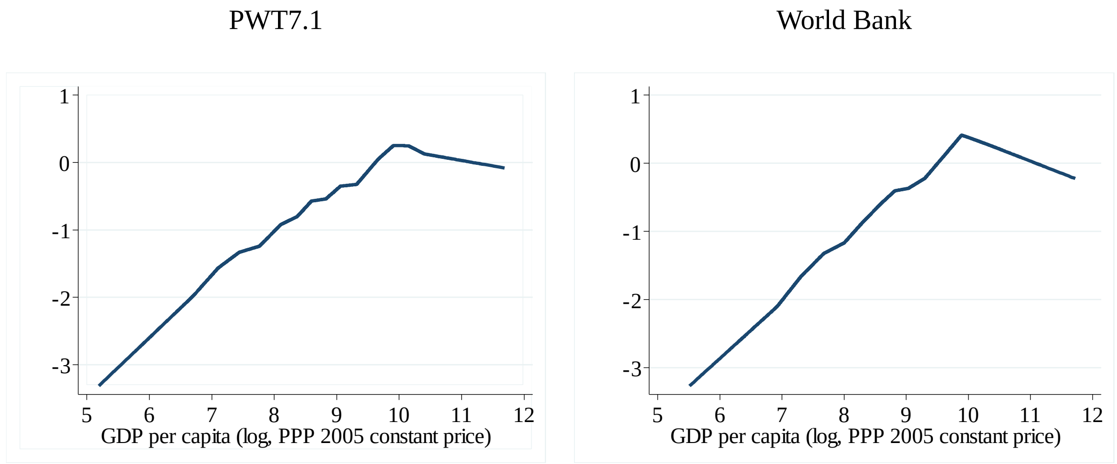

Fig. 2. Estimate result under different GDP data. *Note:* This Figure compares the structure of income effect estimated from two GDP data sources. Though the result under World Bank GDP data shows a sharper downward trend in the upper income levels, main conclusions of this paper stay the same. Values on the vertical axis are computed using income effect.

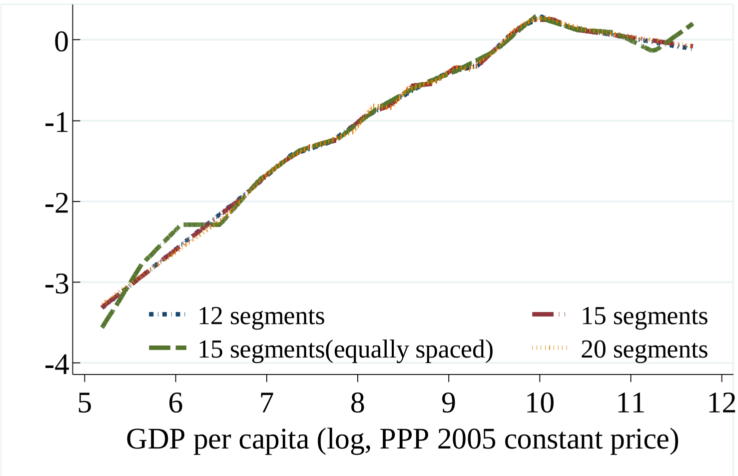

Fig.3. Estimate results under different segmentation. *Note:* The graph shows the results of income effect under different segmentation of income range, of which the 12-, 15-, 20-segment models are segmented by percentile and the 15-segment (equally spaced) model are under segmentation dividing the income range equally into 15 intervals. Values on the vertical axis are computed using income effect.

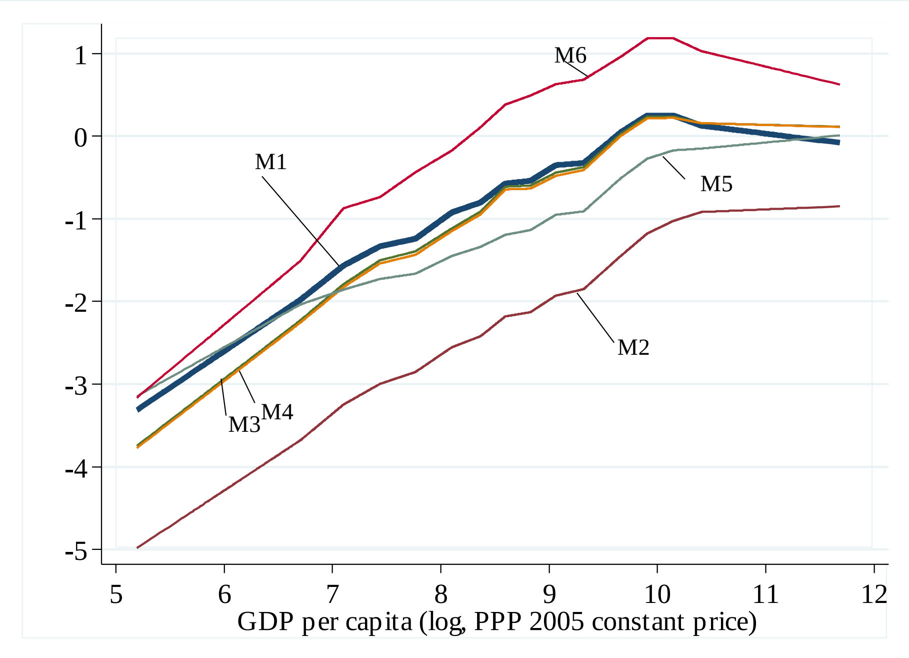

Fig. 4. Income effect plots of the 6 models under OLS. *Note:* In this graph, estimated income effects from the 6 models are plotted. We first obtained the coefficients of each income segment and other included covariates under the 6 model settings described in Table 2, and only the income effects are used to compute the values on the vertical axis.

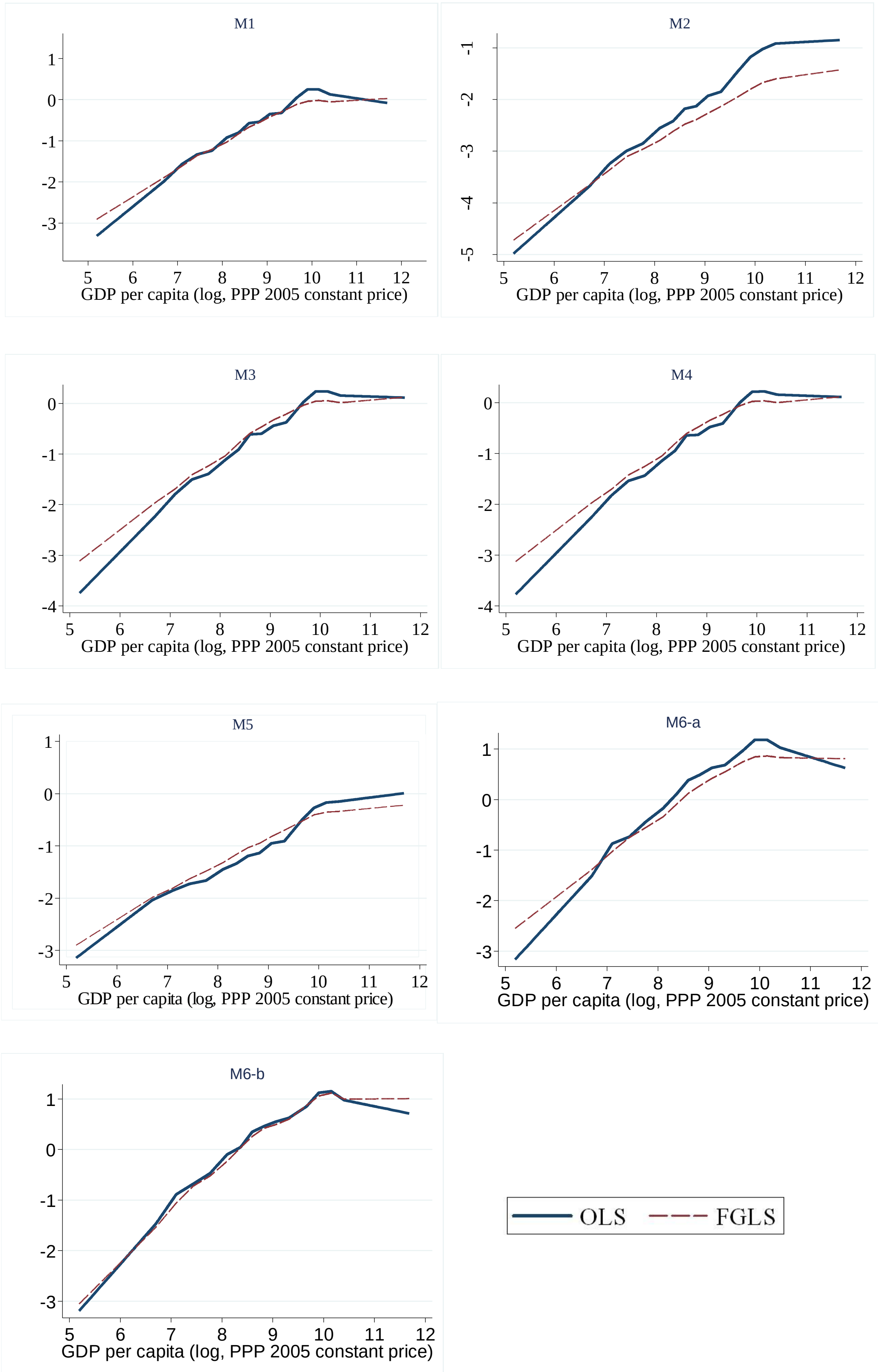
M1
1
0
-1
-2
-3
5 6 7 8 9 10 11 12
GDP per capita (log, PPP 2005 constant price)
M2
-1
-2
-3
-4
-5
5 6 7 8 9 10 11 12
GDP per capita (log, PPP 2005 constant price)
M3
0
-1
-2
-3
-4
5 6 7 8 9 10 11 12
GDP per capita (log, PPP 2005 constant price)
M4
0
-1
-2
-3
-4
5 6 7 8 9 10 11 12
GDP per capita (log, PPP 2005 constant price)
M5
1
0
-1
-2
-3
5 6 7 8 9 10 11 12
GDP per capita (log, PPP 2005 constant price)
M6-a
1
0
-1
-2
-3
5 6 7 8 9 10 11 12
GDP per capita (log, PPP 2005 constant price)
M6-b
1
0
-1
-2
-3
5 6 7 8 9 10 11 12
GDP per capita (log, PPP 2005 constant price)
OLS
FGLS

Fig. 5. Comparison between results under OLS and FGLS estimation. *Note:* Values on vertical axis are CO_2 emission per capita explained by income effect (computed using estimated income effects of the 6 models). Solid plot is from the results of OLS estimation, and dot plot from FGLS.

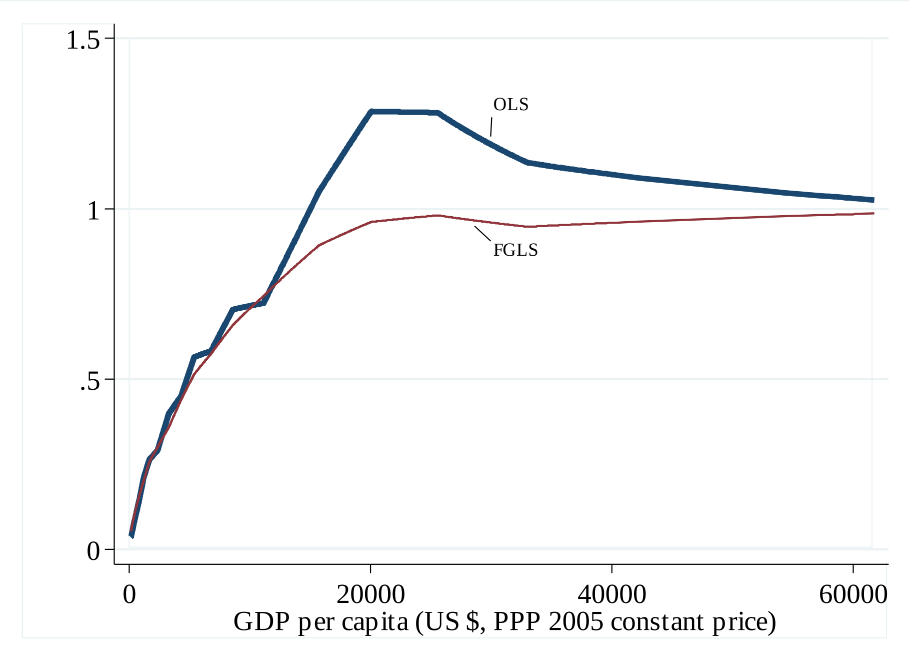

Fig. 6. Historical emission-income relationship under piece-wise linear spline model. *Note*: When calculating the values on the vertical axis, time and country fixed effects are removed.

Tables

Table 1. Variables and descriptive statics

Variable	Definition	Observations	Descriptive Statistics				Source
			Mean	Std. Dev.	Min	Max	
CO2pc	CO2 emission per capita, metric tons	5033	157.04	567.46	0.08	6831.60	IEA
GDPPC	GDP per capita (PPP, 2005 constant price dollars)	4622	11207.1	12824.6	179.8	118770.5	PWT7.1
urban	Rate of urbanization, people live in urban area, % of total population	5246	55.52	22.66	4.16	100	World Bank
popden	People per sq. km of land area	5185	196.34	683.12	0.85	7125.14	World Bank
trade	Dependence of trade, % of GDP	4344	75.89	50.01	0.18	445.91	World Bank
exp	Exports of goods and services, % of GDP	4344	36.72	26.75	0.11	234.35	World Bank
gove	Government size, government expenditure, % of GDP	4144	11.56	8.39	0.43	70.46	World Bank
energy mix	Energy mix measure by CO2 intensity of energy use, tons per ktoe	4757	1.97	0.90	0.051	4.09	World Bank
efi	Economic freedom index	1497	6.42	1.14	2.11	9.21	Fraser Institute

Note: GDP and CO_2 emission data contain observations from some regions, which are not single countries. And the definitions of variables are directly taken from the data providers, but in our operation process, *trade*, *exp* and *gove* are measured in ratios rather than percentages. Throughout this paper, all variables mentioned, both in the texts and graphs, use definitions and units of Table 1.

Table 2. Income elasticity of CO_2 emission in different income segments

Segments	**Per capita income interval**	**Elasticity**
1	<814	0.68
2	814~ 1213	0.69
3	1213~ 1699	0.75
4	1699~ 2358	0.45
5	2358~ 3301	0.54
6	3301~ 4307	0.76
7	4307~ 5409	0.69
8	5409~ 6813	0.46
9	6813~ 8617	0.54
10	8617~ 11149	0.45
11	11149~ 15741	0.48
12	15741~ 20074	0.27
13	20074~ 25579	0.045
14	25579~ 33033	-0.14
15	>=33033	0.066

Note: Segments are created by percentile so that each segment contains the same number of observations. Under FGLS estimate, the elasticity of the highest 3 income segments is not statistically significant.

Table 3. Differences between PWT7.1 and World Bank GDP per capita data for 2009

Country	**GDP per capita**			**Country**	**GDP per capita**			**Country**	**GDP per capita**		
	PWT7.1	World Bank	Difference (%)		PWT7.1	World Bank	Difference (%)		PWT7.1	World Bank	Difference (%)
Algeria	6181	7431	17	Macedonia	7546	9044	17	Panama	10321	11856	13
Argentina	11593	13272	13	Gabon	9487	13009	27	Paraguay	3615	4112	12
Australia	40820	34184	19	Georgia	4957	4319	15	China	7075	6206	14
Benin	1187	1422	17	Ghana	1955	1401	39	Peru	6892	7950	13
Bolivia	3662	4244	14	Guatemala	6016	4281	41	Qatar	118770	65894	80
Bosnia and Herzegovina	5885	7390	20	Haiti	1342	1063	26	Romania	9623	10797	11
Botswana	9280	11795	21	Iceland	37570	34044	10	Senegal	1444	1714	16
Brazil	7977	9468	16	India	3212	2813	14	Serbia	8398	9468	11
Cameroon	1746	2038	14	Iraq	4360	3264	34	South Africa	7306	9356	22
Chile	11832	13832	14	Jamaica	8716	7061	23	Sri Lanka	3860	4302	10
Colombia	7387	8268	11	Jordan	4344	5246	17	Sudan	2214	1986	11
Congo	2134	3592	41	Kazakhstan	11501	10318	11	Syria	3802	4687	19
Cote d'Ivoire	1273	1688	25	Kenya	1161	1441	19	Togo	722	885	18
Cyprus	18878	25790	27	Libya	19137	15361	25	Trinidad and Tobago	30495	23261	31
Dem. Congo	231	303	24	Malaysia	11151	12526	11	Tunisia	5988	8347	28
Dominica	9865	7887	25	Morocco	3535	4119	14	Turkey	9737	11655	16
Ecuador	5967	7051	15	Namibia	4671	5608	17	Turkmenistan	14473	6881	110
Egypt	4712	5365	12	New Zealand	27510	24649	12	Ukraine	6690	5763	16
Eritrea	578	494	17	Nigeria	1685	2030	17	United Arab Emirates	61139	45202	35
Ethiopia	641	866	26	Oman	21426	24226	121	Venezuela	9508	11315	16

Note: The year for demonstrating the differences between of GDP per capita data from PWT 7.1 and World Bank is 2009. Only countries for which difference between the two GDP data sets is greater than 10% are listed in this table. And they account for 42% of all the countries covered in this study.

Table 4. Model specifications for robustness check of income effect on CO2

Model	Covariates included
（1）	GDP per capita (log)
（2）	GDP per capita (log), urbanization rate, populations density (log)
（3） and （4）	GDP per capita (log), export (trade), interaction term of export (trade) and high income countries
(5)	GDP per capita (log), energy mix
（6）	GDP per capita (log), economic environment (government size, economic freedom index)

Note: All the models include country and time fixed effects, and the dependent variables are log per capita CO_2 emission.

Table 5. Empirical results of the 6 models under OLS and FGLS estimation[a, b]

	M1		**M2**		**M3**		**M4**		**M5**		**M6**[c]			
	OLS	**FGLS**	**OLS**	**FGLS**	**OLS**	**FGLS**	**OLS**	**FGLS**	**OLS**	**FGLS**	**M6-a**		**M6-b**	
											OLS	**FGLS**	**OLS**	**FGLS**
spn1	0.884***	0.679***	0.863***	0.709***	1.005***	0.763***	1.006***	0.765***	0.734***	0.607***	1.097***	1.020***	1.142***	1.021***
	(0.0608)	(0.0809)	(0.0571)	(0.0796)	(0.0580)	(0.0809)	(0.0583)	(0.0807)	(0.0519)	(0.0691)	(0.0579)	(0.0261)	(0.138)	(0.0458)
spn2	1.036***	0.690***	1.085***	0.724***	1.079***	0.680***	1.096***	0.685***	0.453***	0.438***	1.598***	1.567***	1.454***	1.362***
	(0.111)	(0.0958)	(0.103)	(0.0943)	(0.109)	(0.0917)	(0.109)	(0.0916)	(0.0955)	(0.0738)	(0.130)	(0.104)	(0.278)	(0.207)
spn3	0.692***	0.754***	0.743***	0.762***	0.850***	0.829***	0.858***	0.831***	0.384***	0.537***	0.401***	0.886***	0.621*	0.917***
	(0.106)	(0.0876)	(0.0989)	(0.0858)	(0.102)	(0.0856)	(0.103)	(0.0857)	(0.0907)	(0.0700)	(0.112)	(0.0825)	(0.255)	(0.154)
spn4	0.278*	0.454***	0.441***	0.447***	0.318**	0.523***	0.333**	0.530***	0.196*	0.448***	0.916***	0.791***	0.630*	0.643***
	(0.112)	(0.0724)	(0.104)	(0.0707)	(0.107)	(0.0718)	(0.108)	(0.0721)	(0.0950)	(0.0608)	(0.121)	(0.0727)	(0.289)	(0.155)
spn5	0.945***	0.537***	0.888***	0.504***	0.856***	0.599***	0.823***	0.593***	0.637***	0.486***	0.783***	0.866***	1.111***	0.940***
	(0.110)	(0.0636)	(0.103)	(0.0609)	(0.107)	(0.0628)	(0.108)	(0.0631)	(0.0942)	(0.0535)	(0.118)	(0.0693)	(0.277)	(0.142)
spn6	0.460**	0.755***	0.505***	0.663***	0.758***	0.928***	0.769***	0.930***	0.416***	0.596***	1.064***	1.377***	0.545	0.918***
	(0.147)	(0.0775)	(0.137)	(0.0711)	(0.147)	(0.0758)	(0.148)	(0.0758)	(0.125)	(0.0684)	(0.147)	(0.0889)	(0.357)	(0.202)
spn7	1.001***	0.690***	1.050***	0.596***	1.324***	0.866***	1.318***	0.868***	0.636***	0.554***	1.195***	0.965***	1.324***	1.063***
	(0.152)	(0.0673)	(0.142)	(0.0631)	(0.149)	(0.0677)	(0.150)	(0.0681)	(0.130)	(0.0570)	(0.146)	(0.0819)	(0.341)	(0.160)
spn8	0.121	0.460***	0.218	0.388***	0.0427	0.549***	0.0590	0.549***	0.248*	0.368***	0.473***	0.747***	0.484	0.666***
	(0.146)	(0.0659)	(0.137)	(0.0624)	(0.142)	(0.0669)	(0.143)	(0.0676)	(0.124)	(0.0547)	(0.139)	(0.0769)	(0.317)	(0.142)
spn9	0.809***	0.574***	0.854***	0.532***	0.660***	0.572***	0.664***	0.582***	0.787***	0.550***	0.585***	0.631***	0.389	0.391***
	(0.141)	(0.0620)	(0.132)	(0.0552)	(0.138)	(0.0632)	(0.139)	(0.0633)	(0.120)	(0.0537)	(0.138)	(0.0733)	(0.311)	(0.109)
spn10	0.0773	0.448***	0.306*	0.506***	0.269*	0.447***	0.260*	0.447***	0.164	0.470***	0.212	0.450***	0.286	0.393***
	(0.131)	(0.0577)	(0.123)	(0.0502)	(0.125)	(0.0571)	(0.126)	(0.0565)	(0.112)	(0.0484)	(0.125)	(0.0644)	(0.277)	(0.0952)
spn11	1.056***	0.481***	1.174***	0.555***	1.206***	0.500***	1.170***	0.509***	1.169***	0.493***	0.811***	0.831***	0.655**	0.739***
	(0.106)	(0.0595)	(0.0997)	(0.0522)	(0.101)	(0.0594)	(0.102)	(0.0586)	(0.0907)	(0.0516)	(0.0933)	(0.0488)	(0.221)	(0.0749)
spn12	0.817***	0.274***	1.107***	0.592***	0.863***	0.347***	0.858***	0.327***	0.963***	0.512***	0.904***	0.826***	1.120***	1.028***
	(0.134)	(0.0648)	(0.127)	(0.0634)	(0.125)	(0.0663)	(0.126)	(0.0648)	(0.114)	(0.0612)	(0.115)	(0.0556)	(0.281)	(0.108)
spn13	-0.0678	0.0446	0.628***	0.524***	0.0225	0.0323	-0.00413	0.0277	0.415***	0.202***	-0.00223	0.143**	0.122	0.188
	(0.134)	(0.0678)	(0.131)	(0.0677)	(0.127)	(0.0701)	(0.128)	(0.0683)	(0.114)	(0.0577)	(0.112)	(0.0504)	(0.282)	(0.102)

	M1		M2		M3		M4		M5		M6^{c}			
	OLS	FGLS	OLS	FGLS	OLS	FGLS	OLS	FGLS	OLS	FGLS	M6-a		M6-b	
											OLS	FGLS	OLS	FGLS
spn14	-0.460***	-0.139	0.417**	0.271***	-0.248*	-0.127	-0.317**	-0.143	0.0806	0.0636	-0.601***	-0.437***	-0.688**	-0.577***
	(0.127)	(0.0728)	(0.129)	(0.0698)	(0.122)	(0.0762)	(0.123)	(0.0748)	(0.109)	(0.0592)	(0.110)	(0.0491)	(0.254)	(0.101)
spn15	-0.162	0.0661	0.0532	0.137	-0.0367	0.0902	-0.0314	0.0849	0.124	0.0920	-0.315***	-0.230***	-0.206	-0.139
	(0.0831)	(0.0532)	(0.0951)	(0.0714)	(0.0832)	(0.0509)	(0.0870)	(0.0513)	(0.0711)	(0.0525)	(0.0875)	(0.0587)	(0.202)	(0.119)
urbanr			1.357***	1.801***										
			(0.118)	(0.134)										
lnpopden			0.741***	0.708***										
			(0.0396)	(0.0372)										
Trade					0.203***	0.0754***								
					(0.0289)	(0.0169)								
Trade×highincome					-0.416***	-0.110***								
					(0.0452)	(0.0250)								
Exp							0.297***	0.102***						
							(0.0557)	(0.0301)						
Exp×highincome							-0.576***	-0.128**						
							(0.0866)	(0.0442)						
Energy Mix									0.673***	0.438***				
									(0.0166)	(0.0097)				
Efi											-0.0349***	-0.0171***	-0.0297	-0.0127
											(0.0079)	(0.0044)	(0.0170)	(0.0074)
R^2	0.974		0.977		0.977		0.977		0.981		0.981		0.981	
Obs.	4515	4515	4454	4454	4208	4208	4208	4208	4515	4515	3453	3453	749	749

Note: Standard errors in parentheses* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. a. For our 6 models, the two columns corresponding to each model in this table are respectively the results from OLS and FGLS. b. *spn1*-*spn15* are the 15 income segments; *urbanr* and *lnpopden* are countries' urbanization rate and log population density respectively; *Exp (Trade)* is the measure of export (trade) dependence degree, and *Exp×highincome* is its interaction with high-income countries; *Energy Mix* is a measure of energy mix using the indicator *Energy Mix=CO2/Energy Use; Efi* means economic freedom index.

c. In model 6, the data for economic freedom index are modified in two approaches: obtain additional data by linear interpolation (Model-6a) and perform a panel data analysis on a 5-year basis (Mode-6b). We first included government size, but the coefficient of this variable is not statistically significant in either of the two models. So we do not display its estimated coefficient here. And considering the feature of *EFI* data, when doing FGLS, we only allow heteroskedasticity in Model-6a and Model-6b.