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LETTER

The long-term relationship between emissions and economic growth for SO_2, CO_2, and BC

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Abstract

Simplified assumptions regarding the relationship between per capita income and emissions are oftentimes utilized to generate future emission scenarios in integrated assessment models (IAMs). One such relationship is an environmental Kuznets curve (EKC), where emissions first increase, then decline with income growth. However, current knowledge about this relationship lacks the specificity needed for each sector and pollutant pairing, which is important for future emission scenarios. To fill this knowledge gap, we analyze the historical relationship between per capita income and emissions of SO_2, CO_2, and black carbon (BC) utilizing widely-used global, country-level emission inventories for the following four sectors: power, industry, residential, and transportation. Based on a modeling setup using long-term growth rates, emissions of SO_2 from the power and industrial sectors, as well as CO_2 from the industrial and the residential sectors, largely follow an EKC pattern. Income-emission trajectories for SO_2 and CO_2 from other sectors, and those for BC from all sectors, do not show an EKC, however. Results across different global inventories were variable, indicating that uncertainties within historical emission trajectories persist. Nonetheless, these results demonstrate that long-term income-emission trajectories of air pollutants are both sector and pollutant specific. Future reference trajectories of SO_2 and BC from three IAMs show earlier estimates of turnover incomes and faster rates of emission declines when compared to historical data. Users of future emission scenarios derived using EKC assumptions should consider the underlying uncertainties in such projections in light of this historical analysis.

Introduction

Society faces steep challenges regarding climate change and atmospheric pollution with several pollutants contributing to both issues. Sulfur dioxide (SO_2) is an air pollutant that oxidizes in the atmosphere to form climate-influencing aerosols; CO_2 is a greenhouse gas and has contributed most to modern climate change; and black carbon (BC) is an aerosol with global impacts on climate and human health. While a large portion of the atmospheric release of these pollutants is related to fuel combustion, there is wide variability in the sectoral processes that drive the emissions of each pollutant. For example, CO_2 emissions are closely related to the energy content of fuels, SO_2 is dependent on the sulfur content of fuels, and BC is mainly generated through incomplete combustion processes. Given the different sources, processes, and economic drivers at work, each pollutant develops distinct emission trajectories. Understanding the long-term income-emission relationship is one useful way to study the trend of emissions associated with social and economic development (Heil and Selden 2001, Aldy 2006, Chakravartya *et al* 2009, Nordhaus 2010, Stern and van Dijk 2017).

The spatial scale of emission impacts traditionally determines the incentives and barriers to emission reductions. Local pollutants, such as SO_2, carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM) are conventionally thought to have more environmental Kuznets curve (EKC)-like patterns, where emissions first increase then decline with income growth (Holtz-Eakin and Selden 1995). Indeed, economists have used EKCs to empirically study SO_2, CO, NO_x, and PM trajectories since the early 1990s (Grossman and Krueger 1991, Selden and Song 1994). SO_2 is the most well studied, with a common view that an EKC pattern exists at the country and state or provincial level in many parts of the world (Carson 2009). However, a consensus has not been reached on the turnover income level for peak emissions, with estimations ranging from \$3000 to \$20 000 USD (Selden and Song 1994, Stern *et al* 1996, Roca *et al* 2001, Stern and Common 2001, Millimet *et al* 2003, Stern 2004, Perkins and Neumayer 2008). Studies have started to consider the income-emission relationship of CO_2, but conclusions on the existence of an EKC pattern are divided (Lantz and Feng 2006). No studies to date have analyzed whether historical BC trajectories feature EKC patterns, even though it is an important factor in public health and climate scenarios. Despite differences in pollutant-by-pollutant trajectories, two findings are common. First, the rate of emissions are largely driven by income and energy consumption, but can be reduced by technological and structural changes. Second, low-income countries often have higher rates of growth in emissions than middle- and high-income countries.

With the prevalence of future scenarios that integrate socioeconomic developments and emission trajectories (e.g. the shared socioeconomic pathways (SSPs) (O'Neill *et al* 2014, Riahi *et al* 2017) increasing, there is a need for a comprehensive examination of the sector-specific long-term income-emission relationships (i.e. EKC patterns) for different pollutants. Without an empirically determined existence of such relationships, the reliability of widespread EKC-like patterns in future long-term emission trajectories may be undermined. This paper analyzes the relationship between per capita income and emissions of SO_2, CO_2, and BC for the power, industry, residential, and transportation sectors. This is in contrast to most previous studies, which exclusively focus on economy-wide results, and allows us to systematically examine how sectoral emissions have evolved with socioeconomic trends.

Methodology

Emission inventories

The main analysis in our study utilizes the global emission inventory developed at Peking University (hereafter referred to as PKU). The PKU dataset includes the three pollutants examined here (Su *et al* 2011, Wang *et al* 2012, 2013, 2014) and has been applied in a number of studies that estimate human exposure to air pollution (e.g. van der Werf *et al* 2010, Liu *et al* 2015, Tao *et al* 2018). The PKU inventory spans 1960–2014. It is composed of 64 individual emission sources, with all sources except for 8 representing biomass burning and international shipping included here. In total, our analysis includes sectoral emissions of SO_2, CO_2, and BC from 199 countries (see table S1 is available online at stacks.iop.org/ERL/13/124021/mmedia). The few, small countries not included lack the information to calculate source-specific emissions. The analysis spans 1980–2014, which was selected for two reasons. First, it is an era of dramatic changes in global emissions of atmospheric pollutants. Second, it features significant temporal overlap with many other studies exploring the relationship between economic growth and emissions (e.g. Stern and van Dijk 2017, Stern *et al* 2017). We aggregate all 56 applicable sources into four sectors: power, industry, residential, and transportation (see table S2). It should be noted that end-use emissions, rather than life-cycle emissions, are used in sectoral classification, following common practice.

In addition, three other widely used global emission inventories are analyzed to test the robustness of historical income-emission trajectories and avoid potential bias due to inventory-dependent assumptions. These inventories include the Emission Database for Global Atmospheric Research (EDGAR; Crippa *et al* 2018), the evaluating the climate and air quality impacts of short-lived pollutants (ECLIPSE) dataset (Stohl *et al* 2015, Klimont *et al* 2017), and the community emissions data system (CEDS) dataset (Hoesly *et al* 2018). Due to data limitations, only the PKU and CEDS datasets are used for analyses of CO_2. In addition, data limitations required use of slightly different time ranges for each of the inventories (1980–2014 in CEDS and PKU, 1990–2010 in ECLIPSE, and 1980–2010 in EDGAR). As long-term trajectories and their growth rates were used in this analysis, the influence of these differences should be quite limited.

Econometric modeling using long-term growth rates

We adopt a recently developed methodology using long-term growth rates to model the income-emission relationship (Stern *et al* 2017). This method reconciles several previous concerns in the EKC literature by integrating the three major approaches, the beta convergence model (Criado *et al* 2011), the IPAT-type green Solow model (Brock and Taylor 2010), and the basic EKC model, into one general modeling framework. We apply this general model in our study on a sectoral and pollutant-by-pollutant basis. The model is summarized by the following equation:

$$\widehat{E_i} = \alpha_0 + \alpha_1 \widehat{G_i} + \beta_1 \widehat{G_i} G_{i0} + \beta_2 E_{i0} + \beta_3 G_{i0} + \sum_j^k \beta_i X_{ji} + \varepsilon_i,$$

where $\widehat{E_i}$ is the natural log of the long-term growth rate of emissions per capita for country i (i.e. the linear change over a specified period, $\widehat{E_i} = (E_{iT} - E_{i0})/T$, where T is the number of years in the studied time range), E_{i0} is the natural log of emission per capita in the initial year. The same notation applies to $\widehat{G_i}$, which is the natural log of the long-term growth rate of GDP per capita for country i. α_0 is an estimate of the mean $\widehat{E_i}$ for countries with no economic growth and all dummy control variables held at the default values and all continuous variables at the mean levels. α_1 is an estimate of the emission-income elasticity. β_1 is the coefficient for the 'EKC interaction term', which is significantly less than zero when the trajectory is said to have a 'turning point.' This 'turning point' can be calculated as $\exp\left(-\frac{\alpha_1}{\beta_1} + \mu_G\right)$, where μ_G is the mean of the initial natural log of GDP per capita across all countries. β_2 and β_3 are the coefficients of the initial levels of income and emissions per capita. These terms are included to test convergence-type theories. X_{ji} is a vector of j control variables for each country i. These control variables are included to capture unobserved effects at individual country levels. Additional details regarding this model can be found in Stern *et al* (2017). We report results on the coefficients of the non-control variables (i.e. α_0, α_1, β_1, β_2, β_3) in tables within the text and coefficients of control-variables in the SI. As a guide to the reader: α_1 describes the linear relationship between emissions and income (when an EKC is not found); a negative β_1 indicates the existence of an EKC pattern; a negative β_2 indicates emissions convergence across countries; and a negative β_3 indicates emissions intensity convergence across countries.

GDP and population data are retrieved from the Penn world table version 9.0 (Feenstra *et al* 2015), which provides a time series of country-level GDP values adjusted for purchasing power parity. Our set of control variables follow the setup described in Stern *et al* (2017). They include: (1) a binary variable indicating if a country has a centrally planned economy; (2) a binary variable for English (default) and non-English (German, French, and Scandinavian, individually) legal origins (La Porta *et al* 2008); (3) average summer and winter temperatures by country, adjusted by hemisphere (Mitchell *et al* 2002); (4) fossil-fuel endowments based on Norman (2009); and (5) average population density for 1980–2014 from the World Bank. Regression results for control variables are reported in the SI (table S3). Continuous variables are standardized by subtracting the sample mean and countries with incomplete data are omitted.

Linking to integrated assessment model (IAM) projections

We compare the historical income-emission trajectories derived from the PKU inventory with future trajectories from several IAMs to assess similarities and differences in the evolution of emissions. IAMs are widely used tools that make long-term projections of emissions, with inputs including, but not limited to, projections of economic development and population change. Our analysis includes output from the Global Change Assessment Model (GCAM), Asia-Pacific Integrated Model (AIM) (Nejat *et al*), and Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE). These IAMs were used to develop several of the Representative Concentration Pathways (RCPs) and the SSPs. The three scenarios considered here were a baseline scenario from GCAM with a radiative forcing of ~6.5 W m^{-2}, RCP 6.0 from AIM, and RCP 8.5 from MESSAGE. All three of these scenarios assume fairly weak, if any, application of climate policy during the century. The projections from these IAMs include 2000 through 2100. Thus, the comparisons of the income-emission relationships from the PKU inventory and the IAMs are not direct, but the historical empirical trajectories can provide insight into the future projections. In addition, data from the IAMs do not include every country, but are classified into several regions: 33 in GCAM and 24 in AIM/MESSAGE. Both the AIM and MESSAGE projections were obtained from the International Institute for Applied Systems Analysis's RCP database. GDP per capita data were obtained from the GEA Public Scenario Pathway Database and AIM's website. Emissions and GDP per capita data for GCAM were obtained from the output of a baseline simulation.

Results

Trajectories in the power and industry sectors

SO_2 emissions exhibit a long-term EKC pattern in both the power and industry sectors (see β_1 in tables 1–2), with turnover incomes of \$19 000 and \$50 000 USD, respectively. However, it should be noted that the turnover in the industry sector exhibits large uncertainty and is less significant. For CO_2, visualization of the emission trajectories suggests that a slowing-down of CO_2 emission growth rates among wealthier countries is occurring in both sectors (figure 1(a)), but the model finds no evidence of a significant turnover (tables 1–2). While the model reports a turnover for CO_2 in the industrial sector, the turnover income is very high (\$190 000 USD per capita) and is not significant. There is significant beta-convergence ($\boldsymbol{\beta}_2$ in table 2) in the industrial sector, however, implying that less wealthy countries tend to have faster growth rates in emissions and high-income countries tend to have lower growth rates. The model reports no EKC pattern

Table 1. Model results for the power sector.

Variable	Sulfur dioxide	Carbon dioxide	Black carbon
α_0	−0.015	−0.035***	−0.071***
Constant	(0.013)	(0.010)	(0.021)
α_1	0.65***	0.54***	0.44***
Coefficient of income growth rate $\widehat{G_i}$	(0.19)	(0.11)	(0.15)
β_1	−0.33***	−0.065	−0.087
Coefficient of product of income growth rate and initial income $\widehat{G_i}G_{i0}$	(0.10)	(0.059)	(0.076)
β_2	0.0013**	−0.0015	−0.0047**
Coefficient of initial emissions E_{i0}	(0.0006)	(0.0012)	(0.0019)
β_3	0.0093**	0.0063**	0.0047
Coefficient of initial income G_{i0}	(0.0045)	(0.0028)	(0.0038)
EKC income per capita turning point	19	NA	NA
(1000s of US dollars)	(15)		
Sample size	89	102	107
R-squared	0.33	0.30	0.29

Note. Values in parentheses are standard errors for each coefficient from the regressions and the EKC turning points. Standard error of EKC income per capita turning point are calculated using a delta method. Significance levels of the regression coefficients are indicated as: *10%, **5%, ***1%. In the regressions, the sample mean has been subtracted from each non-dummy variable. EKC turning point is reported as an income per capita value, in 1000s of US dollars.

Table 2. Model results for the industry sector.

Variable	Sulfur dioxide	Carbon dioxide	Black carbon
α_0	−0.029***	−0.084***	−0.052***
	(0.007)	(0.017)	(0.019)
α_1	0.50***	0.55***	0.46***
	(0.14)	(0.12)	(0.13)
$\beta\beta_1$	−0.17**	−0.13**	−0.070
	(0.07)	(0.06)	(0.069)
β_2	0.0017**	−0.0084***	−0.0038**
	(0.0007)	(0.0021)	(0.0017)
β_3	−0.0045	0.012***	−0.0013
	(0.0034)	(0.004)	(0.0038)
EKC turning point	50	190	NA
	(70)	(410)	
Sample size	80	111	113
R-squared	0.52	0.46	0.48

Note. As in table 1.

for BC in either sector. However, the model again suggests beta-convergence, and also shows a linear increase that is correlated with economic growth in both sectors (see β_2 and α_1 values in tables 1–2).

For these two sectors, historical trajectories vary among the global datasets, indicating that the results are inventory dependent. In the power sector, only the PKU inventory reports an EKC turnover for SO_2, no inventory reports an EKC turnover for CO_2, and only EDGAR reports an EKC turnover for BC (tables S4–S5). The industry sector features more consistency, with the PKU inventory and CEDS reporting an EKC turnover for SO_2, PKU reporting an EKC turnover for CO_2, and only EDGAR reporting an EKC turnover for BC (tables S4–S5). It should be noted that the level of significance for each of these turnovers varies among the inventories, with some results featuring unrealistically high turnover values (e.g. PKU CO_2 emissions in the industry sector). However, there was high consistency among the inventories regarding the existence of beta-convergence (see β_2 in tables S4–S5). Therefore, the magnitude of future emissions will depend greatly on the patterns of emissions growth in less wealthy, developing countries.

Various factors are driving the trends for each sector and pollutant combination. In the power sector, SO_2 trajectories are driven by increasingly strict end-of-pipe regulations originating in high-income countries (Srivastava *et al* 2001, Taylor *et al* 2003, Crippa *et al* 2016, Kharol *et al* 2017). In contrast, the industrial sector SO_2 EKC trajectory is likely driven by the shift to cleaner and more service-based economies, which normally transfers heavily polluting factories to less developed countries (Davis *et al* 2011, Peters *et al* 2011, Bagayev and Lochard, 2017, Zhao *et al* 2017). For CO_2, some countries in the high-income end are rich in resources that produce minimal CO_2 emissions, such as hydropower or nuclear power plants (BP 2018). These include Switzerland, Norway, Iceland, and France (the lower HOECD points in figure 1(a) for CO_2). The shift to a serviced-based economy in developed countries and the globalization of manufacturing could have also contributed to the observed turnover and convergence (Davis and Caldeira 2010, Su *et al* 2010, Feng *et al* 2013). In power plants, BC emissions are small but those that do exist are mainly a product of incomplete combustion and, as discussed previously, generally feature a linear relationship with economic growth. As such, the higher BC emission levels among middle-and-high-income-countries are likely due to their higher per capita demand for electricity.

Trajectories in the residential sector

The income-emission trajectories in the residential sector show different results for each pollutant (figure 2). The relationship is unclear for SO_2

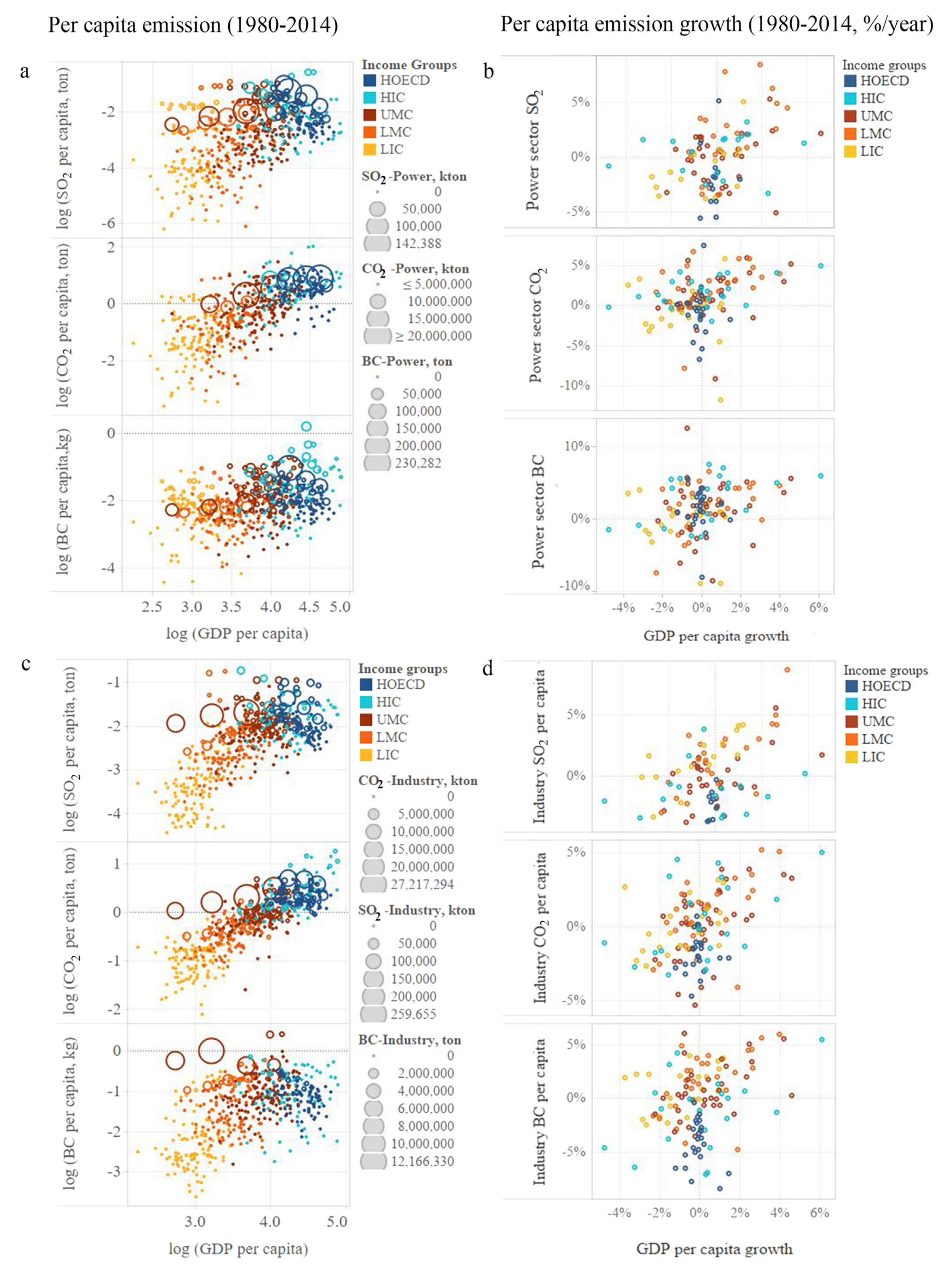

Figure 1. (a) Power sector income-emission trajectories of SO_2, CO_2, and BC. (b) Power sector relationship between long-term growth rates of per capita emissions and income for each country. (c) Industry sector income-emission trajectories of SO_2, CO_2, and BC. (d) Industry sector relationships between long-term growth rates of per capita emissions and income for each country. In (a) and (c), each country shows averages of each of the four periods: 1980–1989, 1990–1999, 2000–2009, and 2010–2014 (i.e. four observations for each country). Colors indicate the five income groups: HOECD: high-income OECD countries; HIC: high-income non-OECD countries; UMC: upper middle-income countries; LMC: lower-middle income countries; LIC: low-income countries. Size of circles represent the relative size of average total emissions (not on per capita basis) over each specific period for the specific country.

emissions. CO_2 emissions feature an EKC turnover (β_1 in table 3) and there is an emission convergence pattern for BC (β_2 in table 3). However, the turnover income for CO_2 (\$1900) is far below a majority of the income levels globally and is likely driven by strong beta-convergence. Two other emission inventories did feature EKC patterns for SO_2 in the residential sector (EDGAR and CEDS; see table S5) and CEDS did not

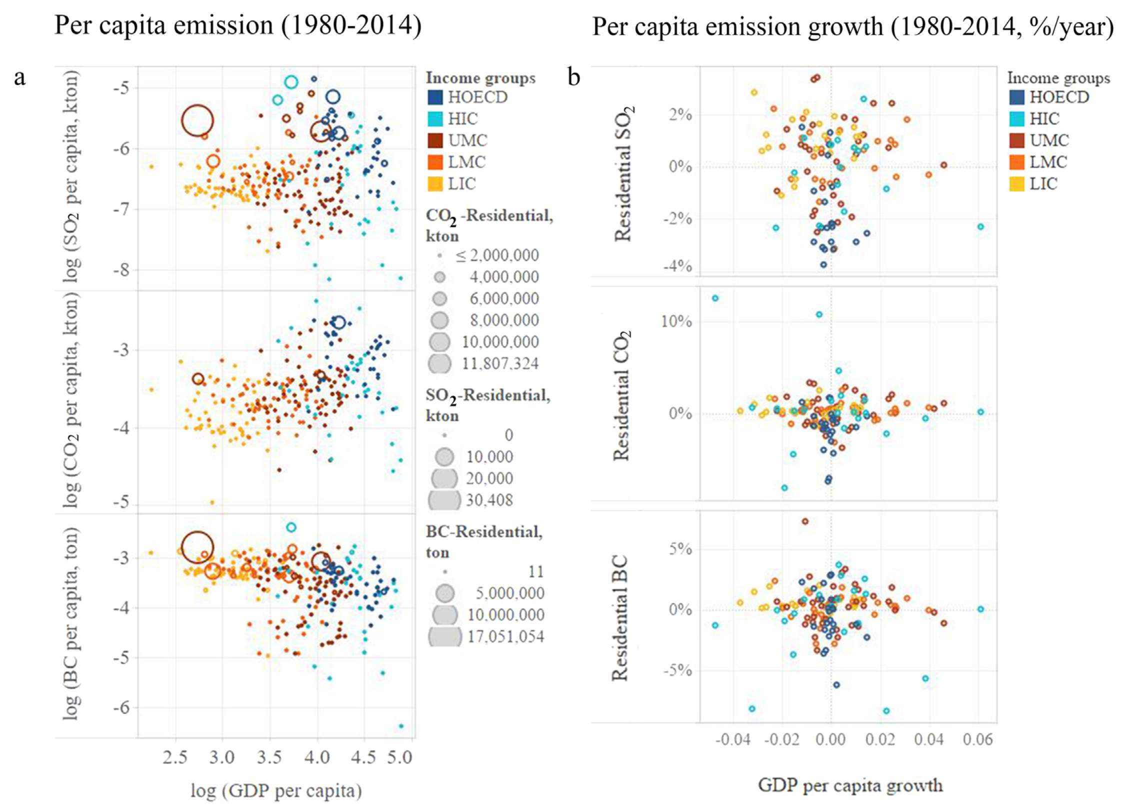

Figure 2. (a) Residential sector income-emission trajectories of SO_2, CO_2, and BC. (b) Residential sector relationships between long-term growth rates of per capita emissions and income for each country.

Table 3. Model results for the residential sector.

Variable	Sulfur dioxide	Carbon dioxide	Black carbon
α_0	−0.0043	−0.018	−0.021*
	(0.0098)	(0.011)	(0.011)
α_1	−0.083	−0.028	−0.059
	(0.14)	(0.058)	(0.059)
β_1	0.022	−0.093***	0.0014
	(0.090)	(0.031)	(0.030)
β_2	−0.00018	−0.0026**	−0.0031**
	(0.00040)	(0.0013)	(0.0013)
β_3	−0.0056	0.0032*	−0.0032**
	(0.0044)	(0.0016)	(0.0015)
EKC turning point	NA	1.9	NA
		(1.1)	
Sample size	100	101	99
R-squared	0.28	0.29	0.23

Note. As in table 1.

feature an EKC turnover for CO_2 (see table S4). This indicates that the trajectory of these emissions in the residential sector is uncertain. In contrast, all inventories did not feature an EKC turnover for BC.

Several factors contribute to these distinct trajectories. First, residential energy use has a lower income elasticity relative to other sectors (Joyeux and Ripple 2011, Fouquet 2014). In other words, residential emission intensities generally start high, and as economies grow, the relative increase in residential energy demand is mild, when compared to other sectors. Second, energy changes in the residential sector are primarily the result of primary fuel replacements, rather than end-of-pipe controls (Pachauri and Jiang 2008, Ruiz-Mercado *et al* 2011, Nejat *et al* 2015). As such, the improvement in efficiency and reduction of emissions is very sharp once cleaner fuels are adopted. Third, economies of scale impact residential emissions, where households with more members have lower emissions per capita (Ru *et al* 2015, Tao *et al* 2018). Lastly, household electrification has led to a re-categorization of an increasing fraction of residential emissions to the power sector. This electrification contributes to the EKC pattern shown for CO_2 emissions. All inventories show a negative relationship between per capita BC emissions and income. This is likely due to the widespread use of inefficient biofuel cook stoves in middle-and-low-income countries, with household cooking in upper income countries equipped with electricity or natural gas burners that produce minimal BC (BP 2018).

Trajectories in the transportation sector

All three pollutants show a combination of linear income effects and emissions convergence in the transportation sector, with no EKC patterns reported (table 4). BC emissions feature reductions among the highest income countries (figure 3(a)), but a turnover was not reported in the model. Results were consistent among the inventories considered here. All inventories

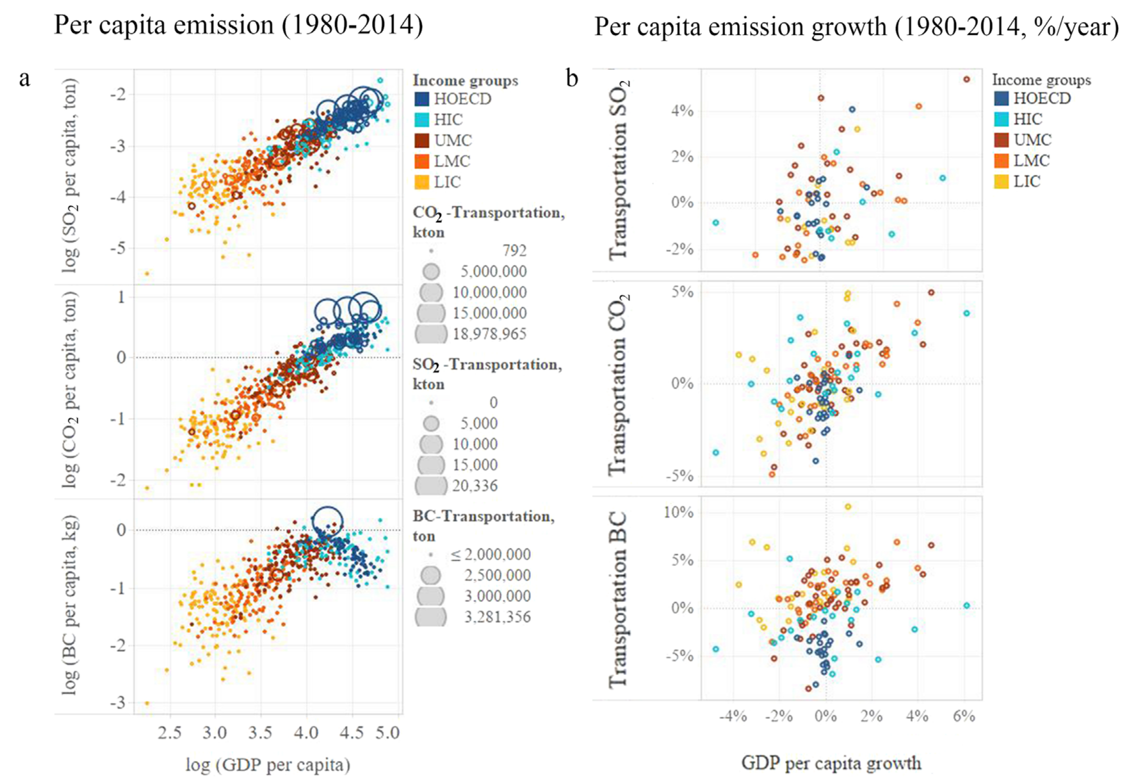

Figure 3. (a) Transportation sector income-emission trajectories of SO_2, CO_2, and BC. (b) Transportation sector relationships between long-term growth rates of per capita emissions and income for each country.

Table 4. Model results for the transportation sector.

Variable	Sulfur dioxide	Carbon dioxide	Black carbon
α_0	0.0079	-0.099^{***}	-0.12^{***}
	(0.0073)	(0.016)	(0.02)
α_1	0.74^{***}	0.60^{***}	0.27^{**}
	(0.14)	(0.09)	(0.11)
β_1	0.017 (0.090)	−0.017	−0.020
		(0.052)	(0.056)
β_2	-0.020^{***}	-0.0092^{***}	-0.013^{***}
	(0.002)	(0.0020)	(0.001)
β_3	0.019^{***}	0.011^{****}	0.0001
	(0.005)	(0.003)	(0.0032)
EKC turning point	NA	NA	NA
Sample size	63	110	116
R-squared	0.72	0.45	0.70

Note. As in table 1.

reported beta-convergence for all three pollutants and no EKC patterns for SO_2 or CO_2 (see tables S4–S5). Only the ECLIPSE inventory featured an EKC pattern for BC in the transportation sector.

The linear increases in emissions with income are due to a high correlation between fuel consumption and income in countries at all income levels. Downward drivers exist in many countries, such as sulfur content limits of fuels and regulations on fuel efficiencies. Yet these drivers are mild and outweighed by the global demand increase (Lakshmanan and Han 1997, Huo *et al* 2007, Lu *et al* 2009).

Technological methods of reducing CO_2 emissions from the transportation sector include electrification of vehicles and use of biofuels, both of which face challenges. Since the early 1960s, developed countries have reduced BC emissions through a variety of technologies and policies, despite continuously increasing diesel consumption (Ban-Weiss *et al* 2008, Kirchstetter *et al* 2008). Some developing countries have learned from these experiences to more quickly reduce emissions (Minjares *et al* 2014). In general, regulations to reduce BC emissions can be achieved via three basic methods: targeting of new vehicles, fuels, and the in-use fleet (Minjares *et al* 2014). Most developed economies utilize standards for new vehicle emissions and fuels (International Enegy Agency 2016), while many developing countries encourage the retrofitting and replacement of high-emission older vehicles (Zhou *et al* 2010, Kaygusuz 2012, Ong *et al* 2012).

Future trajectories projected by IAMs in the context of historical trajectories

Future emission projections retrieved from three IAM reference or minimal/no climate policy simulations show widespread declines in SO_2, CO_2, and BC emissions in all sectors. Historical values of emissions in the calibration years are consistent with historical emissions from the PKU inventory, but significant deviations occur thereafter, driven by the underlying assumptions in the IAMs. Among the more dramatic examples of these differences are the trajectories of

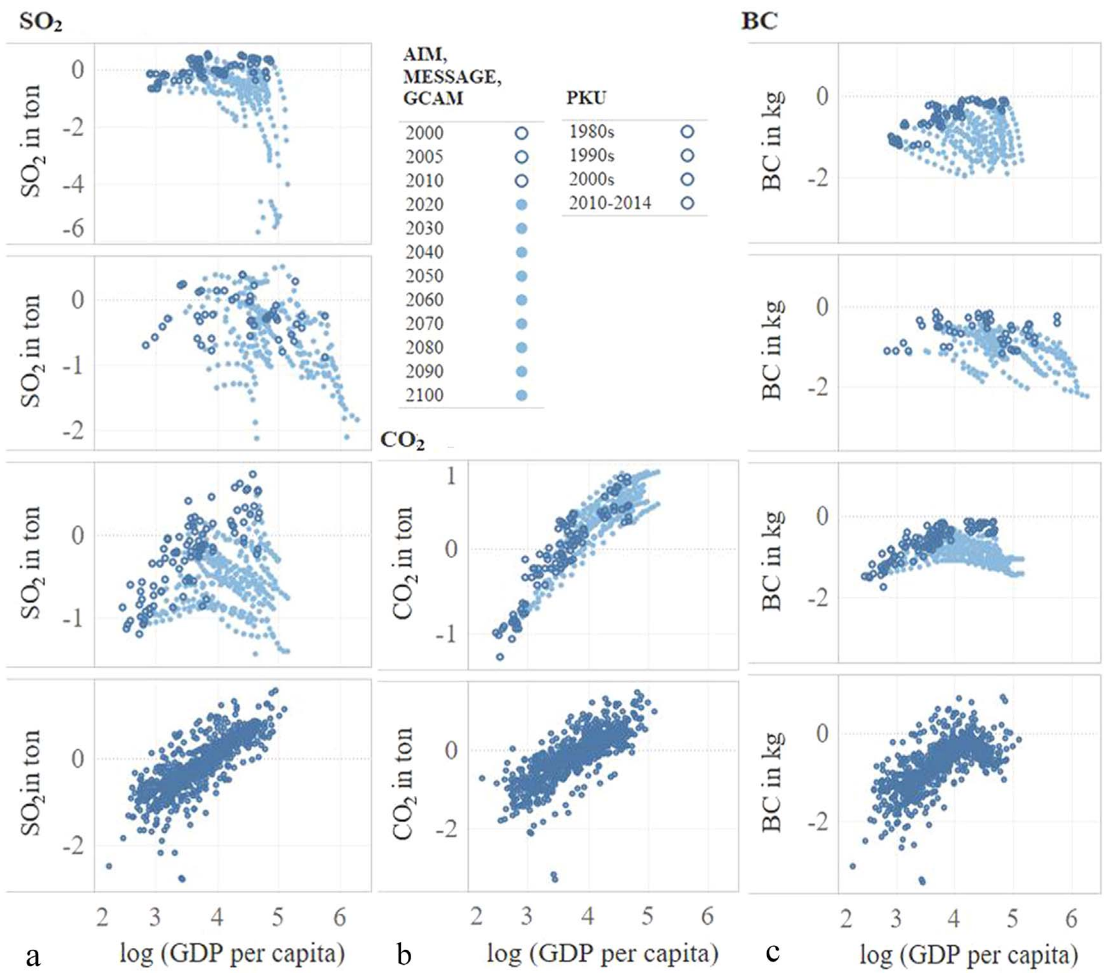

Figure 4. Comparisons of income-emission relationship in the transportation sector between historical emissions from the PKU inventory and future projections from AIM, MESSAGE, and GCAM for SO_2 (a), CO_2 ((b), only data from GCAM is available), and BC (c). Historical emissions from PKU are periodical average of 1980s, 1990s, 2000s, and 2020–2014, and projected emissions from the IAMs are decadal. Historical years are shown in dark blue circles, whereas future years are shown in light blue dots.

SO_2 and BC emissions from the transportation sector (figure 4). Both AIM and MESSAGE show weak increases in emissions with income growth in the historical period, followed-by sharp declines in the future. In comparison, the PKU historical values largely exhibit a slight flattening trend. If such sharp declines were to occur, a significant adoption of electric vehicles and/or extremely strict regulations on sulfur content in fuel and use of particulate filters would need to occur. For CO_2 emissions in the transportation sector, results from GCAM do not diverge significantly from the historical trajectories. The power, industry, and residential sectors show similar patterns. SO_2 and BC emissions decrease significantly in all three IAM projections through the end of the century, whereas CO_2 does not necessarily decline (e.g. in the industrial sector emissions projected by GCAM (figure S1). As noted, the scenarios considered here have modest (AIM; RCP 6.0) to non-existent climate policy (MESSAGE; RCP 8.5), and reductions are likely faster in scenarios that include substantial climate policy.

Conclusion

Empirically derived trajectories of long-term income-emission relationships have been extensively studied and, to date, generated ambiguous conclusions. One reason may be that most results are at economy-wide scales, lacking sectoral analyses. We analyzed the historical, sectoral income-emission trajectories of SO_2, CO_2, and BC using data from four widely used global emission inventory and a statistical model that assesses the relationship between long-term emissions and income rates of change. Our results show that income-emission trajectories for various sector and pollutant combinations differ substantially. SO_2 emissions in the power and industry sectors exhibit EKC patterns, with turnover incomes of \$19 000 and \$50 000 USD, respectively. CO_2 emissions featured an EKC pattern in the industrial and residential sectors. However, the turnover income calculated in the residential sector is far below a majority of the income levels globally and is likely driven by strong emissions-convergence. Emissions from the transportation sector show linear increases with income without any signs of turnover for SO_2 and CO_2. For BC, we find that emissions do not exhibit an EKC pattern in any sector. Rather, BC emissions from the residential sector, which contributes the most to economy-wide BC emissions, shows a negative relationship between per capita BC emissions and income.

Results were sensitive to the global inventory used, due to uncertainties in historical emissions. However, there was consistency for several sectoral and pollutant pairings. A majority of the inventories considered here did not report an EKC turnover for SO_2 in the power and transportation sectors, neither of the two inventories used to analyze CO_2 reported an EKC turnover for CO_2 in the power or transportation sectors, and a majority of the inventories considered here did not report an EKC turnover for BC in any sector. Rather, emissions-convergence, where less wealthy countries tend to have faster growth rates in emissions and high-income countries tend to have slower growth rates, was found in most sectoral and pollutant pairings.

We also compared the income-emission trajectories from the PKU historical emission inventory with projected trajectories from three IAMs. The comparison revealed several differences, especially in the transportation sector. IAMs tend to project a massive decline in emissions from the transportation sector paired with economic growth, whereas historical emissions suggest a more linear positive correlation between emissions and income. The trajectories presented by these widely used scenarios are thus optimistic when compared to historical patterns, even though they are largely baseline scenarios without explicit climate policy (i.e. they appear to assume that very successful air quality policies, or perhaps fuel switching, always accompany income increases).

The results presented here demonstrate that the historical income-emission relationships for many pollutants vary by sector over time and a broad EKC relationship is largely absent from historical data. It thus appears important to carefully consider the sector and pollutant-specific mechanisms at work when generating emission projections based on socioeconomic development.

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