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South-South Ideas

Reducing Carbon Emissions for the Economic Development of the Global South

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As we all know, climate change is a major issue challenging the whole world today. Most northern countries have already crossed the stage of economic development with high carbon dioxide emissions, whereas southern countries are facing the negative decoupling of economic growth and emissions. Therefore, this project is hopefully of great significance to worldwide researchers and policymakers as well as practitioners.

Authors have contributed to the report in well-organized teamwork and based on their individual capacities. The authors include Jianye Yan (Peking University), Huan Zhu (Peking University), Zhe Fu (University of International Business and Economics), Wanqing Zhang (Peking University), Wei Jin (Peking University), Jing He (University of International Business and Economics) and Mingyang Xu (Fudan University). Finally, we also would like to thank the Institute of New Structural Economics of Peking University for research facilities support and professional projects management.

Abbreviations and Acronyms

OECD	Organization for Economic Co-operation and Development
EKC	Environmental Kuznets Curve
BRICS	Brazil, Russia, India, China and South Africa
GDP	Gross domestic product
PPP	Purchasing Power Parity
TFP	Total Factor Productivity

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Executive summary

This paper explores the theme "Reducing Carbon Emissions for the Economic Development of the Global South." To do this, we start by describing the characteristic facts of total carbon dioxide emissions, carbon dioxide emissions intensity and per capita carbon dioxide emissions in the world, Organization for Economic Co-operation and Development (OECD) countries, non-OECD countries and the BRICS (Brazil, Russia, India, China and South Africa) countries. From there, we see that the current non-OECD countries, including the vast majority of southern countries, have become the main global carbon dioxide emitters, especially the BRICS countries, whose carbon dioxide emissions account for more than 40 percent of the world's carbon dioxide emissions. Therefore, we find it essential to study the carbon dioxide emission reduction issues of southern countries in the process of economic development. Second, based on the Environmental Kuznets Curve (EKC) hypothesis and "decoupling" theory, we use the data of 111 economies from 1980 to 2018 to employ regression models to test the EKC hypothesis. The empirical results recover a global EKC and show that when the per capita gross domestic product (GDP) of an economy exceeds US$30,619.735 the double dividend effect of economic growth and carbon dioxide emission reduction can be realized. Then, we select some representative countries based on the principles of population, GDP and per capita GDP to analyze the dynamics of the decoupling elastic coefficients of these representative countries to describe the trajectory of each country's economic development and carbon dioxide emissions. Finally, we develop a macroeconomic model with micro-foundation and emission decisions, calibrate the parameters in the model and apply the model to simulated projection for all representative countries, by which the moment of the EKC turning (inflection) point in southern countries is shown.

1 **The total amount of global CO_2 emissions is increasing, especially in developing countries.**

The global CO_2 emissions trend demonstrates that the total global CO_2 emissions increased from 13,945,200,000 tonnes to 32,839,900,000 tonnes during 1971–2017, representing an average annual growth rate of 1.89 percent. Taking OECD and non-OECD countries as an example, during 1971–2017, the percentage of CO_2 emissions in OECD countries in terms of the whole world declined from 67.00 percent to 35.25 percent, whereas that percentage in non-OECD countries in terms of the whole world increased from 33.00 percent to 64.75 percent, which indicates that non-OECD countries have become major CO_2 emissions countries.

2 **Global per capita CO_2 emissions show a fluctuating trend, especially in that global per capita CO_2 emissions increased significantly from 2000 to 2012, but there is a downward trend after 2012. On the whole, the per capita CO_2 emissions of developed countries are higher than those of developing countries and the gap between them is narrowing.**

Global per capita CO_2 emissions in 1971 was 3.71 tonnes/person and this increased to 3.79 tonnes/person in 2000 after nearly 30 years of development. From then on, the number continued increasing to 4.36 tonnes/person in 2017. The per capita CO_2 emissions in OECD countries fluctuated from 10.4 tonnes/person in 1971 to 8.94 tonnes/person in 2017, whereas the per capita CO_2 emission in non-OECD countries increased from 1.42 tonnes/person in 1971 to 3.21 tonnes/person in 2017.

3 **Global CO_2 emission intensity is declining, and, since 1981, the CO_2 emission intensity of developed countries has been lower than that of developing countries.**

From 1971–2017, global CO_2 emission intensity demonstrated a sharp downtrend by dropping from 0.58 tonnes/$1000 to 0.29 tonnes/$1000. The CO_2 emission intensity in OECD countries reduced from 0.61 tonnes/$1000 in 1971 to 0.23 tonnes/$1000 in 2017. In non-OECD countries, emission intensity reduced from 0.47 tonnes/$1000 in 1971 to 0.32 tonnes/$1000 in 2017.

4 **As the largest developing country in the world, China's total CO_2 emissions and per capita CO_2 emissions have increased significantly since 2000, but its CO_2 emission intensity has been decreasing.**

CO_2 emissions in China increased from 780,180,000 tonnes in 1971 to 9,257,930,000 tonnes in 2017, representing an average growth rate of 5.64 percent. The per capita CO_2 emissions in China rose from 0.93 tonnes/person to 6.68 tonnes/person, representing an average annual growth rate of 4.50 percent. From 1991–2017, the CO_2 emission intensity in China decreased from 1.91 tonnes/$1000 to 0.45 tonnes/$1000, representing an average annual growth rate of -3.01 percent.

5 **Based on the EKC model, this report describes the dynamic relationship between economic development and carbon dioxide emissions. It explains that carbon dioxide emissions show a nonlinear relationship that increases first and then decreases with different stages of economic development. The EKC inflection point and decoupling elasticity coefficient were empirically tested using the panel data of 111 economies from 1980 to 2018.**

Based on the EKC hypothesis, this report set the econometric model expressing the nonlinear relationship between economic growth and carbon emissions and using a fixed effects model to calculate the inflection point. We find that when the per capita GDP of an economy is less than $30,619.735, CO_2 emissions are positively correlated with per capital GDP, whereas when per capita GDP is greater than $ 30,619.735, CO_2 emissions are negatively correlated with per capita GDP.

6 **The impact of trade on a country's carbon dioxide emissions is important. Trade causes a net inflow of carbon dioxide emissions in BRICS countries, whereas trade causes a net outflow of carbon dioxide emissions in the United States.**

Because of the increasingly fragmented nature of production processes across countries, domestic CO_2 emissions are sometimes generated by the production of goods consumed in other countries. Such global interconnectedness carries the risk that uneven domestic policies on emissions regulations may lead to pollution havens, whereby countries with lax environmental regulations would specialize in producing pollution-intensive goods that are exported to other countries with more stringent environmental policies. Southern countries dominate the net inflow of CO_2 and northern countries dominate the net outflow of CO_2. Trade has led to a large amount of "carbon leakage." Using the database of the OECD, we find that CO_2 emissions embodied in the export trade of the BRICS countries are higher than those embodied in the import trade, which means that the BRICS countries became net CO_2 inflow countries through trade from 1995 to 2011. The carbon emissions embodied in the export trade of the United States, a representative of northern countries, are lower than those embodied in its import trade, which means that the United States becomes a net carbon dioxide outflow country through trade.

Thus, when advanced economies transfer manufacturing to southern countries, the development stage of these countries must be considered. Northern countries should provide environmental assistance to those recipient countries. In addition, from the perspective of trade fairness, the costs of environmental protection or governance need to be included and reflected in the trade price, e.g., some international intervention or mechanism aiming to correct environmental externality in the process of global manufacturing transferring. At the same time, the United Nations needs to play a supervisory and coordinating role and pay more attention, with guidance and support, to the dynamics of environment evolution of southern countries when they are recipients of manufacturing industries.

7 **Decoupling theory reveals the correlation between economic development and carbon dioxide emissions. The decoupling elasticity coefficient was also empirically tested using the panel data of 111 economies from 1980 to 2018.**

According to the three indicators of population, GDP and per capita GDP, 18 representative countries (Angola, Argentina, Australia, Bolivia, Brazil, China, Germany, India, Japan, Mongolia, Morocco, Nigeria, Seychelles, Singapore, Tunisia, Ukraine, United Kingdom and United States) were selected by region to analyze the decoupling state. According to the EKC inflection point and decoupling elasticity coefficient, economic development is divided into six statuses, which are sustainable absolute decoupling, mild coupling, pollutive coupling, recessionary coupling, pollutive recessionary coupling and pollutive decoupling. We see that sustainable absolute decoupling is most desirable, which means per capita GDP is increasing and CO_2 emissions are decreasing. We calculated the decoupling elasticity coefficient and five-year rolling window average decoupling elasticity coefficient for each year of each representative country.

8 **We have established a neoclassical growth model that considers emissions, has an optimized micro-foundation and uses it to simulate the CO_2 emissions of an economy. The forecast analysis shows that some countries have a CO_2 peak and some countries do not have a CO_2 peak. The actual CO_2 emission data of representative countries from 1970 to 2018 verifies the reliability of the model prediction results.**

It mainly includes the following points to establish the micro-optimization foundation based on the Green Solow model: 1) set up a profit maximization model of representative enterprises and consider the pollution emissions in the production process of enterprises; 2) set up a representative household model to maximize lifetime utility and optimize the selection of pollution emission reduction costs; and 3) establish a dynamic equilibrium model with an analytical condition system of those equilibria. For the first category of countries (China, Nigeria and Singapore), the carbon emission inflection point will be shown soon. For the second category of countries (Australia, Germany, Japan, Mongolia, Ukraine, the United Kingdom and the United States), the carbon emission inflection point has already shown and will further descend in the future. For the third category of countries (India, Angola, Argentina, Bolivia, Brazil, Morocco, South Africa and Tunisia), the carbon emission inflection point has not shown and is not expected to show in future.

9

Adjusting industrial structure and trade structure, strengthening environmental regulations and improving technological progress are all effective policies to achieve economic growth and carbon dioxide emission reduction in the future.

Either from empirical models or analysis of representative countries, we find that sometimes an overly high proportion of industrialization is not necessarily conducive to carbon emission reduction. From our previous numerical simulations of representative countries, we find that emission reduction technology is a very important parameter. The higher it is, the earlier the EKC inflection point is reached. So governments should increase investments in emission reduction technologies to promote technological progress.

Also, in the simulation and projection, to demonstrate and reveal the potential of technology transfer in the emission reduction process from international cooperation and instruction, we offer a scenario experiment by assuming that a country can obtain the more advanced emission reduction technology of the leading country in their region (i.e., the number one country in emission reduction technology progress). We show that the sharing of emission reduction technologies internationally can especially help those southern countries that initially face difficulty in obtaining a U-shaped EKC solely drawn from domestic parameters to become able to achieve an inflection point in EKC, i.e., to be able to realize the win-win result of economic growth and environmental sustainability at the same time. This indicates the importance of the international transfer of emission reduction technologies. International organizations should make full use of various means to promote countries with backward emission reduction technologies to obtain faster technological progress. Proactive international cooperation (e.g., that initiated by United Nations) on emission reduction technologies can help realize a win-win result of economic growth and environmental sustainability for the whole southern world.

1. Stylized facts: CO_2 emissions (aggregation, per capita and intensity)

Countries worldwide have launched carbon emission reduction programmes in view of their respective conditions to coordinate the development of their social economy and the goal of reducing carbon emissions.

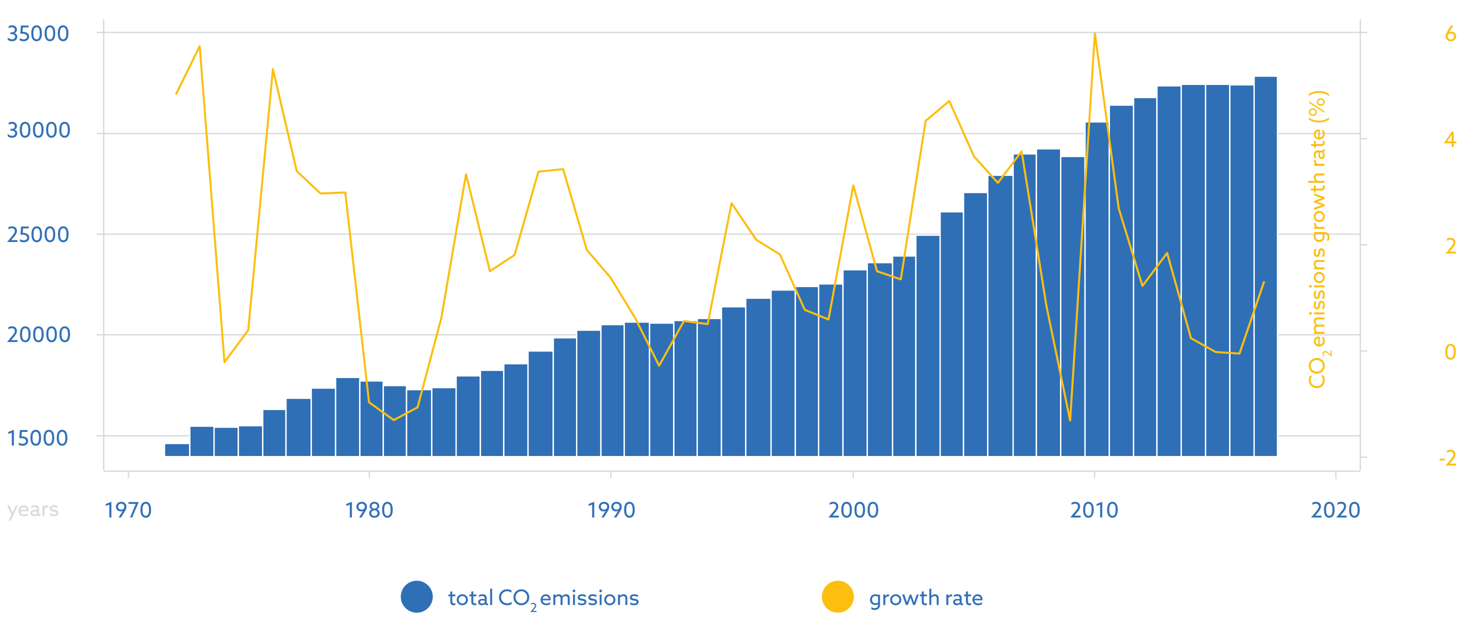
Global climate change has long been a major concern for humans. Countries worldwide have launched carbon emission reduction programmes in view of their respective conditions to coordinate the development of their social economy and the goal of reducing carbon emissions. Due to the diverse levels of economic and social development and industrialization worldwide, each country has demonstrated heterogeneous development in terms of total CO_2 emissions, per capita emissions and CO_2 emission intensity. In addition, the economic growth of various types of countries has different effects on the environment. We will apply a decoupling theory to elaborate if a synchronous relationship exists between economic growth and CO_2 emissions and seek to identify an applicable theoretical basis for realizing control over total carbon emission reduction from the aspects of practice and policies. Therefore, first, we compared and analyzed the stylized facts concerning total carbon emissions, per capita carbon emissions and carbon emission intensity of developing countries (southern countries) and developed countries (northern countries) by their different development stages.

1.1 Total carbon emissions

1.1.1 Globe

The global CO_2 emissions trend demonstrates that total global CO_2 emissions increased from 13,945,200,000 tonnes to 32,839,900,000 tonnes from 1971–2017, representing an average annual growth rate of 1.89 percent.

Figure 1-1 Global CO_2 emissions



1.1.2 Developed countries and developing countries (using OECD and non-OECD as examples)

From 1971–2017, the percentage of CO_2 emissions in OECD countries in terms of the whole world declined from 67.00 percent to 35.25 percent, whereas that percentage in non-OECD countries in terms of the whole world increased from 33.00 percent to 64.75 percent, which indicates that non-OECD countries have become major CO_2 emission countries. The total CO_2 emissions in OECD countries showed an uptrend and then a downtrend, which reached its peak in 2007 by increasing from 9,343,940,000 tonnes in 1971 to 12,930,600,000 tonnes and then decreasing to 11,578,500,000 tonnes in 2017, with an average annual growth rate of 0.49 percent. During the same period, the total CO_2 emissions in non-OECD countries increased significantly and surpassed that in OECD countries in 2005. The total CO_2 emissions in non-OECD countries increased from 4,078,450,000 tonnes to 19,979,300,000 tonnes, with an average annual growth rate of 3.54 percent, far higher than the 0.49 percent in OECD countries.

Figure 1-2 CO_2 emission share: OECD countries and non-OECD countries

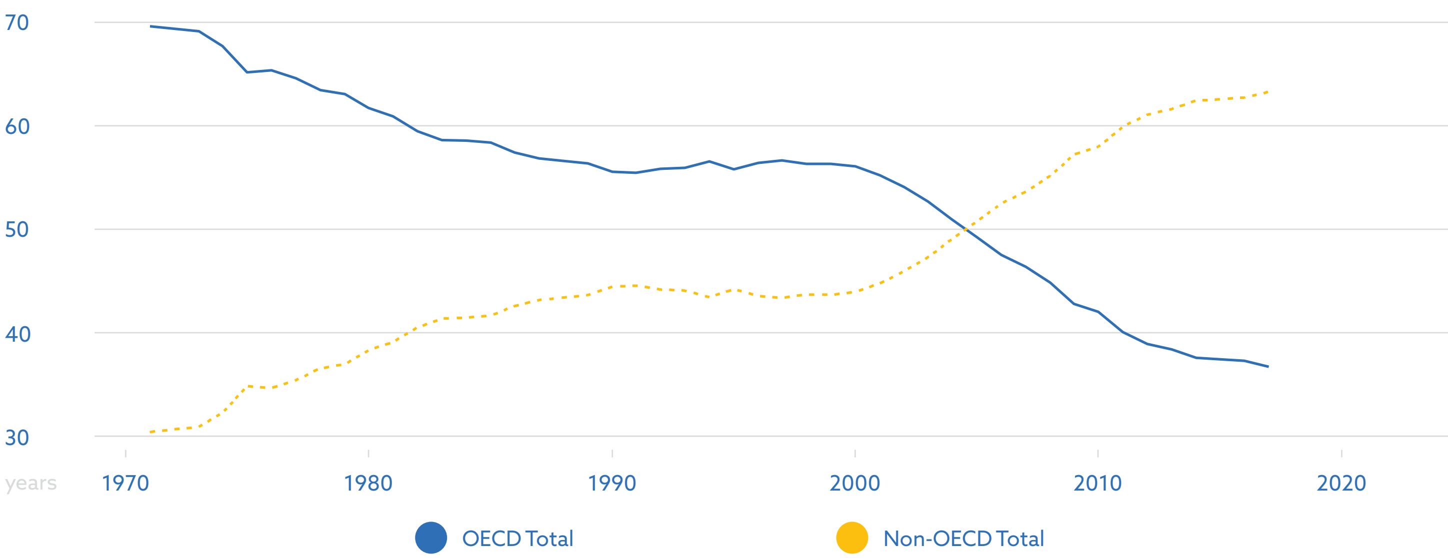
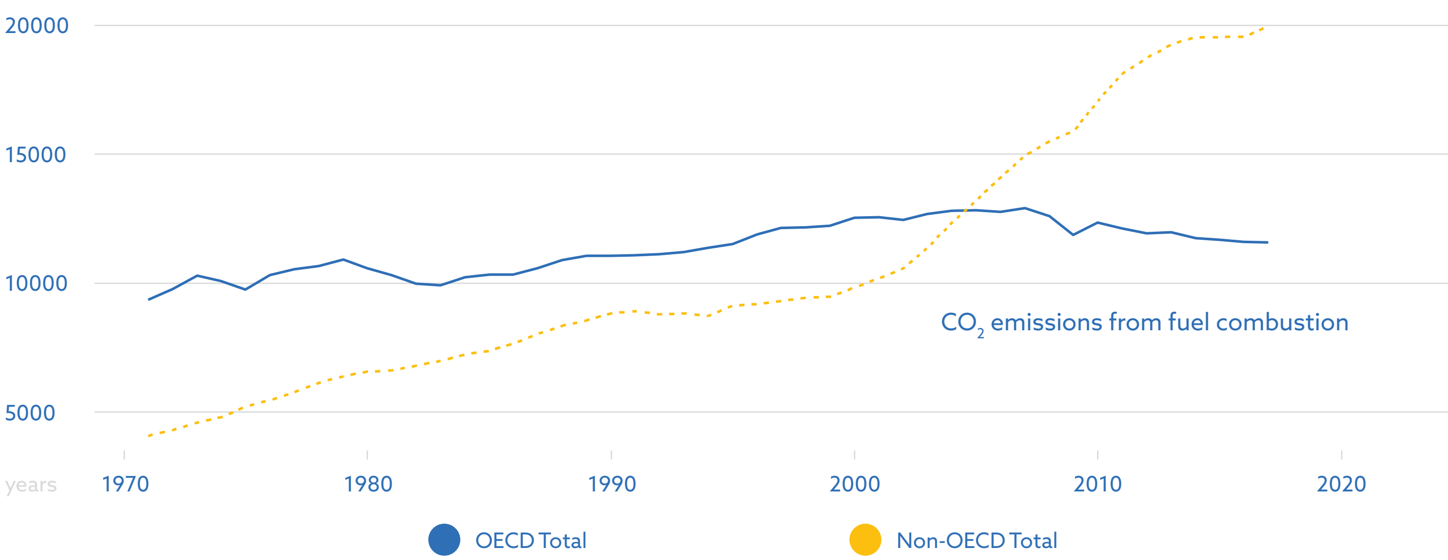


Figure 1-3 Total CO_2 emissions: OECD countries and non-OECD countries



1.1.3 Developing countries (using BRICS countries as examples)

The BRICS (Brazil, Russia, India, China and South Africa) countries are considered representative of developing countries. From 1971 to 2017, the four BRICS countries, other than Russia, showed a significant increase in total CO_2 emissions and the total CO_2 emissions of BRICS countries in terms of the whole world increased from 25.38 percent in 1990 to 42.03 percent in 2017, accounting for nearly half of total global emissions. For China, this increase is especially the case: since its admission into the World Trade Organization (WTO) in 2000, China's total CO_2 emission has been rising dramatically, creating an increasing gap with the other four countries. The CO_2 emissions in China increased from 780,180,000 tonnes in 1971 to 9,257,930,000 tonnes in 2017, representing an average growth rate of 5.64 percent and this average growth rate was 6.78% percent during 2000–2017. In Russia, the total CO_2 emissions from 1990 to 2017 declined slowly from 2,163,530,000 tonnes to 1,536,880,000 tonnes, which made it the only country delivering decreasing total CO_2 emissions among BRICS countries. India also demonstrated a CO_2 emission increase from 1970–2017, from 181,050,000 tonnes to 2,161,570,000 tonnes, representing an average annual growth rate of 5.58 percent. The total CO_2 emissions in South Africa and Brazil maintained at a relatively lower level compared with the other BRICS countries. From 1971–2017, South Africa's CO_2 emissions increased from 157,110,000 tonnes to 421,680,000 tonnes, with an average annual growth rate of 2.27 percent and Brazil's CO_2 emissions increased from 87,480,000 tonnes to 427,630,000 tonnes, with an average annual growth rate of 3.64 percent.

Figure 1-4 CO_2 emission share: BRICS

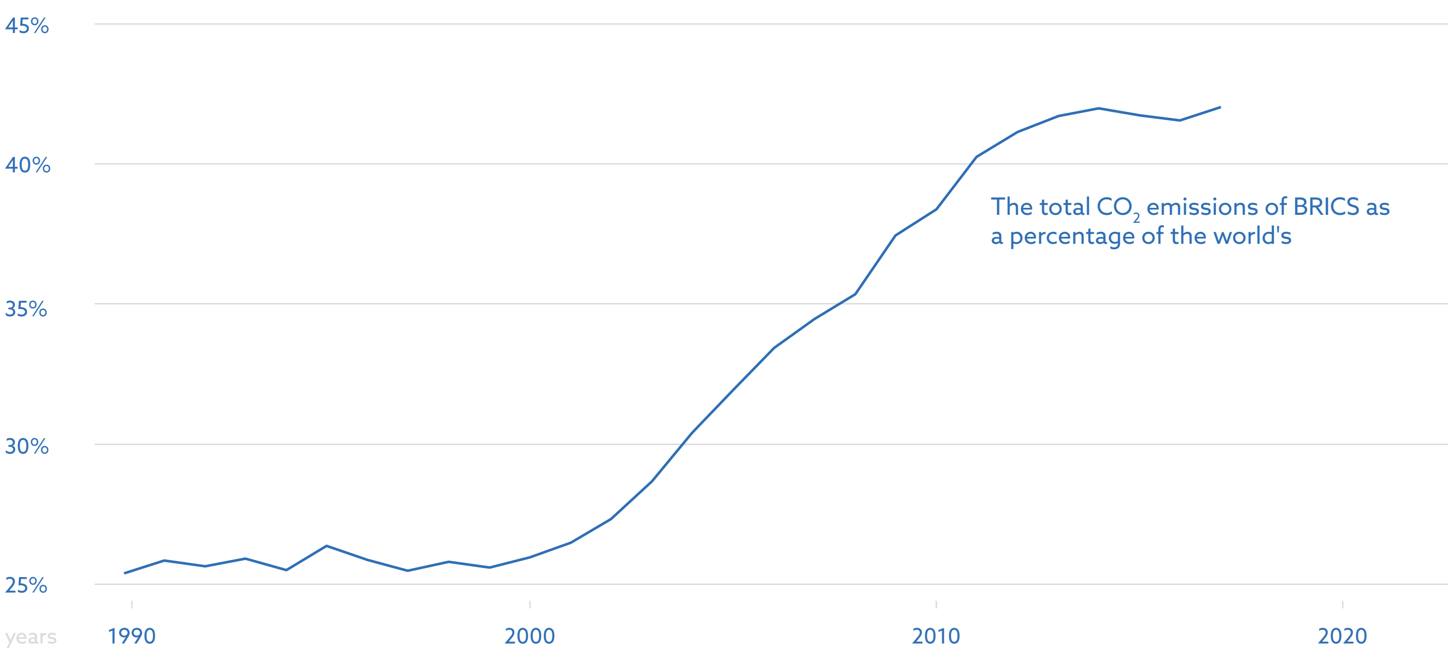
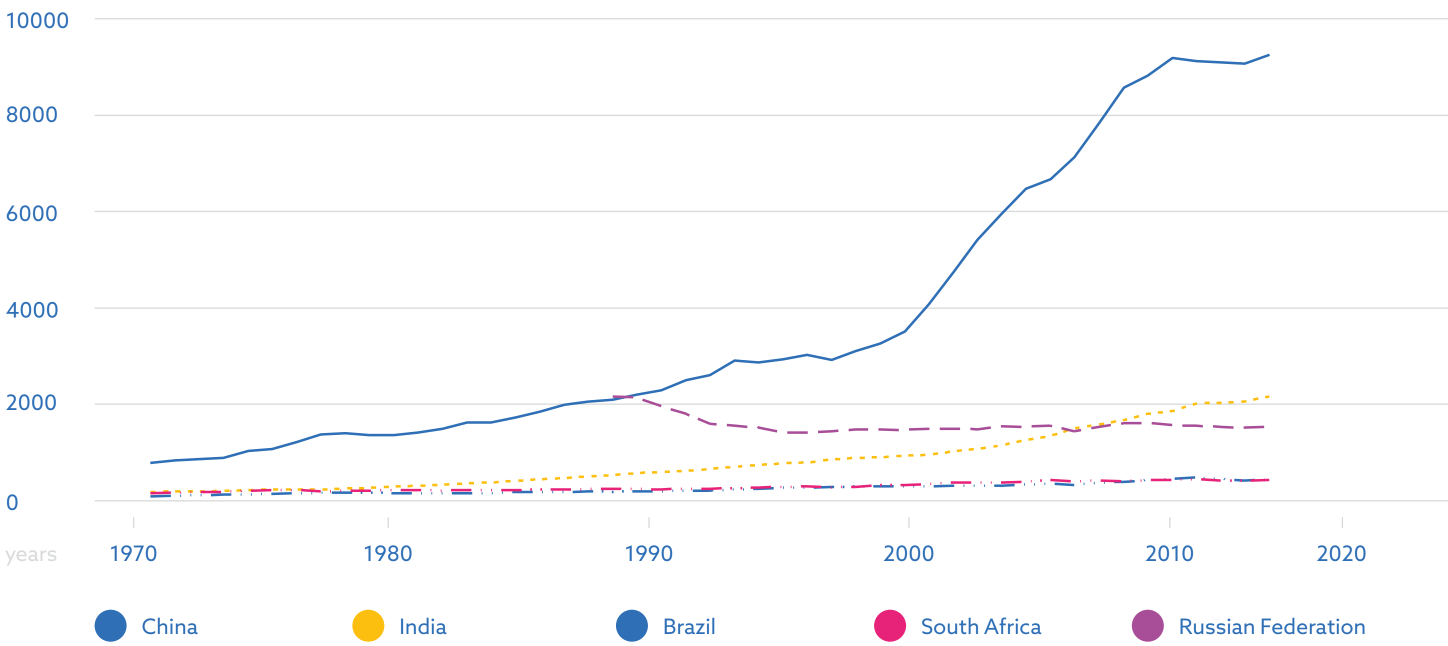


Figure 1-5 CO_2 emissions from fuel combustion: BRICS

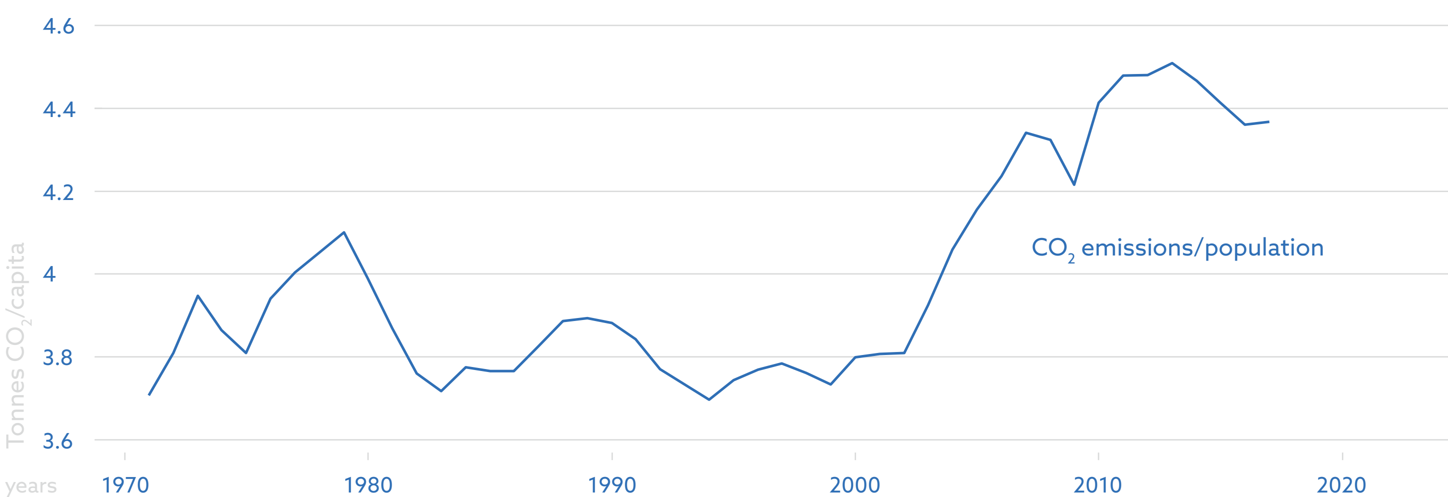


1.2 Per capita carbon emissions (divide total CO_2 emissions by population)

1.2.1 Globe

Other than the investigation on the stylized facts about the total CO_2 emission of various economies, it is also necessary to investigate the stylized facts about per capita CO_2 emissions. In view of the dynamic distribution trend of per capita CO_2 emissions worldwide, emissions fluctuated downwards from 1971–2000 but have risen since 2000. To be specific, global per capita CO_2 emissions were 3.71 tonnes/person in 1971 and increased to 3.79 tonnes/person in 2000. Subsequently, the figure continued increasing to 4.36 tonnes/person in 2017. The average growth rate of global per capita CO_2 emissions was 0.37 percent from 1971–2017.

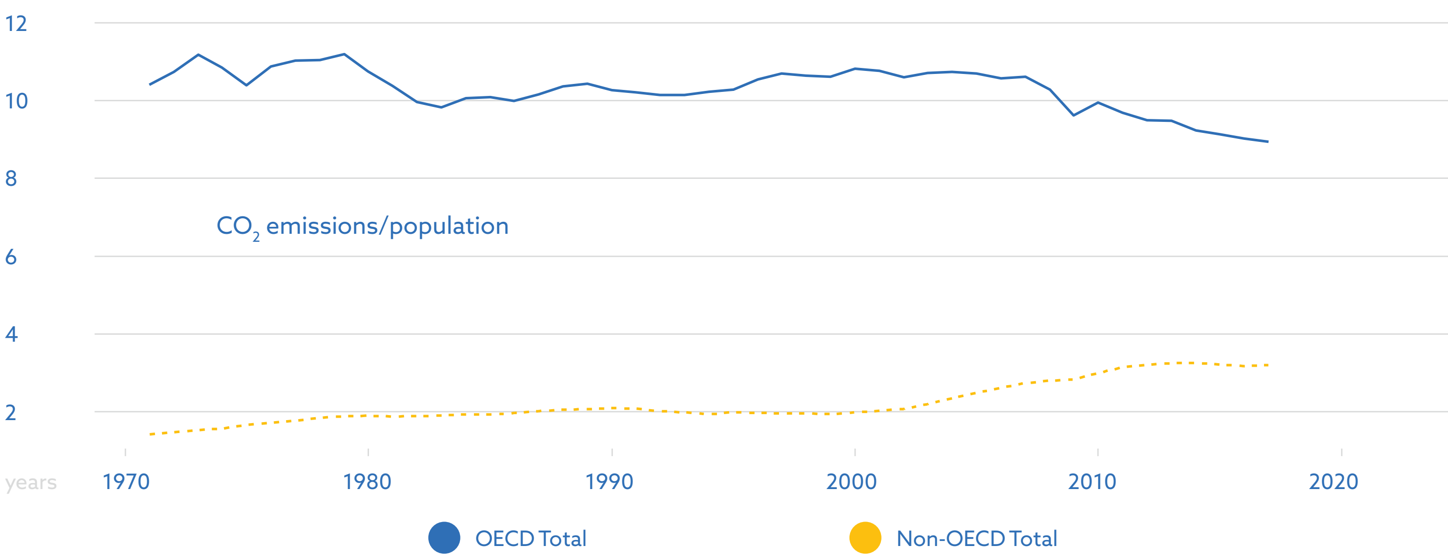
Figure 1-6 Global CO_2 emissions per capita



1.2.2 Developed countries and developing countries (using OECD and non-OECD as examples)

From 1971–2017, per capita CO_2 emissions fluctuated downwards in OECD countries, but it rose significantly in non-OECD countries. However, the per capita CO_2 emissions in OECD countries was far higher than that in non-OECD countries. Specifically, the per capita CO_2 emissions in OECD countries fluctuated from 10.4 tonnes/person in 1971 to 8.94 tonnes/person in 2017, representing an average annual growth rate of -0.30 percent. By contrast, the per capita CO_2 emission in non-OECD countries increased from 1.42 tonnes/person in 1971 to 3.21 tonnes/person in 2017, representing an average annual growth rate of 1.81 percent. The difference between the per capita CO_2 emissions in OECD countries and non-OECD countries shrunk from 7.29 times in 1971 to 2.78 times in 2017, and that gap continues to decrease.

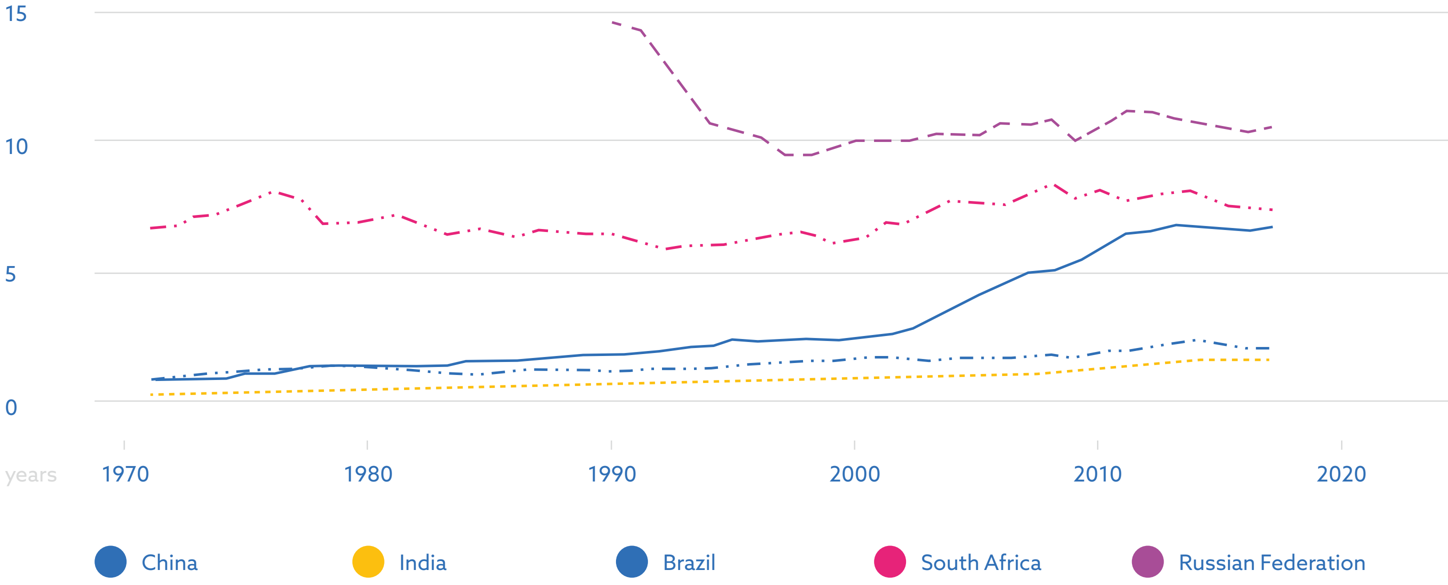
Figure 1-7 CO_2 emissions per capita: OECD countries and non-OECD countries



1.2.3 Developing countries (using BRICS countries as example)

Similarly, we can see from the BRICS countries, representatives of southern countries, that other than Russia, the other four countries demonstrated an uptrend in per capita carbon emissions. However, from the view of parallel comparison, Russia ranked first in per capita CO_2 emissions, followed by South Africa, China, Brazil and India. From 1991–2017, the per capita CO_2 emissions in Russia decreased from 14.59 tonnes/person to 10.64 tonnes/person, representing an average annual growth rate of -1.07 percent; the per capita CO_2 emission in South Africa fluctuated from 6.69 tonnes/person to 7.43 tonnes/person, representing an average annual growth rate of 0.33 percent; the per capita CO_2 emission in China rose from 0.93 tonnes/person to 6.68 tonnes/person, representing an average annual growth rate of 4.50 percent; the per capita CO_2 emission in Brazil increased from 0.89 tonnes/person to 2.04 tonnes/person, representing an average annual growth rate of 1.94 percent; and the per capita CO_2 emission in India raised from 0.32 tonnes/person to 1.61 tonnes/person, representing an average annual growth rate of 3.62 percent. Given the information above, even though China did not deliver the highest per capita CO_2 emissions, it had the highest annual growth rate among BRICS countries. South Africa had a comparatively low per capita CO_2 emission growth rate among BRICS countries.

Figure 1-8 CO_2 emissions per capita: BRICS

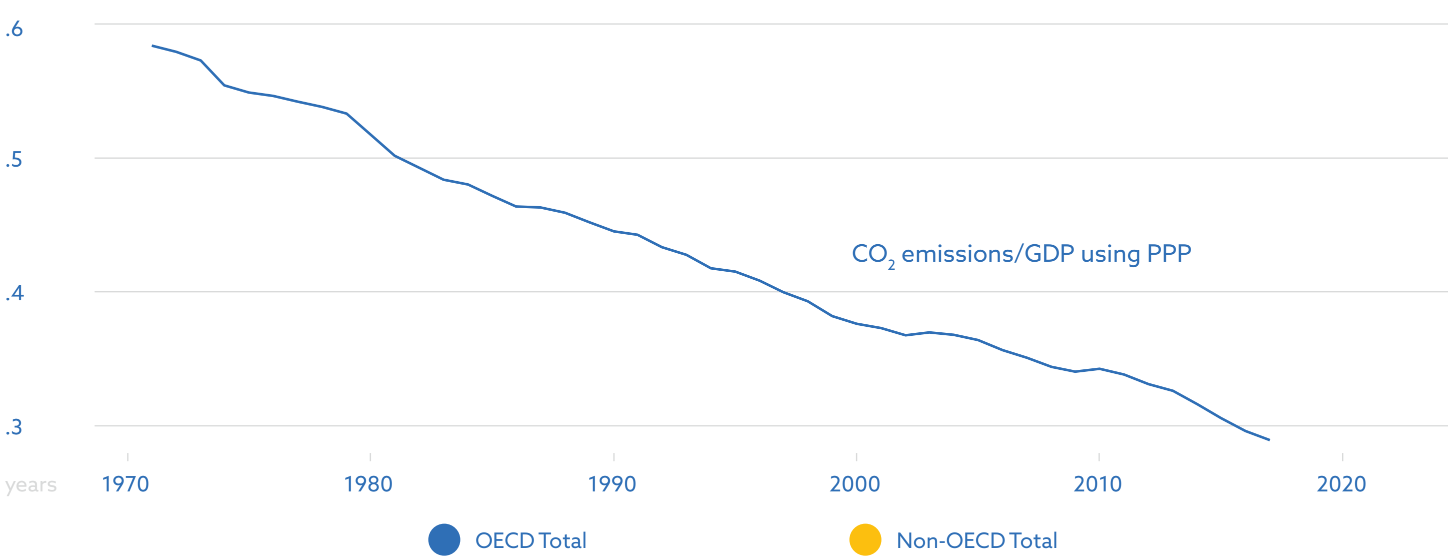


1.3 Carbon emissions intensity (CO_2 emissions/ GDP)

1.3.1 Globe

In addition to the investigation of the total CO_2 emissions and per capita CO_2 emissions of various economies, it is necessary to investigate the impact of economic activities on carbon emissions or the stylized facts about CO_2 emission intensity. From 1971–2017, global CO_2 emission intensity demonstrated a sharp downtrend by dropping from 0.58 tonnes/$1000 to 0.29 tonnes/$1000 with an annual growth rate of -1.51 percent. This reflected that economic activities showed declining dependence on CO_2 emissions.

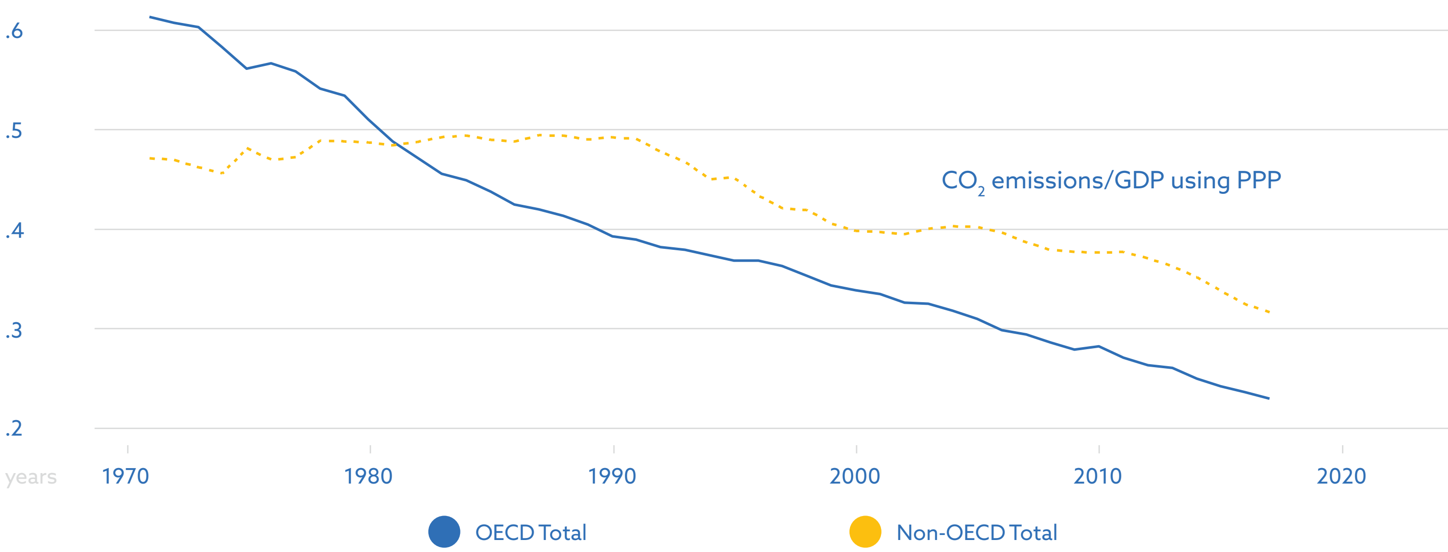
Figure 1-9 Global CO_2 emissions per unit of GDP (PPP)



1.3.2 Developed countries and developing countries (using OECD and non-OECD countries as examples)

From 1971–2017, the CO_2 emission intensity fluctuated downwards in both OECD countries and non-OECD countries. However, the CO_2 emission intensity in OECD countries was stronger than that in non-OECD countries during 1971–1981, yet weaker than that in non-OECD countries during 1982–2017. To be specific, the CO_2 emission intensity in OECD countries fluctuated from 0.61 tonnes/$1000 in 1971 to 0.23 tonnes/$1000 in 2017, representing an average annual growth rate of -2.10 percent; whereas that in non-OECD countries reduced from 0.47 tonnes/$1000 in 1971 to 0.32 tonnes/$1000 in 2017, representing an average annual growth rate of -0.85 percent. It can be concluded that the dependence of economic activities on CO_2 emissions in OECD countries was far lower than that in non-OECD countries. On the one hand, the reduced total CO_2 emissions caused by economic restructuring in OECD countries might have contributed to such a result; on the other hand, technical advancement might also have contributed. The advancement of both production technologies and emission reduction technologies significantly mitigated the impact of economic activities on the ecological environment.

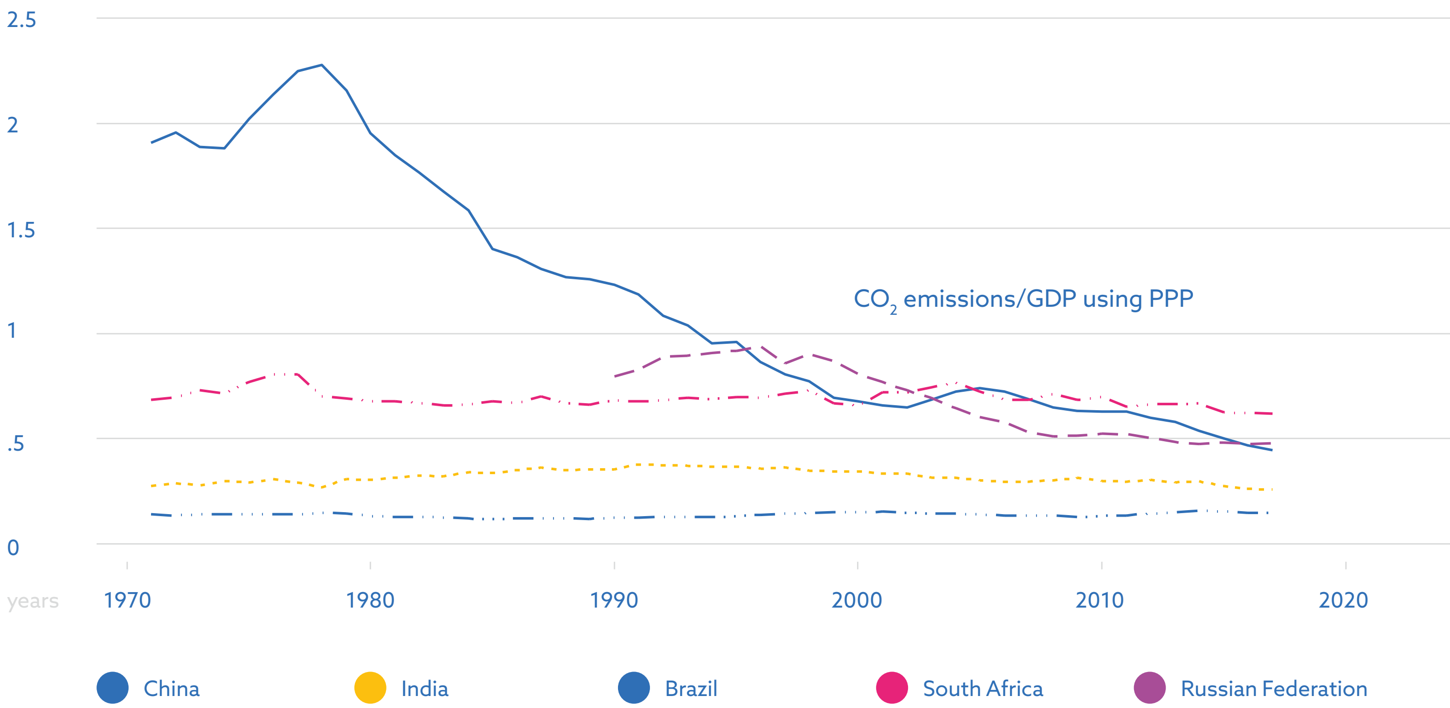
Figure 1-10 CO_2 emissions per unit of GDP (PPP): OECD countries and non-OECD countries



1.3.3 Developing countries (using BRICS countries as an example)

Similarly, we can see from the BRICS countries, representatives of southern countries, that other than China and Russia, the other three countries demonstrated fluctuating carbon emission intensity. However, in view of parallel comparison, China ranked first in carbon emission intensity, followed by Russia, South Africa, India and Brazil. From 1991–2017, the CO_2 emission intensity in Russia dropped from 0.79 tonnes/$1000 to 0.47 tonnes/$1000, representing an average annual growth rate of -1.80 percent; the CO_2 emission intensity in China decreased from 1.91 tonnes/$1000 to 0.45 tonnes/$1000, representing an average annual growth rate of -3.01 percent; the CO_2 emission intensity in South Africa fluctuated from 0.68 tonnes/$1000 to 0.61 tonnes/$1000, representing an average annual growth rate of -0.14 percent; the CO_2 emission intensity in India fluctuated from 0.27 tonnes/$1000 to 0.26 tonnes/$1000, representing an average annual growth rate of -0.07 percent; and the CO_2 emission intensity in Brazil fluctuated from 0.14 tonnes/$1000 to 0.15 tonnes/$1000, representing an average annual growth rate of 0.21 percent.

Figure 1-11 CO_2 emissions per unit of GDP (PPP): BRICS



2. Current status of established research

2.1 Environmental Kuznets Curve

In the early stage of economic development, the level of environmental pollution will augment. When per capita income keeps increasing gradually and emission reduction technology keeps improving, the level of environmental pollution will eventually cross an "inflection point"; after this point, the degree of environmental pollution will decline.

The study on environmental quality and economic growth can be traced back to the Environmental Kuznets Curve (EKC), the inverted U-shaped curve relationship that exists between environmental pollution and per capita income, as proposed by Grossman and Krueger (1991) based on cross-border panel data. In the early stage of economic development, the level of environmental pollution will augment with the process of economic development. When per capita income keeps increasing gradually and emission reduction technology keeps improving, the level of environmental pollution will eventually cross an "inflection point" (turning point); after this "inflection point," the degree of environmental pollution will (continually) decline with economic development and income growth, possibly by way of scale effect, structure effect and technology effect. So the EKC is also used to identify the factors affecting environmental pollution:

$$CO2_{it} = \alpha_0 + \alpha_1 y_{it} + \alpha_2 y_{it}^2 \tag{1}$$

where in (1), $CO2_{it}$ is carbon emissions of economy i in year t; y_{it} is per capita GDP of economy i in year t; and y_{it} and y_{it}^2 are used to identify the existence of EKC. If $\alpha_1 > 0$ and $\alpha_2 < 0$, per capita GDP and carbon emissions demonstrate an inverted U-shaped relationship.

Many scholars have been inspired by the EKC theory and have conducted extensive studies on the existence of the EKC using cross-section, time-series and panel data. Empirical literature represented by Grossman and Krueger (1995) and Seldon and Song (1994) confirmed the existence of the EKC in the United States by using pollution data from the United States. Since then, a series of studies has confirmed the existence of the EKC in France (Ang, 2007), Austria (Friedl and Getzner, 2003) and other developed countries. Halkos and Tzeremes (2009) confirmed the existence of EKC and predicted the inflection point by using cross-country data of 17 OECD countries.

2.2 Decoupling carbon emissions and economic growth

OECD describes the co-movement relationship between economic growth and industrial pollutions and emissions as "coupling/decoupling." A *decoupling coefficient* is defined as the intensity measure of pollutive emissions over GDP in the base period divided by the same intensity measure in the current period (or the period to be investigated). The invention of the OECD decoupling coefficient gives a way to quantify the relationship between economic growth and industrial pollutions and emissions. The "decoupling" theory has become a widely used tool to measure and evaluate the mode and sustainability of the economic development in a country or region. However, initially, the OECD decoupling coefficient may not be coherent because of different choices of the base period. Therefore, there is hardly a unified judge of decoupling status and its associated development characteristics for an area due to the caveat from the above OECD decoupling coefficient calculation. Further, the model of the *Tapio decoupling elasticity coefficient* is from Tapio (2005), whose initial research motive was to uncover the elastic movement relationship between economic development, transportation capacity and CO_2 emissions in Europe. The Tapio decoupling elasticity coefficient can exhibit a dynamic linkage between economic growth and carbon emissions. It not only avoids the subtlety in choosing a base period but also creates room for further analysis of the endogenous reason for the current decoupling status of a country.

$$e_{it} = \frac{(CO2_{it} - CO2_{i,t-1})/CO2_{i,t-1}}{(Y_{it} - Y_{i\,t-1})/Y_{i\,t-1}} = \frac{\Delta CO2/CO2}{\Delta Y/Y} \tag{2}$$

In (2), *e* represents the decoupling elasticity coefficient; $CO2$ and Y represents emissions and GDP in a country/region i, respectively; and t is year. Similar to Tapio (2005), we define six economy and emission statuses based on the value of the decoupling elasticity coefficient and the signs of $\Delta CO2$ and ΔY.

Table 2-1 The six economy and emission statuses

Economy and Emission Status	Δemissions	ΔGDP	Decoupling elasticity coefficient
Sustainable absolute decoupling	$\Delta P < 0$	$\Delta Y > 0$	$e \leq 0$
Mild coupling	$\Delta P > 0$	$\Delta Y > 0$	$0 < e < 1$
Pollutive coupling	$\Delta P > 0$	$\Delta Y > 0$	$e \geq 1$
Recessionary coupling	$\Delta P < 0$	$\Delta Y < 0$	$e \geq 1$
Pollutive recessionary coupling	$\Delta P < 0$	$\Delta Y < 0$	$0 < e < 1$
Pollutive decoupling	$\Delta P > 0$	$\Delta Y < 0$	$e \leq 0$

3. Empirical analysis

3.1 A regression to the global panel sample's Environmental Kuznets Curve

Based on the EKC hypothesis, this study set the econometric model expressing the nonlinear relationship between economic growth and carbon emission as below:

$$CO2_{it} = \alpha_0 + \alpha_1 y_{it} + \alpha_2 y_{it}^2 + \alpha_3 X + \varepsilon_{it} \tag{3}$$

where in (3), the dependent variable is the total carbon emissions $CO2_{it}$ of economy i in year t. To ensure stationary data while eliminating or mitigating heteroscedasticity in the empirical process, this study adopted logarithmic processing to obtain lnco2. Logarithmic processing was also used on the core explanatory variables y_{it} and y_{it}^2, namely per capita GDP of economy i in year t. Because we adopted a cross-nation study, to maintain the comparability among the samples during the research period, this study generated per capita GDP by calculating purchasing power parity using 2010 prices. X is a set of control variables affecting carbon emissions, mainly including economic structure, urbanization level, opening up degree and technical level. To be specific, in this study, economic structure is expressed in the ratio of industrial output to GDP. Generally speaking, if industry accounts for a higher proportion in a country, the carbon emissions is expected to be elevated. The urbanization level is expressed in the proportion of the urban population to the total population, the opening up degree of a country or region is expressed in the ratio of total import and export to GDP, and total factor productivity (TFP) is used to indicate the technical level of a country or region. We expect that a higher technical level will lead to lower carbon emissions. See Table 3-1 for the descriptive statistics of these variables.

Table 3-1 Descriptive statistics of variables

Variables	Meaning	Average value	Standard deviation	Min.	Max.
lnco2	Logarithm of CO_2 emissions (in 10,000 tonnes)	7.0633	2.4120	1.0986	12.4422
lnrgpd	Logarithm of real GDP per head (PPP US$ at 2010 prices)	9.0308	1.1910	6.5023	11.4961
INDP	Industry to GDP (%)	29.3176	12.9053	6.8000	74.0000
lnur	Logarithm of urbanization rate (%)	3.8912	0.5246	2.2725	4.6052
lnfd	Logarithm of import and export to GDP (-)	4.2964	0.5819	2.2848	5.7911
rtfpna	TFP (-)	0.9925	0.1970	0.4781	1.9115

The sources of data in this study are from the *Economist Intelligence Unit Country Report*,[1] the International Energy Agency, the World Bank's 'World Development Indicators' and the Penn World Table 9.1 (personal disposable income).

This study took the unbalanced panel data of 111 countries and regions from 1980 to 2018 as an example and used Stata 14.1 software for empirical analysis. The corresponding estimation results are recorded in Table 3-2. The dependent variable is the logarithm of CO_2 emissions (in 10,000 tonnes).

Table 3-2 Estimation results from the EKC model

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
lnrgpd	3.8021***	3.3245***	1.3204***	3.3553***	2.8592***	0.3030***	3.1230***
	(0.3710)	(0.3630)	(0.3840)	(0.3645)	(0.3049)	(0.1104)	(0.3222)
lnrpgd2	-0.1602***	-0.1313***	-0.0274	-0.1333***	-0.1384***	-0.0160***	-0.1533***
	(0.0211)	(0.0195)	(0.0193)	(0.0196)	(0.0155)	(0.0058)	(0.0163)
INDP		0.0237***	0.0117***	0.0269***	0.0151***	0.0023***	0.0153***
		(0.0029)	(0.0013)	(0.0029)	(0.0013)	(0.0004)	(0.0013)
lnur		0.5484***	1.0189***	0.4611***	0.1103	0.0169	0.0863
		(0.1053)	(0.0860)	(0.1072)	(0.0777)	(0.0303)	(0.0772)
lnfd		-1.6515***	-0.1323***	-1.7239***	-0.2124***	-0.0022	-0.2126***
		(0.0477)	(0.0320)	(0.0489)	(0.0288)	(0.0108)	(0.0282)
rtfpna		-1.4677***	-0.7997***	-1.5153***	-0.5421***	0.0190	-0.5156***
		(0.1551)	(0.0640)	(0.1579)	(0.0599)	(0.0227)	(0.0593)
_cons	-13.8440***	-5.8680***	-5.2475***	-5.6359***	-7.3009***	-1.0915**	-8.4117***
	(1.6091)	(1.6286)	(1.8012)	(1.6678)	(1.4851)	(0.4554)	(1.5827)
Country fixed effect	NO	NO	YES	NO	YES	YES	YES
Time fixed effect	NO	NO	NO	YES	YES	YES	YES
inflection point	**11.8667**	**12.6599**	**24.0948**	**12.5855**	**10.3294**	**9.4687**	**10.1859**
R^2	0.2308	0.5175	0.9846	0.5355	0.9882	0.9982	0.9882
N	5590	3019	3019	3019	3019	2986	3005

Note: Robust standard errors are reported in parentheses below the coefficient estimates; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

1 The *Economist Intelligence Unit Country Report*, covering 190 economies worldwide, provides analysis and five-year forecasts on the policy tendencies and major economic transitions of countries, indicating the potential risks affecting policies and economic stability and follows up on global hot topics in a consistent and profound way. As a flagship report, the *Economist Intelligence Unit Country Report* started to be distributed worldwide in 1946 and it has become a first selection for international macroeconomics and cross-nation study professionals.

In Column (1), we did not take into account any control variables and found that the linear term and the quadratic term of per capita GDP were positive and negative, respectively, and passed the 1 percent significance test. It can be seen that carbon emissions EKC exists during the study period. With every 1 percent increase in per capita GDP, the quadratic of carbon dioxide emissions will drop by 0.16 percent, which means that economic growth will eventually be decoupled from carbon emissions.

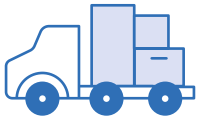
In addition, industrial structure, trade structure and urbanization should also affect carbon emissions. Then we considered the control variables in column (2) and found that the nonlinear relationship between per capita GDP and carbon emissions still held. In this regression, we use the proportion of industry to capture the industrial structure, the rate of urbanization to capture the development stages of different countries, the proportion of imports and exports to express the trade access of a country and the total factor productivity to express the speed of technological progress. After adding the aforementioned control variables, we found that the decoupling relationship between carbon emissions and economic growth still exists.

To control other factors, we considered the individualized differences of different countries and the common development trend of all countries over time in the model. We term the former an individual fixed effect and the latter a time fixed effect. They appear controlled in columns (3)–(4), respectively and the results were still robust. When these two effects are controlled separately, we cannot simultaneously capture the individual factors of different countries and the effects of the common development of all countries over time. So we need to control both time fixed effects and individual fixed effects.

Accordingly, in column (5), we controlled other variables affecting carbon emissions as well as individual fixed effects and time fixed effects. The results demonstrated that the linear term of the logarithm of per capita GDP was 2.8592 and the quadratic term was -0.1384, both of which were significant at 1 percent. This proved that a significant inverted U-shaped curve relationship exists between carbon emissions and actual per capita GDP. Based on the linear term and quadratic term estimation parameters of lnrgpd, it can be calculated that at the EKC inflection point, the corresponding actual per capita GDP shall be $30,619.735. This shows that our model predicts a satisfactory result after separating other disturbance factors, which means that with economic growth, carbon emissions will first increase and then decrease (after reaching a per capita GDP of $30,619).

Columns (6) and (7) are robustness tests. To identify the lag effect, we controlled the impact of lagging carbon emissions by one period in the former column and we lagged all explanatory variables by one period in the latter column. Similarly, the empirical research results show that the estimated coefficient sign and significance of each variable are basically consistent with the previous results, which proves that the study in this paper has strong robustness.

The estimation results of other explanatory variables show that the estimation coefficient of economic structure (i.e., INDP) is significantly positive, which indicates that a more developed industry of a country or region will lead to higher carbon emissions, which is due to the fact that the developed industry, especially heavy industry, requires a large number of upstream enterprises with high energy consumption and high pollution as support. When the industry has already developed or has been expanding rapidly, carbon emissions follow.



Urbanization increased carbon emissions. This reason is that the process of urbanization often indicates an increase in the consumption level of industrial products, which will contribute considerable carbon dioxide emissions compared to a rural decentralized production regime.

The estimation coefficient of urbanization level is positive and passed the significance test in columns (1)–(4), indicating that urbanization increased carbon emissions. This reason is that the process of urbanization often indicates an increase in the consumption level of industrial products, which will contribute considerable carbon dioxide emissions compared to a rural decentralized production regime.

The estimation coefficient of opening up degree is significantly negative (except that column (6) is not significant). Opening to the outside world often promotes production specialization, as a result of which all countries will produce according to the comparative advantage determined by their own endowment structure: the improvement of production efficiency saves emissions. Nevertheless, the trade structure of a country, instead of total trade relevance (measured by the logarithm of import and export to GDP, as in the previous regression), will matter more in the sense of inter-country linkages related to pollution transfer issues. We will develop this in much more detail with an additional regression model in the next section.

Technical level significantly reduces carbon emissions (except that column (6) is not significant). This makes an analogous argument with the preceding point: a higher technical level leads to improvement in energy efficiency, which brings cost and emission savings.

3.2 International trade and emissions

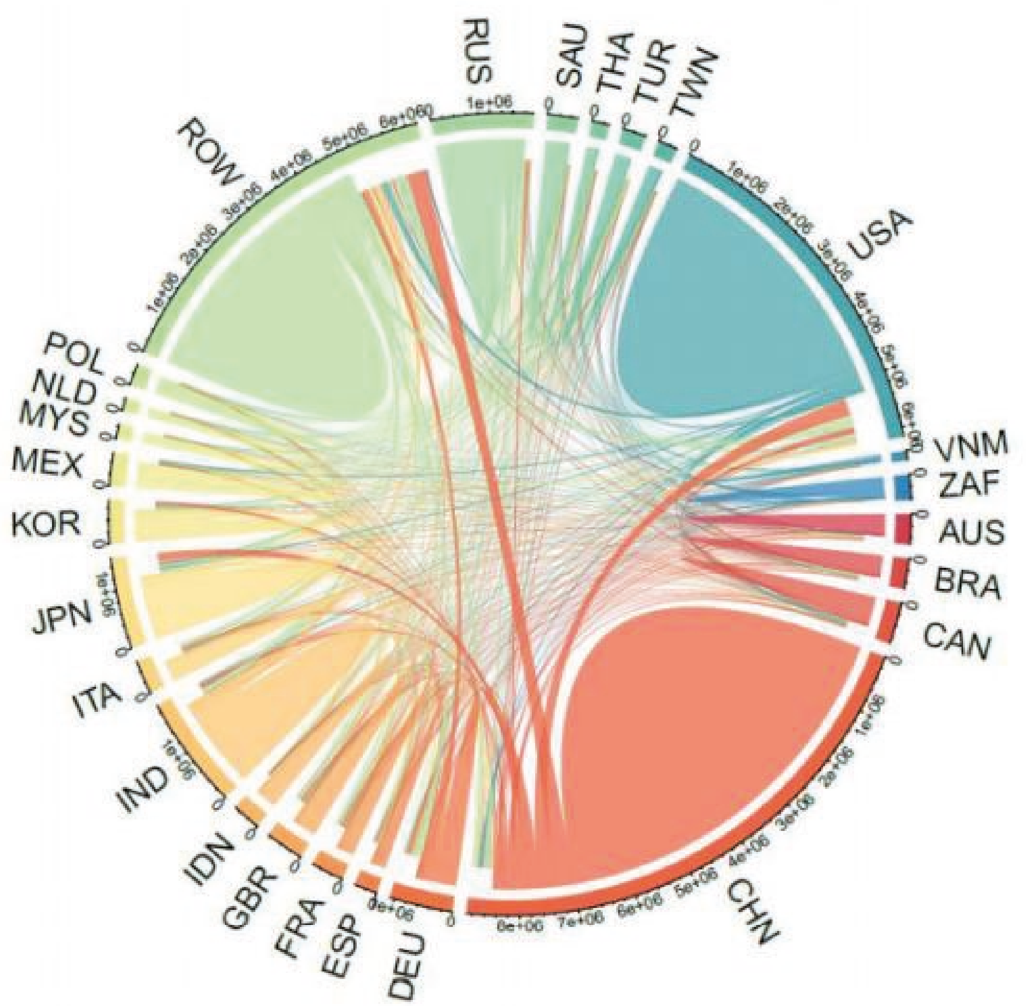
3.2.1 Emissions embodied in international trade

Although in the above empirical model, we have controlled the impact of the ratio of import and export trade to GDP on carbon dioxide emissions to identify the impact of international trade on environmental performance between countries. From this we can see that the coefficient is significantly negative, indicating that the higher the trade openness of a country or region, the lower the corresponding carbon dioxide emissions. This indicates the double dividend of economy and environment. To further explore inter-country variables, such as pollution transfer, we first describe the characteristic facts of the structure and flow of the foreign trade of the BRICS countries. The typical facts of the BRICS countries are based on the following considerations: first, the BRICS countries are very important countries in the South and they are at the same stage of development; and second, the foreign trade volume and total carbon dioxide emissions of the BRICS countries account for a large share of the global market. From this, we describe the typical facts based on the trade structure data of the BRICS countries. We then expand the scope of research to multiple economies, not just the BRICS countries, and we incorporate the trade structure data of each country into the EKC empirical model and test the impact of different commodity trade imports and exports on carbon dioxide emissions.

Because of the increasingly fragmented nature of production processes across countries, domestic CO_2 emissions are sometimes generated by the production of goods consumed in other countries. Such global interconnectedness carries the risk that uneven domestic policies on emission regulations may lead to pollution havens, whereby countries with lax environmental regulations would specialize in producing pollution-intensive goods that are exported to other countries with more stringent environmental policies. Examining carbon emissions embodied in trade can help improve the understanding of the magnitude of this effect.

Since 1995, carbon emissions embodied in trade have been increasing both in absolute value and as a share of global emissions. However, the volume of global trade has grown more rapidly than the carbon emissions embodied in it, probably reflecting the general trends of relative decoupling between economic growth and CO_2 emissions (OECD, 2017). The origin and destination of the flows indicate where the goods embodying carbon emissions are produced and then consumed. In 2011, carbon emissions embodied in trade accounted for 21 percent of global emissions. While this is significant, it also indicates that the bulk of carbon emissions are generated domestically by the production of goods and services that are eventually consumed internationally. For example, China accounts for 23 percent of all carbon emissions embodied in exports, whereas it makes up for 13 percent of global trade value (Figure 3-1).

Figure 3-1 Carbon emissions embodied in bilateral trade flows in 2011



Source: OECD Trade and Environment Working Papers: Trends in Policy Indicators on Trade and Environment.

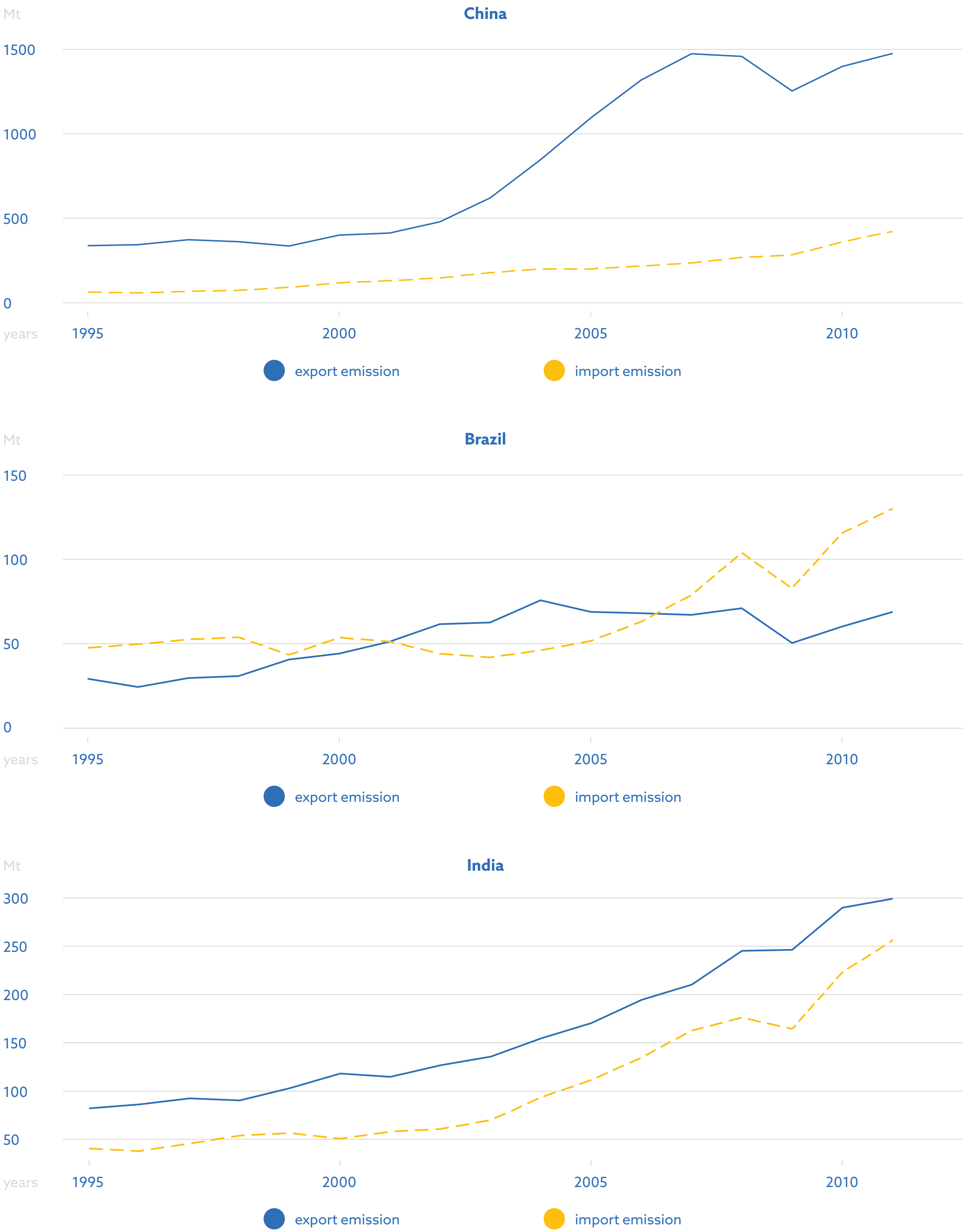
The northern countries not only obtained economic benefits in commodity trade but also received environmental dividends. In other words, southern countries emit a huge amount of CO_2 for the consumption in northern countries through international trade.

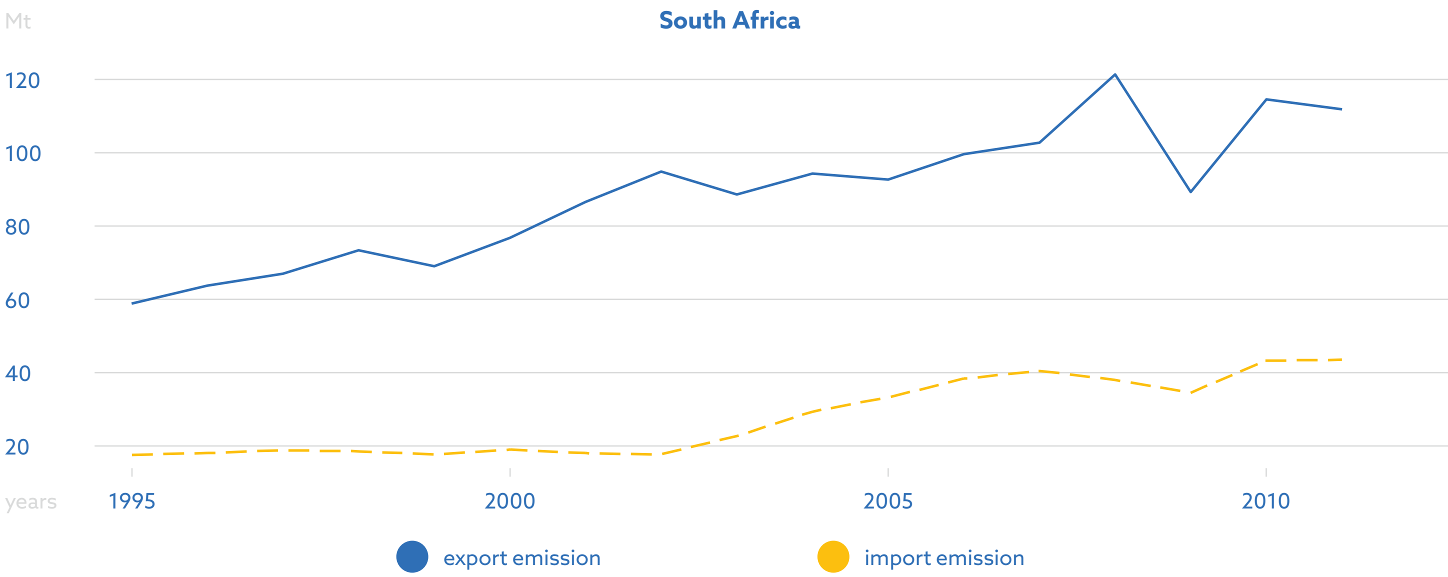
We can see from the embodied carbon emissions of China's import and export trade that the volume of import and export trade is closely related to the embodied carbon emissions in trade, and both are showing an increasing trend. We can further see from the structure of trade products that China's import and export commodities are mainly manufactured products, but the embodied carbon emissions of export trade are much higher than those of import trade, which is to say, the net inflow of CO_2 to China is significantly large (Figure 3-2). It can also be seen from Figure 3-2 that trade is an important reason for the increase in China's CO_2 emissions. There have been fluctuations in the embodied carbon emissions of Brazil's import and export trade. From 2001 to 2006, the embodied carbon emissions of Brazil's export trade were higher than those of the import trade. In other years, the opposite was true, indicating that the import and export trade did not bring much CO_2 emissions to Brazil. Similarly, India, South Africa and Russia have higher embodied carbon emissions from exports than imports and trade has led to an increase in CO_2 emissions from these countries. To compare with developed countries and verify whether there is a pollution refuge effect in the southern countries, we use the United States, in Figure 3-2, as a representative of the northern countries. The study found that the embodied carbon emissions of United States exports are far lower than the embodied carbon emissions of imports. In other words, the United States net CO_2 migration is negative, which at least shows that the United States has obtained an environmental dividend in international trade. Through the description of the characteristic facts of six typical countries, we can see that international trade has brought close ties between countries. At the same time, it has also made southern countries become pollution refuges in trade, whereas northern countries gain environmental protection through trade.

Based on the abovementioned characteristic facts, we have a series of observations. From the perspective of carbon dioxide reduction, the southern countries have become pollution refuges and commodity processing plants for the northern countries, generating a large amount of carbon dioxide emissions. The northern countries not only obtained economic benefits in commodity trade but also received environmental dividends. In other words, southern countries emit a huge amount of CO_2 for the consumption in northern countries through international trade. Southern countries dominate the net flow of CO_2 and northern countries dominate the net outflow of CO_2. Trade has led to a large amount of "carbon leakage."

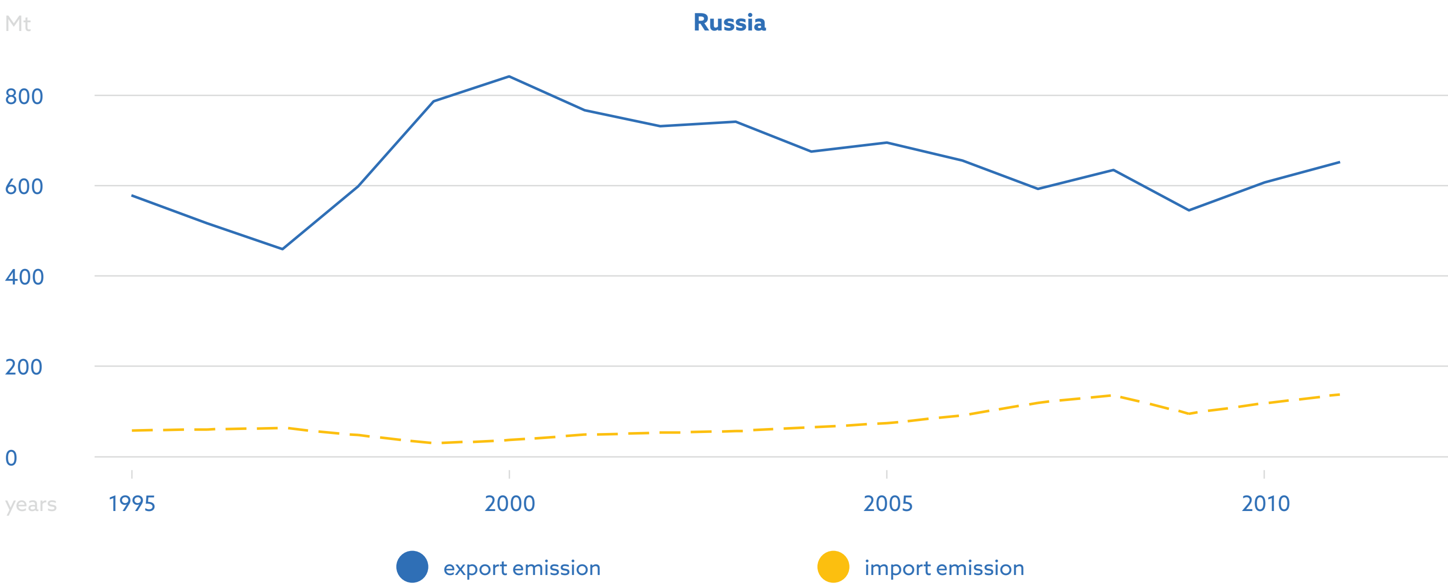
Northern countries transfer high-pollution, high-energy consumption and resource-based industries to southern countries through export trade, where they are processed by southern countries. Then, semi-final and final products are brought back through import trade, reducing northern countries' carbon emissions, but increasing southern countries' and global carbon emissions. If the burden of carbon emissions embodied in trade cannot be shared well, then "carbon leakage" will aggravate the global climate change process. Facing the fact that carbon dioxide emissions are unfair in the trade process between the southern and northern countries, how policy designers and international organizations can alleviate this situation is a topic worthy of study.

Figure 3-2 Export emissions and import emissions of BRICS countries and the United States

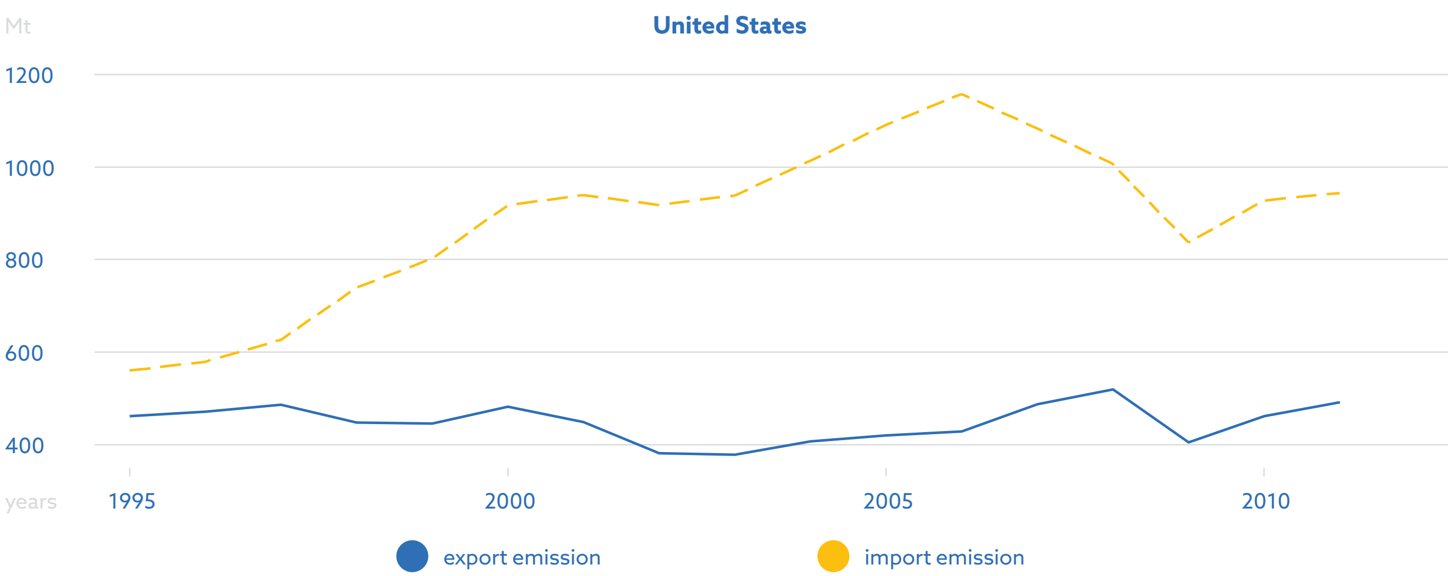




Mt
South Africa
120
100
80
60
40
20
years
1995
2000
2005
2010
export emission
import emission



Mt
Russia
800
600
400
200
0
years
1995
2000
2005
2010
export emission
import emission



Mt
United States
1200
1000
800
600
400
years
1995
2000
2005
2010
export emission
import emission

3.2.2 A regression to the global Environmental Kuznets Curve with trade

From the previous analysis and argument on the relationship between trade structure and emissions, we add trade structure as explanatory variables, including net exports of agricultural raw materials "Agrinetex," net exports of food "Foodnetex," net exports of fuel "Fuelnetex," net exports of manufactures "Manufanetex" and net exports of minerals and metals "Minenetex" ($100 million) into regression equation (3) to study the impact of trade and its structure on carbon dioxide emissions. Furthermore, in terms of sample selection, we use full-sample data and only-southern-countries data. The results of these two regressions are shown in the first and second columns of Table 3-3, respectively.

From the results of the full sample in the first column, we find that the coefficient of the net export of agricultural products is significantly positive at 1 percent. With other conditions unchanged, the carbon dioxide emissions of a country on average increases by 3.623 percent when net exports of agricultural products increase by $100 million. For the sample of southern countries (the second column), the coefficient is also significantly positive, but the value decreases. For each $100 million increase in net exports of agricultural products, the average carbon dioxide emissions of southern countries will increase by 2.269 percent, which indicates that agricultural production increases carbon dioxide emissions and the impact of southern countries is relatively less. For net exports of food, the coefficient of the full sample is significantly negative. With other conditions unchanged, the carbon dioxide emissions of a country decreases by 0.915 percent when the net food export increases by $100 million. And for the southern countries, the value drops to 0.698 percent. For net exports of fuel, the regression results show that the coefficient is not significant in both the full sample and the only-southern-countries sample. For the net exports of manufactured goods, the regression results show that in the full sample, the carbon dioxide emissions of a country increase by 0.0694 percent when the net exports of manufactured goods increase by $100 million. In the sample of southern countries, the carbon dioxide emissions of a country increase by 0.0707 percent when net exports of manufactured goods increase by $100 million. For the net exports of minerals and metals, results show that the carbon dioxide emissions of a country decrease by 0.246 percent when net exports of minerals and metals increase by $100 million, whereas this effect is 0.596 percent in the samples of the southern countries. Besides, for the variables lnrgdp, lnrgdp2, lndp, lnur, lnfd and rtfpna, we find that the values of coefficients are similar to those in Table 3-2 as is the inflection point, which verifies the robustness of the regression results in Table 3-2.

Table 3-3 Estimation result from the EKC model with trade

Agrinetex	3.623***	2.269***		
	(0.665)	(0.774)		
Foodnetex	-0.915***	-0.698***		
	(0.161)	(0.197)		
Fuelnetex	0.00993	0.00587		
	(0.007)	(0.042)		
Manufanetex	0.0694***	0.0707***		
	(0.007)	(0.007)		
Minenetex	-0.246*	-0.596**		
	(0.130)	(0.243)		
iManu			0.451***	0.416***
			(0.070)	(0.094)
lnrgdp	3.806***	3.559***	6.095***	5.419***
	(0.470)	(0.844)	(0.398)	(0.827)
lnrgdp2	-0.163***	-0.146***	-0.288***	-0.246***
	(0.026)	(0.499)	(0.021)	(0.049)
INDP	0.0354***	0.0381***	0.0208***	0.0121*
	(0.005)	(0.011)	(0.004)	(0.007)
lnur	0.630***	0.643***	0.353***	0.288**
	(0.139)	(0.146)	(0.121)	(0.123)
lnfd	-0.957***	-0.657***	-0.501***	-0.253***
	(0.084)	(0.097)	(0.045)	(0.049)
rtfpna	-1.445***	-2.464***	-1.336***	-1.842***
	(0.296)	(0.517)	(0.165)	(0.217)
_cons	-14.895***	-13.930***	-25.807***	-23.326***
	(2.322)	(3.411)	(1.713)	(3.112)
Time fixed effect	YES	YES	YES	YES
inflection point	**11.675**	**12.188**	**10.582**	**11.014**
R^2	0.4626	0.4645	0.4569	0.4632
N	2215	1196	2567	1488

Note: Robust standard errors are reported in parentheses below the coefficient estimates; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

Manufacturing becomes the focus of our study on the relationship between trade and emissions. If a country's net export of manufactures is positive, then it indicates that the country is a recipient in the process of global manufacturing industry transferring. On the contrary, if a country's net export of manufactures is negative, it indicates that the country is transferring its manufacturing industry to the rest of world. Hence, to study the impact of being a recipient in the process of global manufacturing industry transferring, we introduce solely and separately a dummy variable, iManu (iManu = 1 when the country's net export of manufactures is positive), into the regression equation (3). And as before, we use the full sample and the samples only from southern countries. The regression results are shown in columns 3 and 4 of Table 3-3, respectively.

It can be seen that in the full sample, the coefficient of iManu is significantly positive at the level of 1 percent. With other conditions unchanged, if a country's net exports of manufactures are positive, then the country's carbon dioxide emissions will increase by 0.451 percent on average, which indicates that for a recipient country in the process of global manufacturing transferring, carbon dioxide emissions will be higher than before. For the southern-countries sample, the coefficient is also significantly positive, 0.416, which means that in the southern countries, if net exports of manufactures in a country are positive, the country's carbon dioxide emissions will increase by 0.416 percent. In comparing the regression coefficients of these two samples, the coefficient value of iManu in the sample of southern countries is smaller, which may imply that the global manufacturing transferring from northern to southern countries is possibly more probable and critical than the transferring within southern countries. Finally, for the variables lnrgdp, lnrgdp2, lndp, lnur, lnfd and rtfpna, we find that the values of coefficients are similar to those in Table 3-2 as well as the inflection point, which verifies the robustness of the regression results in Table 3-2.

To sum up, by introducing trade structure, we present the following arguments. First, countries with more net exports of agricultural products and net exports of manufactures generate more carbon dioxide emissions, whereas countries with more net exports of food or net exports of mineral and metal have less carbon dioxide emissions. Second, the manufacturing industry will increase a country's carbon dioxide emissions; therefore, a country as a recipient of global manufacturing transferring tends to create more carbon dioxide emissions domestically. Third, the global manufacturing transferring from northern to southern countries may be more possible and critical than the transferring within southern countries.

3.3 Economy and emission status of representative countries based on the "decoupling" theory

3.3.1 Selection of sample countries

According to the World Bank, we divide the world into East Asia and Pacific, South Asia, Europe and Central Asia, North America, Latin America and the Caribbean, the Middle East and North Africa and sub-Saharan Africa. We rank the countries in terms of population, GDP and per capita GDP, excluding East Asia. The first countries in each region are listed below.

Table 3-4 Countries in descending order (by population)

Country	Region	Ave_Popn
India	South Asia	1051.046
Ukraine	Europe & Central Asia	47.12812
Bolivia	Latin America & Caribbean	8.485366
Morocco	Middle East & North Africa	28.62927
Nigeria	Sub-Saharan Africa	128.5

Table 3-5 Countries in descending order (by GDP)

Country	Region	Ave_Gdpn
India	South Asia	965.2439
Ukraine	Europe & Central Asia	96.14286
Bolivia	Latin America & Caribbean	15.69444
Morocco	Middle East & North Africa	57.80488
Nigeria	Sub-Saharan Africa	230.45

Table 3-6 Countries in descending order (by per capita GDP)

Country	Region	Ave_Ypca
Mongolia	East Asia & Pacific	1968.097
Ukraine	Europe & Central Asia	2130.536
Bolivia	Latin America & Caribbean	1597.333
Tunisia	Middle East & North Africa	2568.39
Angola	Sub-Saharan Africa	2505.808

Table 3-7 List of representative countries

Country	Region
India	South Asia
Ukraine	Europe & Central Asia
Bolivia	Latin America & Caribbean
Morocco	Middle East & North Africa
Nigeria	Sub-Saharan Africa
Mongolia	East Asia & Pacific
Tunisia	Middle East & North Africa
Angola	Sub-Saharan Africa
Japan	East Asia & Pacific
Singapore	East Asia & Pacific
UK	Europe & Central Asia
Germany	Europe & Central Asia
Argentina	Latin America & Caribbean
Brazil	Latin America & Caribbean
US	North America
Australia	East Asia & Pacific
China	East Asia & Pacific
Seychelles	Sub-Saharan Africa

Given the overall development status of a region, we took out the developed countries in Europe and Central Asia as well as all countries in sub-Saharan Africa, except South Africa, in the above ordering and selection.

According to the World Bank, different countries can be classified into four categories by incomes: high income, medium and high income, medium and low income and low income. Other than the above countries representing different income categories, we also took into account the representativeness and data availability of the samples and we added certain developed countries for reference and comparison. The countries in Table 3-7 were selected as representative countries as a whole.

3.3.2 Decoupling elasticity coefficient based on two adjacent years

For these representative countries, we calculate their decoupling elasticity coefficients defined by Equation (2) of each year from 2008 to 2018, as seen in the table below.

Table 3-8 Decoupling elasticity coefficients of representative countries

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Angola	1.00	-1.10	0.83	0.32	0.09	1.24	1.29	4.86	-1.63	-2.91	
Argentina	0.83	32.18	0.19	0.30	0.77	-0.23	-5.08	0.39	-0.76	0.00	16.20
Australia	0.15	0.26	-0.30	-0.08	-0.25	-0.11	-0.91	19.82	0.62	-0.14	0.16
Bolivia	0.99	1.49	1.61	1.57	1.60	0.09	1.05	0.05	1.89	0.42	0.45
Brazil	0.69	-10.22	1.50	0.75	1.91	1.34	2.04	2.07	2.93	0.69	-0.35
China	0.19	0.69	0.82	0.84	0.21	0.45	0.11	-0.02	0.20	0.15	0.20
Germany	0.30	2.63	1.11	-0.45	0.65	0.55	-0.98	0.40	0.10	-0.05	-1.93
India	1.12	1.47	0.53	0.72	0.99	0.23	1.01	0.34	0.40	0.34	0.79
Japan	-7.36	1.20	0.83	2.13	0.83	0.40	-7.60	-1.20	-0.40	0.01	-0.97
Mongolia	-0.04		0.89	0.41	0.72	0.51	-0.17	-1.52	0.54	0.53	0.62
Morocco	0.77	-0.04	1.25	1.13	0.82	-0.10	0.56	0.58	1.56	0.74	0.54
Nigeria	0.57	-0.90	1.75	0.77	0.70	-0.15	-0.59	0.86	-12.96	1.46	0.69
Singapore	0.16	2.75	0.57	0.62	-0.16	0.15	-0.43	-0.43	0.52	1.04	0.13
South Africa	1.24	7.51	0.53	-0.77	0.83	0.58	0.63	-0.61	0.82	-0.64	0.31
Tunisia	0.35	0.01	1.97		0.99	-0.13	1.15	1.09	-0.09	1.93	0.67
Ukraine	-0.93	1.20	1.42	0.71	-1.26	-2.29	2.97	2.19	1.34	-2.94	0.12
United Kingdom	-0.70	2.53	0.77	-2.58	1.33	-0.64	-2.07	-1.02	-1.74	-0.57	-0.99
United States	-1.77	4.04	1.20	-0.64	-0.79	0.38	0.31	-0.76	-0.46	-0.15	0.53

By the categorization of our Table 2-1, the economy and emission status of each country in each year is as seen in the table below.

Table 3-9 Economy and emission status dynamics of representative countries

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Angola	2	6	2	2	2	3	3	3	6	1	
Argentina	2	4	2	2	2	1	6	2	6		4
Australia	2	2	1	1	1	1	1	3	2	1	2
Bolivia	2	3	3	3	3	2	3	2	3	2	2
Brazil	2	1	3	2	3	3	3	4	4	2	1
China	2	2	2	2	2	2	2	1	2	2	2

Germany	2	4	3	1	2	2	1	2	2	1	1
India	3	3	2	2	2	2	3	2	2	2	2
Japan	1	4	2	3	2	2	1	1	1	2	1
Mongolia	1		2	2	2	2	1	1	2	2	2
Morocco	2	1	3	3	2	1	2	2	3	2	2
Nigeria	2	1	3	2	2	1	1	2	6	3	2
Singapore	2	3	2	2	1	2	1	1	2	3	2
South Africa	3	4	2	1	2	2	2	1	2	1	2
Tunisia	2	2	3		2	1	3	3	1	3	2
Ukraine	1	4	3	2	1	1	4	4	3	1	2
United Kingdom	1	4	2	1	3	1	1	1	1	1	1
United States	1	4	3	1	1	2	2	1	1	1	2

The numbers 1–6 in Table 3-10 correspond to the six economy and emission statuses defined in Table 2-1, as seen below.

Table 3-10 Mapping from numbers to economy and emission statuses

Number	Name of status
1	Sustainable absolute decoupling
2	Mild coupling
3	Pollutive coupling
4	Recessionary coupling
5	Pollutive recessionary coupling
6	Pollutive decoupling

From the above and the definitions in Table 2-1, we see that Status 1 is most desirable, whereas Status 6 represents the worst case (the economy in recession while emissions deteriorate). For all numbers (including the intermediate numbers), less is better.

Because the decoupling elasticity coefficient attempts to evaluate the countries comprehensively in terms of the dynamic movements of economic development and carbon emissions, with reference to the figures in each row in Table 3-9, we could trace the development track of each country. We could also see that different countries deliver different performances from the results in Table 3-9.

Angola mainly fell in “mild coupling” and “pollutive coupling,” which was inseparable from its high-speed economic growth. Meanwhile, it also revealed that its economic growth was accompanied by elevated pollution intensity.

Argentina fluctuated between “mild coupling” and “pollutive coupling.” On the one hand, its carbon emission intensity remained at a high level; on the other hand, its economic growth fluctuated greatly.

Australia was moving steadily from “mild coupling” to “sustainable absolute decoupling,” which reflected that its economic growth and environmental protection correlated with each other.

Bolivia mainly fell in “mild coupling” and “pollutive coupling,” and its economic growth was accompanied by elevated pollution intensity.

Brazil mainly fell in “mild coupling,” “pollutive coupling” and “recessionary coupling.” As a developing country, its carbon emissions remained at a high level yet was also closely related to economic prosperity.

China mainly fell in “mild coupling,” with a gradually decreasing decoupling elasticity coefficient. This implied that although China’s economic growth still polluted the environment, the situation was improving gradually.

Germany has been moving gradually from “mild coupling” to “sustainable absolute decoupling,” indicating that during economic growth, it paid equal attention to environmental protection.

Japan has been moving gradually from “mild coupling” to “sustainable absolute decoupling,” which reflected that its economic growth and environmental protection are effective.

Mongolia mainly fell in “middle coupling” in recent years and its decoupling elasticity coefficient tended to become negative, which indicated that its economic development and environmental protection were improving gradually.

Morocco mainly fell in “mild coupling,” which illustrated that its economic development was at the cost of environmental pollution.

Nigeria fell in “mild coupling,” “pollutive coupling” and “pollutive decoupling.” Like many other developing countries, it had an unstable relationship between economic growth and environmental protection.

Singapore was gradually moving from “mild coupling” to “sustainable absolute decoupling,” which showed that its economic growth and environmental protection were effective.

South Africa fell in “mild coupling,” “pollutive coupling,” “recessionary coupling” and “pollutive decoupling.” It was still at a relatively primary stage in terms of economic development and environmental protection and their relationship was unstable.

Tunisia mainly fell in “mild coupling,” and there was no evidence showing a decoupling elasticity coefficient downtrend, indicating that plenty of room for environmental control.

Ukraine fell in "sustainable absolute coupling," "mild coupling," "pollutive coupling," "recessionary coupling" and "pollutive decoupling." Due to well-known reasons, Ukraine had volatile economic growth and thus great potential for environmental protection.

The United Kingdom was mainly transforming to "sustainable absolute coupling" and showing a relatively harmonious relationship between economic growth and environmental protection.

Like the United Kingdom, the United States was also transforming into "sustainable absolute coupling," but the downward trend of the decoupling elasticity coefficient was relatively flat.

3.3.3 Decoupling the elasticity coefficient based on five-year rolling window average

As per equation (2), the decoupling elasticity coefficient is closely related to two factors: the percentage of change in carbon emission intensity and the percentage of economic growth. Due to some well-known reasons, the fluctuation of economic growth is relatively significant and, thus, the results calculated with equation (2) always show great volatility. To stabilize this volatility, we will calculate with the following formula:

$$e_{it} = \frac{\left(\overline{CO2_{it}} - \overline{CO2_{it-1}}/\overline{CO2_{it-1}}\right)}{\left(\overline{Y_{it}} - \overline{Y_{it-1}}\right)/\overline{Y_{it-1}}} = \frac{\Delta\overline{CO2}/\overline{CO2}}{\Delta\overline{Y}/\overline{Y}} \tag{4}$$

where, $\overline{CO2_{it}}$ refers to the average carbon emission intensity for the past five years, $\overline{Y_{it}}$ is the average GDP for the past five years, i is country or region and t is year. In other words, the above formula attempts to calculate the decoupling elasticity coefficient using the average value of five years to stabilize temporary fluctuations and obtain tendency results.

Using the above formula, we can obtain decoupling elasticity coefficients as in Table 3-11, Compared with Table 3-8, the volatility is significantly reduced. At the same time, we get the economy and emission status after stabilizing the fluctuation, as in Table 3-12.Refer to Table 3-10 for the definition of numbers. Both Table 3-11 and Table 3-12 showed significantly reduced volatility in terms of the decoupling elasticity coefficient and economy emission status. The trend of each country are generated as shown below.

Angola mainly fell in "mild coupling" and "pollutive coupling," but its decoupling elasticity coefficient did not show stable descending.

Argentina fell in "mild coupling" with a stable descending decoupling elasticity coefficient.

Australia was moving steadily from "mild coupling" to "sustainable absolute decoupling," which indicated that its economic growth and environmental protection compensated each other.

Bolivia mainly fell in "mild decoupling" and "pollutive coupling," with a gradually descending decoupling elasticity coefficient, reflecting a balanced relationship between economic development and environmental protection.

Brazil mainly fell in "mild coupling," "pollutive coupling" and "recessionary coupling." As a developing country, its carbon emissions remained at a high level, yet this was also closely related to economic prosperity.

China mainly fell in "mild coupling," with a gradually decreasing decoupling elasticity coefficient. This implied that although China's economic growth still polluted the environment, its situation was improving gradually.

Germany has been gradually moving from "mild coupling" to "sustainable absolute decoupling" this year, with a significantly descending decoupling elasticity coefficient, which reflects that the environment has been greatly improved during economic growth.

Japan has been gradually moving from "mild coupling" to "sustainable absolute decoupling" this year, with an unstable decoupling elasticity coefficient, which might be caused by its volatile economic growth during recent years.

Mongolia mainly fell in "mild coupling" in recent years and its decoupling elasticity coefficient tended to be negative, which indicated that its economic development and environmental protection were improving gradually.

Morocco mainly fell in "mild coupling" with an insignificantly decreasing decoupling elasticity coefficient, which illustrated that its economic development was at the cost of environmental pollution.

Nigeria fell in "mild coupling," "pollutive coupling," and "pollutive decoupling" with a gradually rising decoupling elasticity coefficient, which indicated that its economic growth was at the expense of the environment.

Singapore was gradually moving from "mild coupling" to "sustainable absolute decoupling," which showed that its economic growth and environmental protection were effective.

South Africa mainly fell in "mild coupling," with a recessionary decoupling elasticity coefficient, indicating that from the view of the long-term tendency, its economic development and environmental protection achieved balance.

Tunisia mainly fell in "mild coupling," with an uptrend decoupling elasticity coefficient, indicating that there was still plenty of room for environmental control.

Ukraine fell in "sustainable absolute coupling," "recessionary coupling" and "pollutive coupling." Due to well-known reasons, Ukraine had volatile economic growth and thus great potential for environmental protection.

The United Kingdom mainly fell in "sustainable absolute coupling," showing a relatively harmonious relationship between economic growth and environmental protection.

Like the United Kingdom, the United States also fell in "sustainable absolute coupling," with a relatively flat and small decoupling elasticity coefficient compared to the United Kingdom.

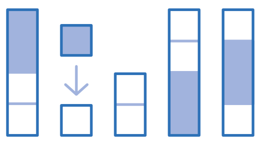
Table 3-11 Decoupling elasticity coefficients of representative countries (Five-year rolling window average)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Angola	0.17	0.45	1.02	1.05	0.88	0.94	0.69	0.91	1.34	1.54	1.02
Argentina	0.60	0.36	0.35	0.27	0.28	0.07	0.33	0.39	0.55	0.31	0.67
Australia	0.31	0.25	0.19	0.11	0.00	-0.06	-0.22	-0.13	0.06	0.03	0.13
Bolivia	0.97	1.02	1.22	1.34	1.44	1.07	1.02	0.78	0.86	0.64	0.75
Brazil	0.39	0.13	0.50	0.64	0.89	1.04	1.40	1.21	0.97	0.23	-1.27
China	0.66	0.60	0.61	0.63	0.55	0.59	0.48	0.33	0.20	0.18	0.12
Germany	-0.21	-0.68	-0.13	-0.39	-0.16	-0.09	0.06	-0.18	0.00	-0.08	-0.43
India	0.71	0.85	0.85	0.87	0.92	0.74	0.70	0.64	0.57	0.46	0.57
Japan	-0.24	-1.10	-0.63	-0.10	-0.12	0.72	0.64	0.17	-0.18	-0.48	-1.05
Mongolia	0.58	0.78	0.73	0.45	0.59	0.62	0.43	0.31	0.27	0.19	0.18
Morocco	0.66	0.43	0.47	0.70	0.81	0.59	0.69	0.59	0.54	0.54	0.70
Nigeria	-0.35	-0.47	-0.22	0.12	0.41	0.24	0.42	0.18	0.32	0.38	0.69
Singapore	0.16	0.16	0.41	0.51	0.45	0.42	0.25	0.02	-0.09	0.17	0.17
South Africa	0.58	0.25	0.28	0.08	0.06	-0.16	0.30	0.14	0.51	0.15	0.06
Tunisia	0.42	0.33	0.57	0.40	0.57	0.44	0.69	0.44	0.63	0.75	0.97
Ukraine	-0.21	-1.49	-1.01	-0.78	-3.83	-15.97	-0.71	11.85	5.39	9.44	55.35
United Kingdom	-0.20	-1.10	-0.75	-1.75	-1.12	-1.03	-0.54	-0.94	-0.79	-1.15	-1.31
United States	-0.08	-0.65	-0.49	-0.61	-1.03	-0.56	0.07	-0.31	-0.26	-0.12	-0.04

Table 3-12 Economy and emission status dynamics of representative countries (Five-year rolling window average)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Angola	2	2	3	3	2	2	2	2	3	3	3
Argentina	2	2	2	2	2	2	2	2	2	2	2
Australia	2	2	2	2	2	1	1	1	2	2	2
Bolivia	2	3	3	3	3	3	3	2	2	2	2
Brazil	2	2	2	2	2	3	3	3	2	2	1
China	2	2	2	2	2	2	2	2	2	2	2
Germany	1	1	1	1	1	1	2	1	2	1	1
India	2	2	2	2	2	2	2	2	2	2	2
Japan	1	1	1	1	1	2	2	2	1	1	1
Mongolia	2	2	2	2	2	2	2	2	2	2	2
Morocco	2	2	2	2	2	2	2	2	2	2	2
Nigeria	1	1	1	2	2	2	2	2	2	2	2
Singapore	2	2	2	2	2	2	2	2	1	2	2
South Africa	2	2	2	2	2	1	2	2	2	2	2
Tunisia	2	2	2	2	2	2	2	2	2	2	2
Ukraine	1	1	1	1	1	1	1	4	4	4	4
United Kingdom	1	1	1	1	1	1	1	1	1	1	1
United States	1	1	1	1	1	1	2	1	1	1	1

4. Analytical model, simulation and projection



Numerical simulation methods provide a scientific decision-making basis for environmental and sustainable development for countries engaged in South-South cooperation.

We have recovered a global EKC by a cross-country panel-data regression based on existing data collected by our team. Also, in academia, scholars have used quantitative regression analysis and decomposition analysis methods in empirical papers to estimate the effects of various influencing factors on pollution and emissions. However, relatively little research combines the results of empirical data analysis with theoretical models, especially dynamic macroeconomic models with a microscopic optimization basis (collectively referred to as the structural models). In what follows, we will focus on the turning point prediction model of the EKC, which is beneficial to exploring the dynamic relationship between economic development stage and environmental quality, supplementing and enriching the relevant research on empirical and structural models. Besides, numerical simulation methods in the environmental field provide a practical study with a theoretical basis of the relationship between economic development and environmental pollution in southern countries. In practice, based on sustainable development challenges alongside economic development, this can help governments and enterprises understand the stage difference of the relationship between economic development and environmental pollution in the countries involved in South-South cooperation. It is of great practical significance to provide a scientific decision-making basis for environmental and sustainable development for countries engaged in South-South cooperation.

We start with a theoretical and analytical model. We employ the Green Solow model which was proposed by Brock and Taylor (2010) and closely combines theoretical interpretation with patterns emerging from actual data. As a newer theoretical development, the Green Solow model can provide an explanation of the relevant principles and mechanisms of EKC and has the potential to be used to predict the inflection point of EKC. To the best of our knowledge, we are the first to predict the inflection point of the EKC based on the principle of the Green Solow model by supplementing the microscopic basis of the model and analyzing the numerical simulation.

Our steps are described below.

1. Establish a micro-optimization foundation based on the Green Solow model. In terms of methods, Brock and Taylor (2010) proposed to add a micro-optimization basis into the framework of Green Solow's neoclassical growth model and solved the dynamic optimal condition system in the model by using the Bellman equation.

2. The inflection point of the EKC should be predicted by means of the calibration of the parameters in the model. The main idea of *calibration* is to find a combination of a set of parameters that can make the numerical simulation output of the model in a steady state consistent with the relevant actual data characteristics of the target country of the calibration. In the process of our calibration, we collected relevant macro data variables for target countries. The main data include: (i) the proportion of national labour income in total output; (ii) the total capital stock data in different years; (iii) the capital depreciation rate data; (iv) the pollution emission reduction expenditure; and (v) other relevant data.

3. Substitute calibrated parameters into the computer for numerical simulation analysis, i.e., the dynamic optimal system is substituted into the computer and the numerical simulation analysis is carried out with MATLAB programming language and the Dynare dynamic optimization model.

We will calculate and scientifically predict the turning point of the EKC for each representative country in Table 3-7, most of which are countries that practice South-South cooperation.

4.1 Model setup

The model setup mainly includes the following points to establish the micro-optimization foundation based on the Green Solow model: 1) set up a profit maximization model of representative enterprises and consider the pollution emission in the production process of enterprises; 2) set up a representative household model to maximize lifetime utility and optimize the selection of pollution emission reduction costs; and 3) establish a dynamic equilibrium model with an analytical condition system of those equilibria.

We set up a neoclassical growth model with emissions and an optimal micro basis to simulate an economy.

4.1.1 Representative enterprise and emissions

A representative enterprise is set to conduct production activities as per the following Cobb–Douglas production function in the economy:

$$Y_t = (K_t)^{1-\alpha}(Z_t L_t)^{\alpha} \tag{5}$$

where Z_t represents labour technology level in year t and Y_t represents output (GDP) in year t. Representative enterprises choose capital K_t and labour force L_t as input factors and parameter α measures the proportion of labour income in the total income.

Representative enterprises sell their products in competitive markets and pursue profit maximization and, thus, we need to solve the following profit maximization problems:

$$max\ \pi_t = Y_t - w_t L_t - r_t K_t \tag{6}$$

Based on the study of Copeland and Taylor (1994), it is assumed that each unit of output is accompanied by Ω_t units of emissions. Therefore, $\Omega_t Y_t$ represents the total emission level at the output of Y_t.

In what follows, g_z is defined as the average annual progress rate of labour technology level and g_ω is defined as the annual average progress rate of emission reduction technology level:

$$Z_{t+1} = Z_t(1 + g_z) \tag{7}$$

$$\Omega_{t+1} = \frac{\Omega_t}{1 + g_\omega} \tag{8}$$

4.1.2 Households and emission reduction

Correspondingly, this study sets a representative household in the model economy, whose goal was to maximize lifetime utility:

$$max\sum_{t=0}^{\infty}\beta^{t}U(C_t,E_t) \tag{9}$$

where β represents subjective time preference and C_t represents consumption in period t. The utility function $U(C_t,E_t)$ rises with C_t and declined with net emission E_t. Based on Michel and Rotillon (1995), the form of utility function is set as follows:

$$U(C_t,E_t)=log(C_t)-E_t \tag{10}$$

s.t.

$$C_t+A_t+K_{t+1}=(1-\delta)K_t+r_tK_t+w_t\bar{n} \tag{11}$$

Equation (10) represents the budget constraint of representative households, where A_t represents expenditure on emission control, w_t represents wage level, r_t is return on rental capital goods and $\bar{n}$ is labour supply. The stock of capital goods K_t is determined in period $t-1$ and put into production in period t and parameter δ represents capital depreciation rate. Based on the above discussion, the final total net emission E_t equals the difference between total emission Ω_tY_t and emission control amount $a(A_t)$:

$$E_t=\Omega_tY_t-a(A_t) \tag{12}$$

where the emission control amount $a(A_t)$ is a function of emission control expenditure $A_t : a(A_t) = \varepsilon log(A_t), \varepsilon>0$. As per Brock and Taylor (2005), for function a, this study assumed that the emission control amount rose with emission control expenditure, and we calculated the first derivative as $a'>0$. At the same time, the marginal effect of emission control expenditure A_t on the emission control amount decreased and, thus, the second derivative was calculated as $a''<0$. Generally speaking, this study set the specific functional forms according to those widely recognized in the literature on the basis of data and economic intuition.

4.1.3 Model solution and equilibrium

By solving the optimization problem of representative households, the following Euler equation (13) and optimal emission control expenditure are obtained as below:

$$\frac{1}{C_t}=\frac{1}{C_{t+1}}\beta(1-\delta+r_t+1) \tag{13}$$

$$\varepsilon C_t=A_t \tag{14}$$

By solving the profit maximization problem of representative enterprises, two first-order conditions are obtained as below:

$$r_t = (1-a)\left(\frac{K_t}{Z_t L_t}\right)^{1-\alpha} \tag{15}$$

$$W_t = Z_t \alpha \left(\frac{K_t}{Z_t L_t}\right)^{1-\alpha} \tag{16}$$

Generally speaking, the dynamic general equilibrium of a competitive market is constituted of a series of resource allocation combination C_t, A_t, K_t and price combination $\{w_t, r_t\}$ and it is required to satisfy two conditions:

(i) when prices are given, the resource allocation combination can satisfy and solve the optimization problems of representative households and representative enterprises in equations (6) and (9); and

(ii) all markets clear.

First, labour market clearing means:

$$L_t = \bar{n} \tag{17}$$

Second, the conditions for product market clearing can be deduced from equations (11), (15) and (16):

$$C_t + A_t + K_{t+1} = (1-\delta)K_t + Y_t \tag{18}$$

Given that the model has a growth trend, to solve the model with a numerical method, this study has to stabilize it using certain technical means. To do so, first, this study defined the corresponding lowercase letter x_t of any variable X_t (X_t can be replaced with $C_t, K_t, A_t, or\ Y_t$) as $x_t = \frac{X_t}{Z_t}$. Based on equations (5), (13), (14), (16) and (18), the dynamic general equilibrium of a competitive market can be determined as follows:

$$y_t = {k_t}^{1-\alpha} \tag{19a}$$

$$c_{t+1}(1+g_z) = c_t\beta[1-\delta+(1-a)k_{t+1}-\alpha] \tag{19b}$$

$$\varepsilon c_t = a_t \tag{19c}$$

$$c_t + a_t + (1+g_z)k_{t+1} = (1-\delta)k_t + y_t \tag{19d}$$

4.1.4 Calibration of model parameters

Table 4-1 Parameter calibration (annual value)

Subjective time preference	β	0.98
Capital depreciation	δ	0.1
Labour income ratio	α	to be estimated[2]
Emission control parameters	ε	0.028
Average annual progress rate of labour technical level	g_z	to be estimated
Labour supply	$\overline{n}$	1
Initial value of labour technology level	Z_0	1
Initial value of emission reduction technology level	Ω_0	100
Initial value of per capita capital stock	K_0	to be estimated

In view of the commonly used parameter values in the mainstream literature and the estimation on China's capital depreciation rate by Bai et al. (2006), this study set the subjective time preference β at 0.98 and the capital depreciation rate δ at 0.1. Meanwhile, this study set the emission control parameter ε at 0.028. The corresponding average proportion of environmental protection expenditure in GDP from 2000–2015 is 1.4 percent, which is consistent with China's data. Considering data availability, we set the emission control parameter at 0.028 for developing countries and 0.04 for developed countries using the same theory. Last, this study set the initial value of the labour technology level and labour supply standardization at 1 and the initial value of emission reduction technology at 100.

The specific calibration method for labour income proportion is to select the labour income proportion of the corresponding countries from Penn World Table 9.1 and calculate the average value. The calibration method for the average annual progress rate of labour technology level is to calculate the average TFP value of each country. The carbon dioxide emission reduction technical progress parameter g_ω is the average compound interest of CO_2 emission reduction intensity per unit GDP in the past 20 years. When calibrating the initial value of per capita stock K_0 , we chose 1997 as the base year of our model calibration and divided the per capita capital stock of the corresponding countries in 2017 by per capita capital stock in 1997:

$$k_{ratio} = \frac{capital\ stock\ 2017\ in\ real\ world}{capital\ stock\ 1997\ in\ real\ world} \tag{20}$$

2 See below for a detailed parameter calibration method.

Then, we selected the appropriate K_0 so that the ratio of the per capita capital stock of period 20 to period 0 is K_{ratio}:

$$\frac{K_{20}\ in\ simulation}{K_0\ in\ simulation} = K_{ratio} \tag{21}$$

The calibration results for all representative countries are as seen in the table below.

Table 4-2 Calibrated parameters (all representative countries)

Country	TFP	g_ω	Labour share	K_0 in simulation
Ukraine	0.0024	0.0337	0.5407	11.9222
India	0.0274	0.0090	0.6687	0.3326
Nigeria	0.0204	0.0267	0.3049	2.7908
Bolivia	0.0049	-0.0039	0.5240	1.9134
Morocco	0.0157	-0.0015	0.5038	3.6302
Mongolia	0.0084	0.0311	0.4048	3.0621
Tunisia	0.0138	0.0074	0.5320	3.3388
Angola	0.0083	0.0058	0.2869	27.1925
Japan	0.0062	0.0080	0.5817	5.4509
Singapore	0.0235	0.0365	0.4290	2.2200
United Kingdom	0.0060	0.0363	0.5646	3.0358
Germany	0.0051	0.0260	0.6566	2.1744
Argentina	0.0056	0.0051	0.4343	14.2538
Brazil	0.0001	-0.0045	0.5267	2.5534
United States	0.0111	0.0231	0.6199	2.8446
Australia	0.0064	0.0156	0.6411	1.7711
China	0.0400	0.0410	0.5000	1.0002
South Africa	0.0006	0.0003	0.5831	1.8775

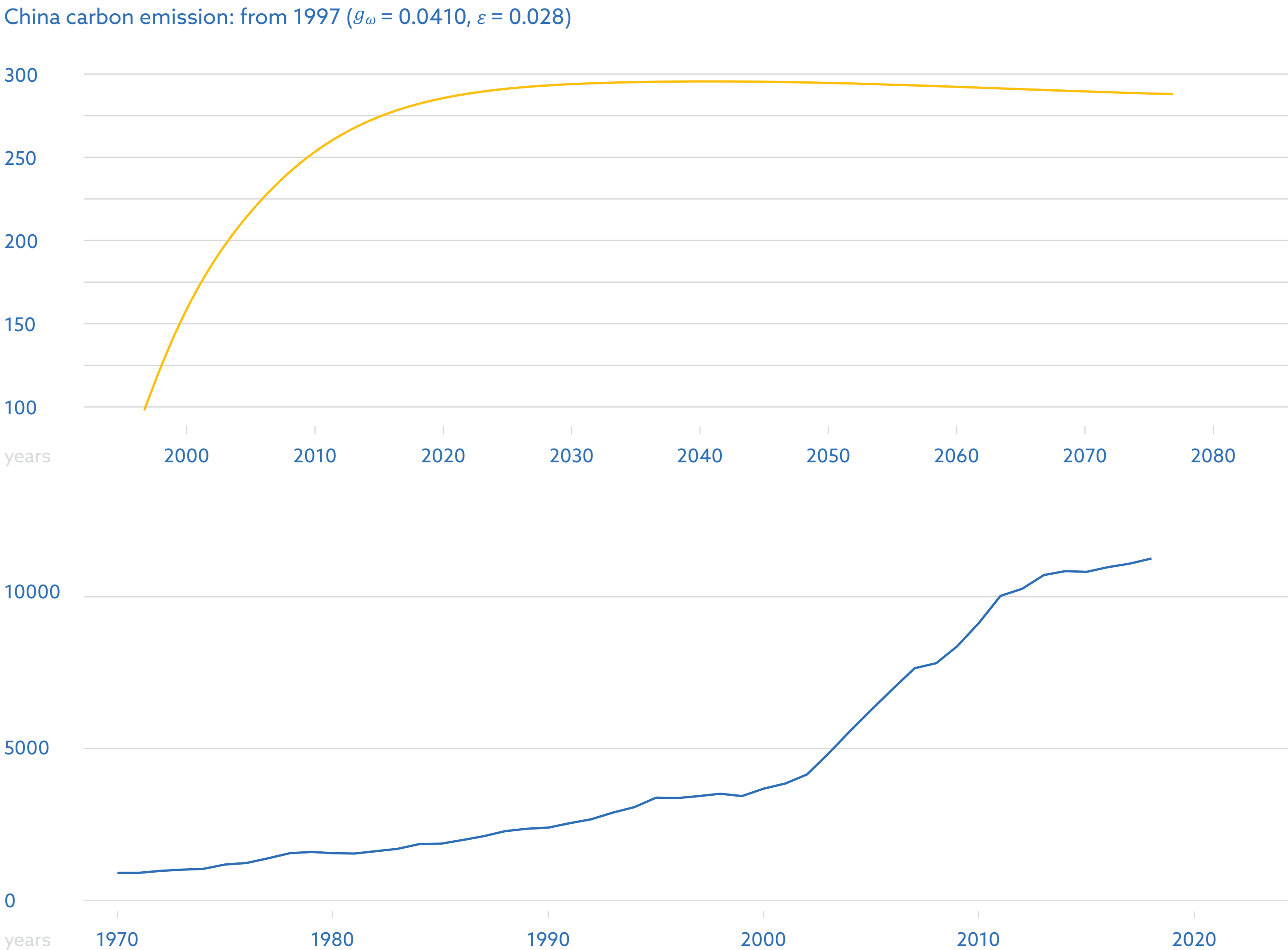
4.2 Numerical simulation results of representative countries

We took the 1997 value of each representative country as the initial value and extrapolated forward until 2077 (80 years). Meanwhile, we also recorded the actual carbon emission of each country from 1970 to 2018 in a graph. It is obvious that the two graphs (forecast and reality) match well for many countries from 1997 to 2017, proving the credibility of our model.

Based on the carbon emission curve derived from the numerical simulation, we can classify the countries into the following categories: 1) the carbon emission inflection point has not shown yet will in the future; 2) the carbon emission inflection point has shown and will further descend in the future; and 3) the carbon emission inflection point has not shown and is not expected to show in the future given the current trend.

For the first category of countries, the carbon emission inflection point is to show soon (using China as an example).

Figure 4-1 China's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)



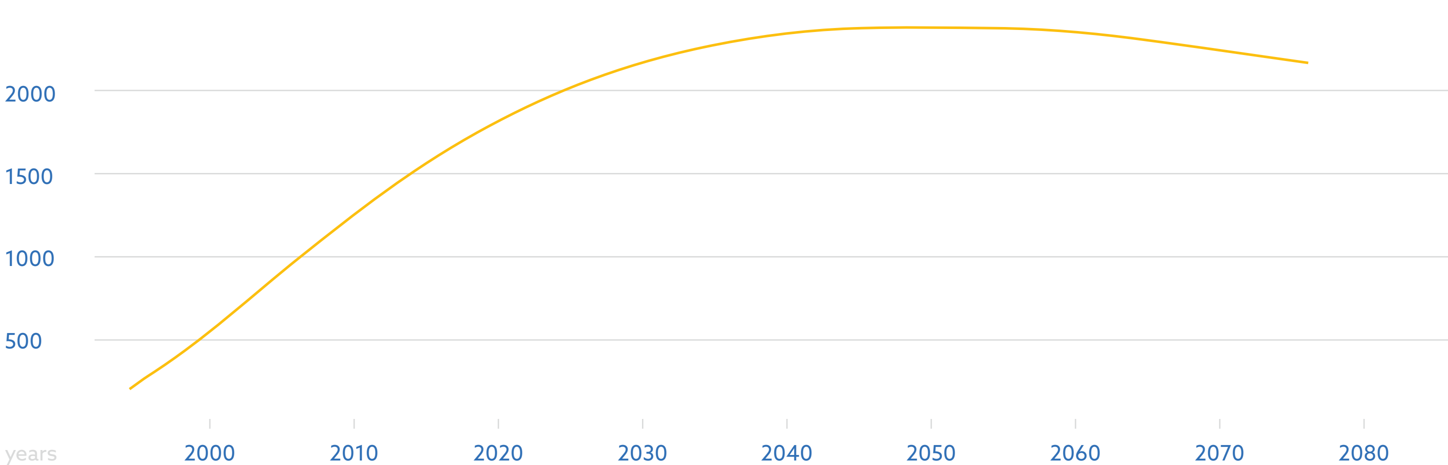
It can be seen that the dynamic process of carbon dioxide emissions during China's economic development is obtained by numerical simulation (Figure 4-1). With the economic development and income growth, the carbon dioxide emissions present an inverted U-shaped dynamic (i.e., the EKC), rising and then descending. According to the theory of the neoclassical growth model, in the early stage of economic development, the marginal return of capital is higher, and the speed of economic growth is faster. Correspondingly, the emissions also increase faster. When the technical progress of environmental control and emission reduction cannot catch up with the rapid growth in the early stage of economic development, the emission level will increase with the income increase. However, as time goes on, with technical progress and capital accumulation, the economic growth will slow down relatively and enter into a comparatively stable stage. The speed of technical progress in environmental control and emission reduction will be more than enough to offset the emission increase brought by economic growth. Thus, we can see that the carbon dioxide emission level declines with further economic development. The above discussion is overall consistent with the mainstream interpretation of the inverted U-shaped relationship between emissions and economic development in the relevant literature concerning the EKC. From a qualitative point of view, the model determination and numerical simulation results basically match the interpretation of the EKC in the literature.

The countries that have not shown a carbon emission inflection point yet will in the future demonstrate the following features: 1) in the early stage of economic development, the emission reduction technology is not advanced enough to offset the rapid emission growth driven by high-speed economic growth; 2) when the economic development level gradually rises until a stabilized state, between the average annual improvement of the labour technology level and emission reduction technology level, the emission reduction effect brought by the emission reduction technology level will be greater than the emission increase effect brought by economic growth, driving overall emission reduction; and 3) in the late stage of economic development, environmental protection expenditure should be high enough to achieve the goal of reducing carbon emissions.

Countries in the same category as China include these below.

Figure 4-2 Nigeria's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Nigeria carbon emission: from 1997 (g_ω = 0.0267, ε = 0.028)



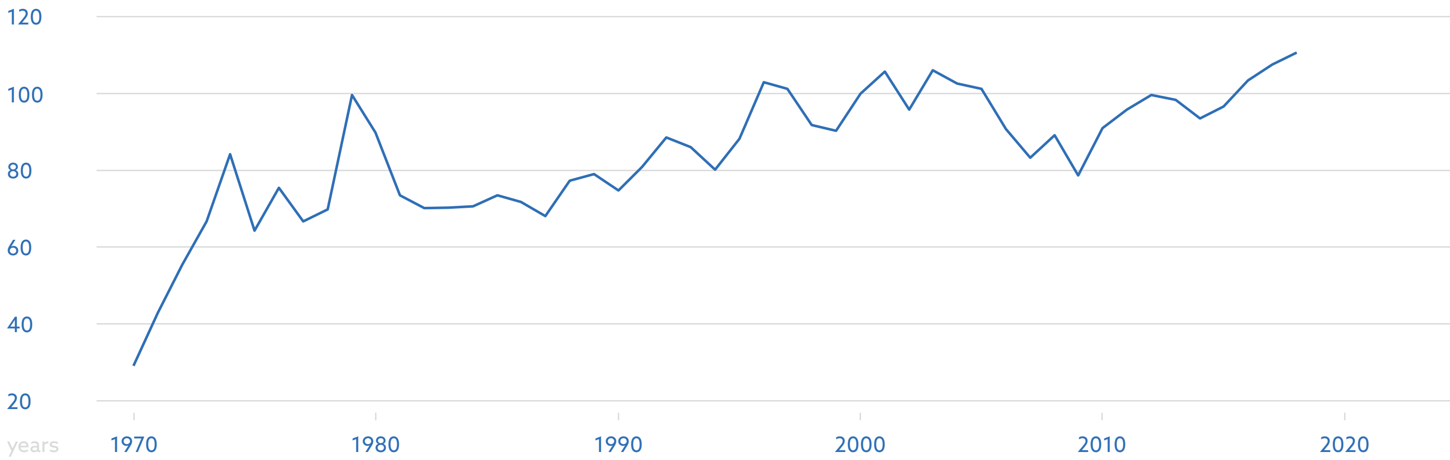
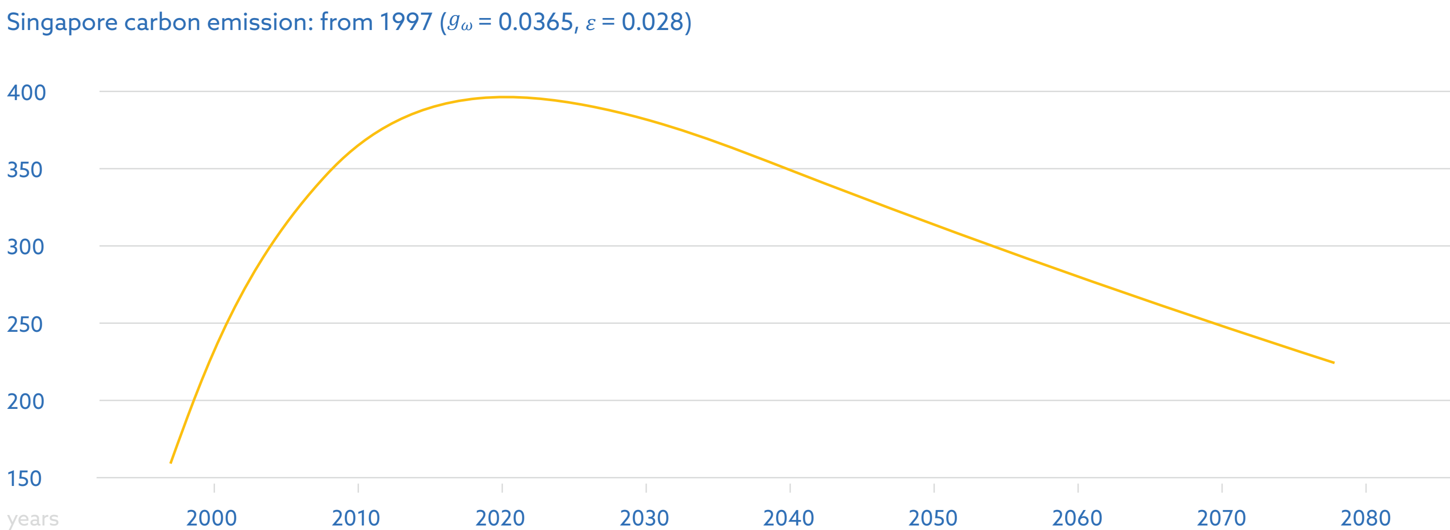
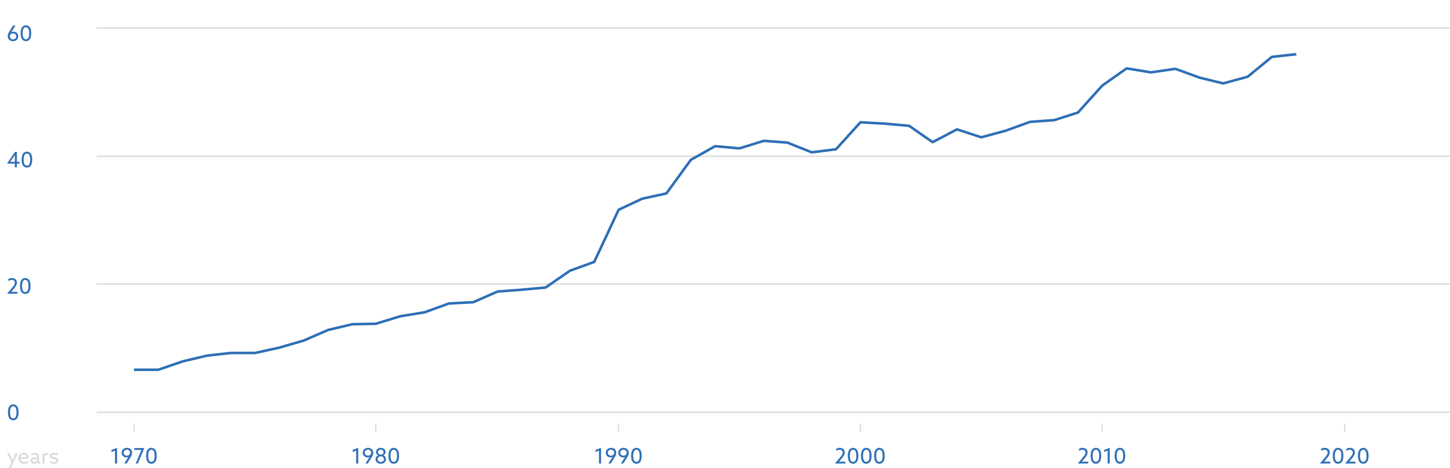


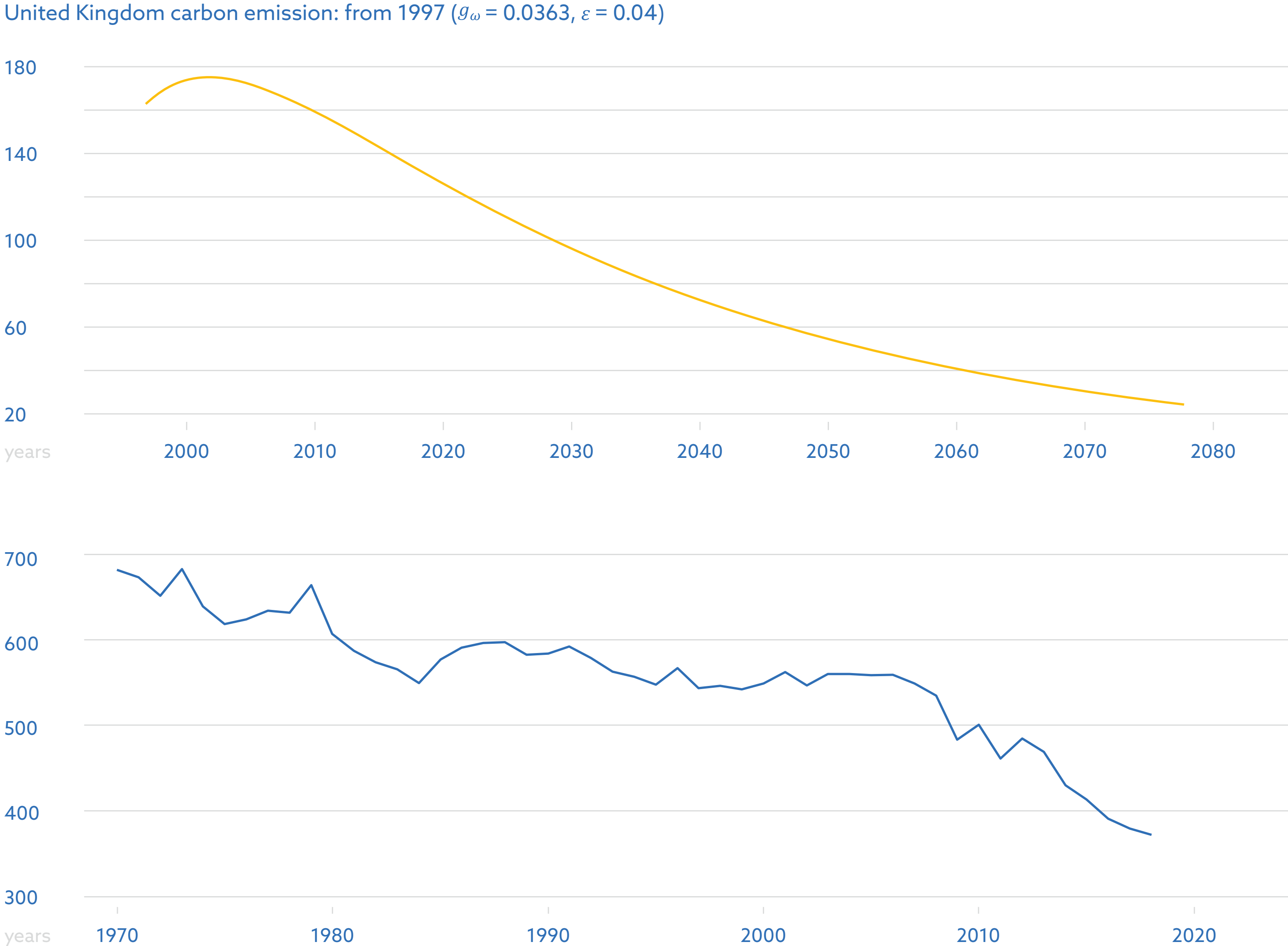
Figure 4-3 Singapore's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)





For the second category of countries, the carbon emission inflection point has already shown and will further descend in the future (take the United Kingdom, as an example).

Figure 4-4 The United Kingdom's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)



It can be seen that the dynamic process of carbon dioxide emissions during the United Kingdom's economic development is obtained by numerical simulation (Figure 4). With the economic development and income growth, the carbon dioxide emissions present an inverted U-shaped dynamic (i.e., the EKC), showing rising and then descending. Unlike the first category of countries, these countries have already shown the carbon emission inflection point, which is expected to further descend based on our simulation. According to the theory of the neoclassical growth model, in the middle and late stages of economic development, further capital accumulation will generate a decreasing margin and economic growth will slow down relatively and enter into a comparatively stable stage. The speed of technical progress in environmental control and emission reduction will be more than enough to offset the emission increase brought by economic growth; therefore, we can see that the carbon dioxide emission level shows a downtrend with further economic development.

The countries that have not shown a carbon emission inflection point demonstrate the following features: 1) the economic growth rate of these countries is not high compared with emerging economies, which means that the carbon emission growth driven by economic development is not high; 2) the carbon emission reduction caused by environmental control expenditure and emission reduction technology progress has become the main driving force to promote the emission reduction technology progress; and 3) these countries are mainly developed countries or countries with stagnant economies.

Countries in the same category as the United Kingdom include these below.

Figure 4-5 Australia's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

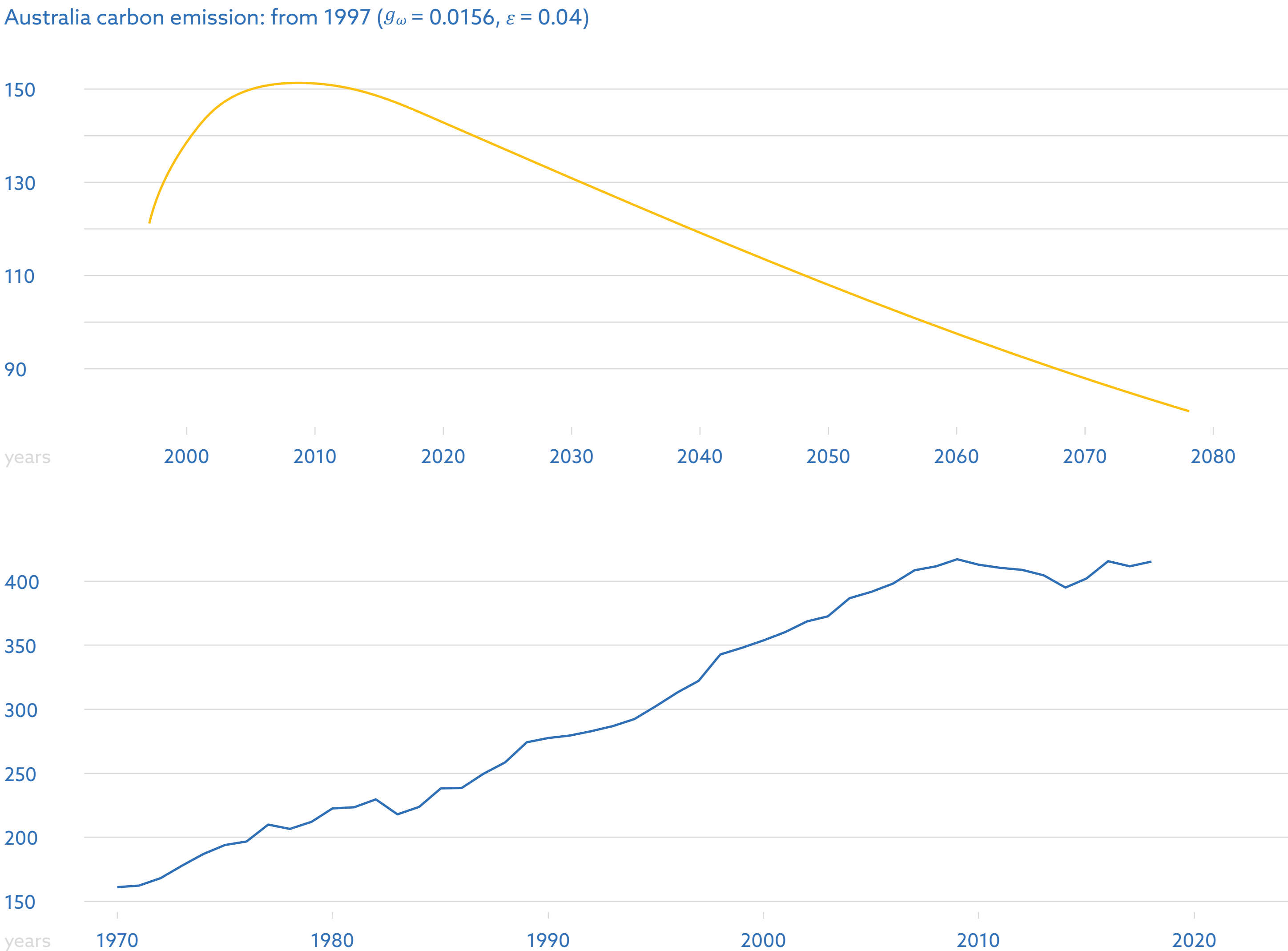


Figure 4-6 Germany's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Germany carbon emission: from 1997 ($g_\omega = 0.0260$, $\varepsilon = 0.04$)

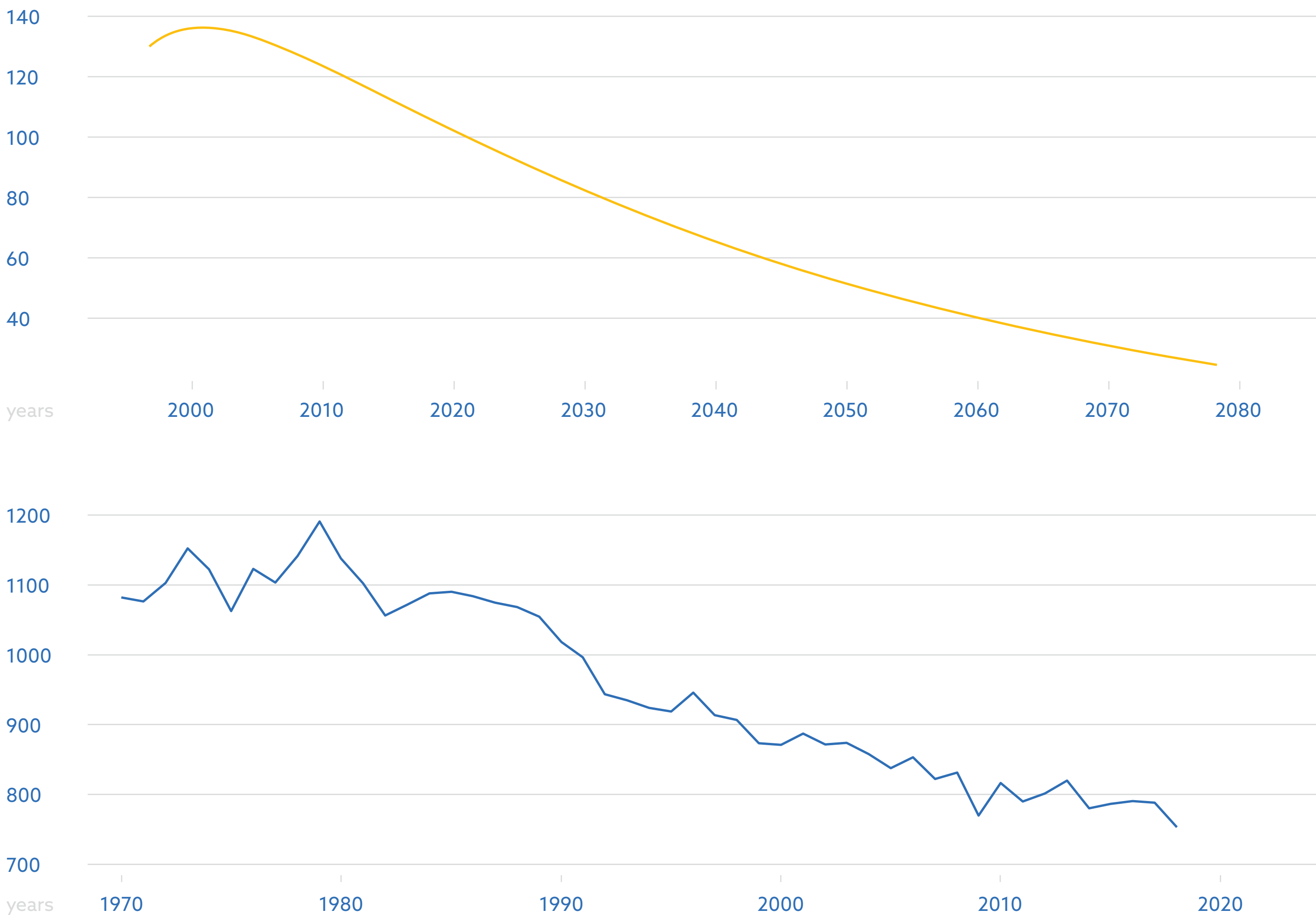
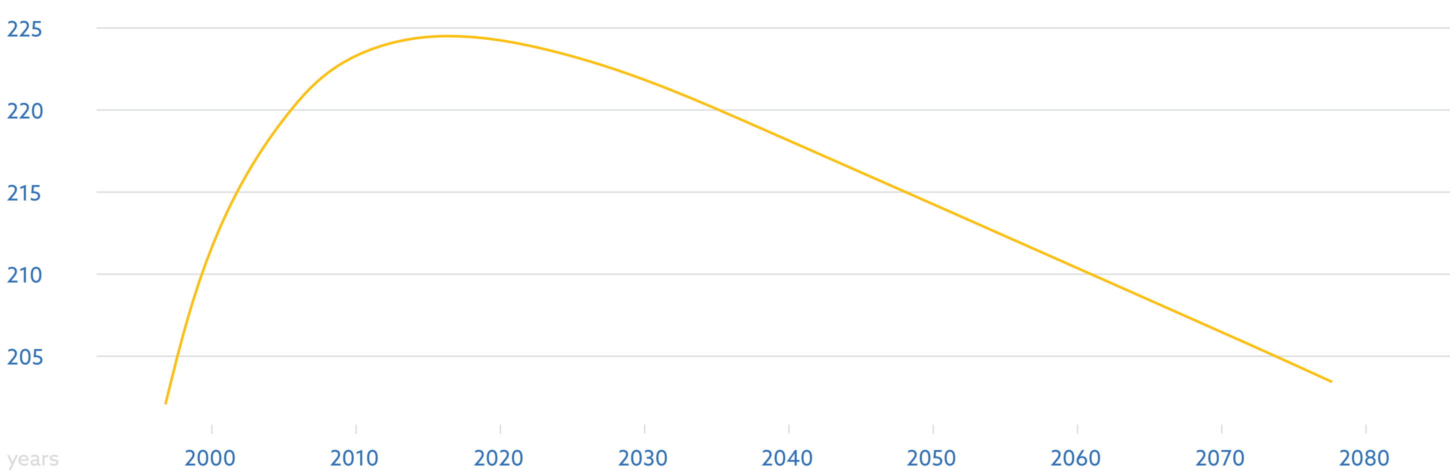


Figure 4-7 Japan's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Japan carbon emission: from 1997 ($g_\omega = 0.0080$, $\varepsilon = 0.04$)



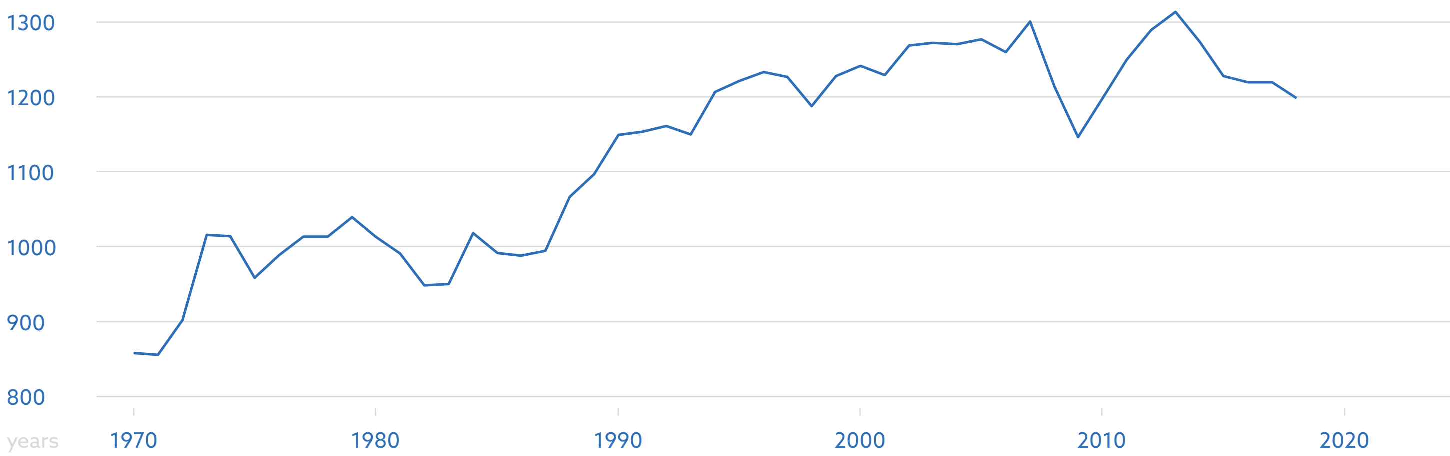
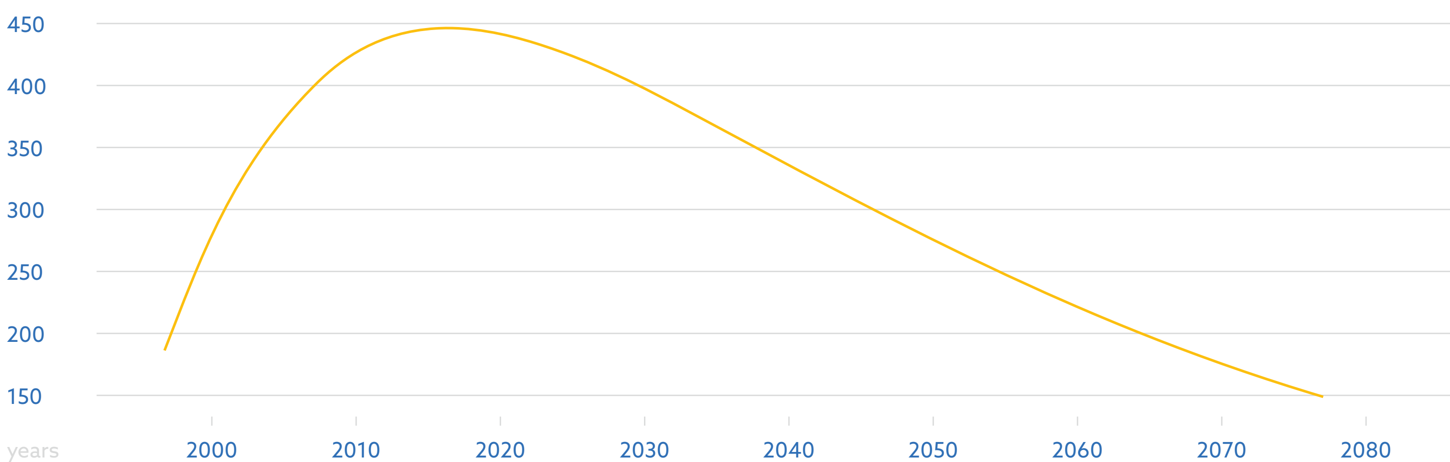


Figure 4-8 Mongolia's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Mongolia carbon emission: from 1997 (g_{ω} = 0.0311, ε = 0.028)



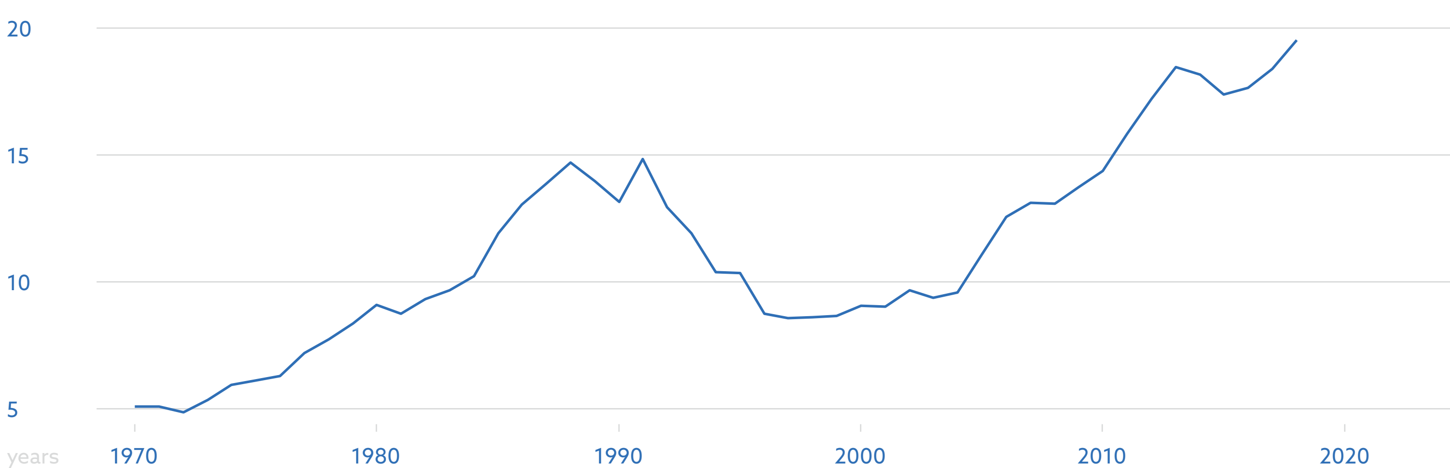


Figure 4-9 Ukraine's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Ukraine carbon emission: from 1997 (g_ω = 0.0337, ε = 0.04)

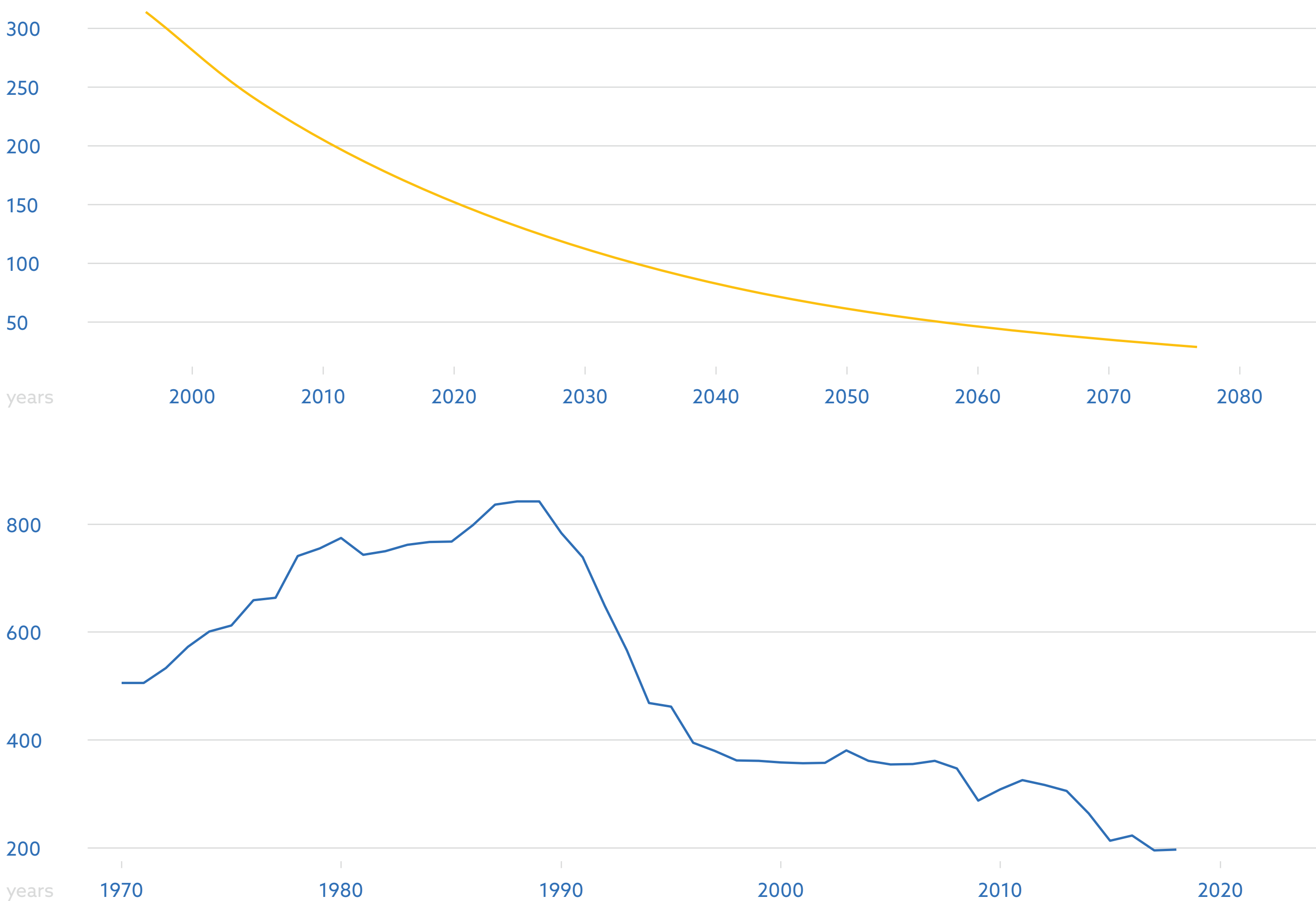
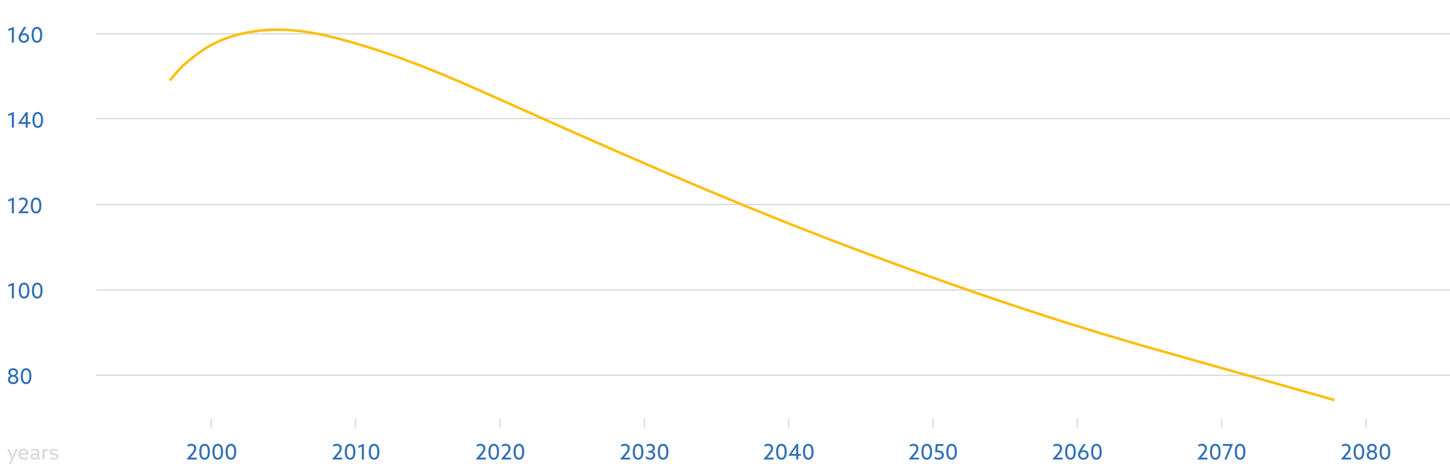
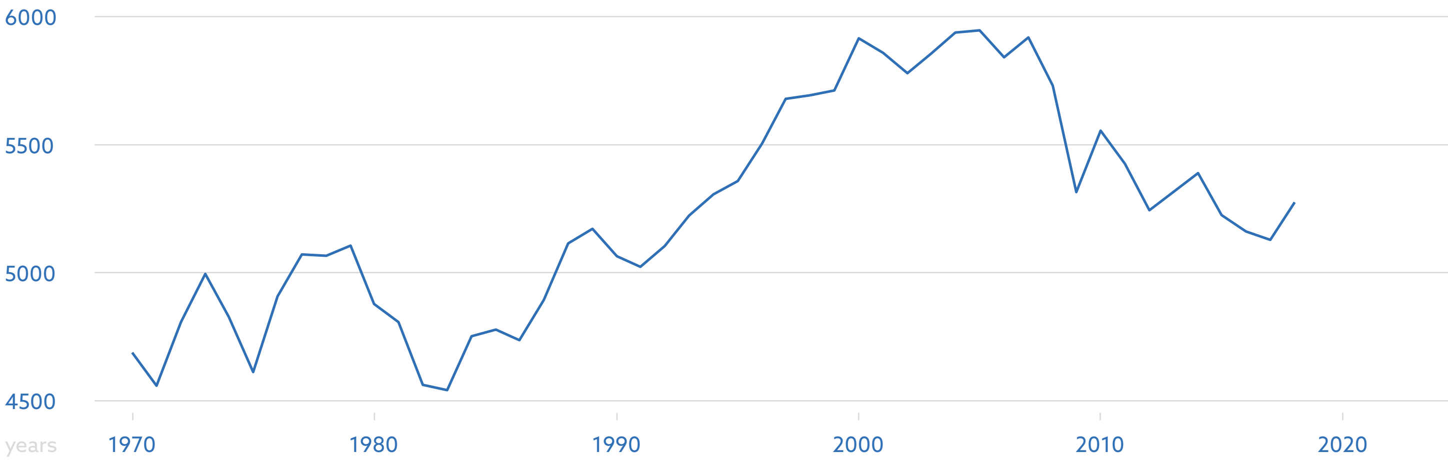


Figure 4-10 United States' emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

United States carbon emission: from 1997(g_ω = 0.0231, ε = 0.04)

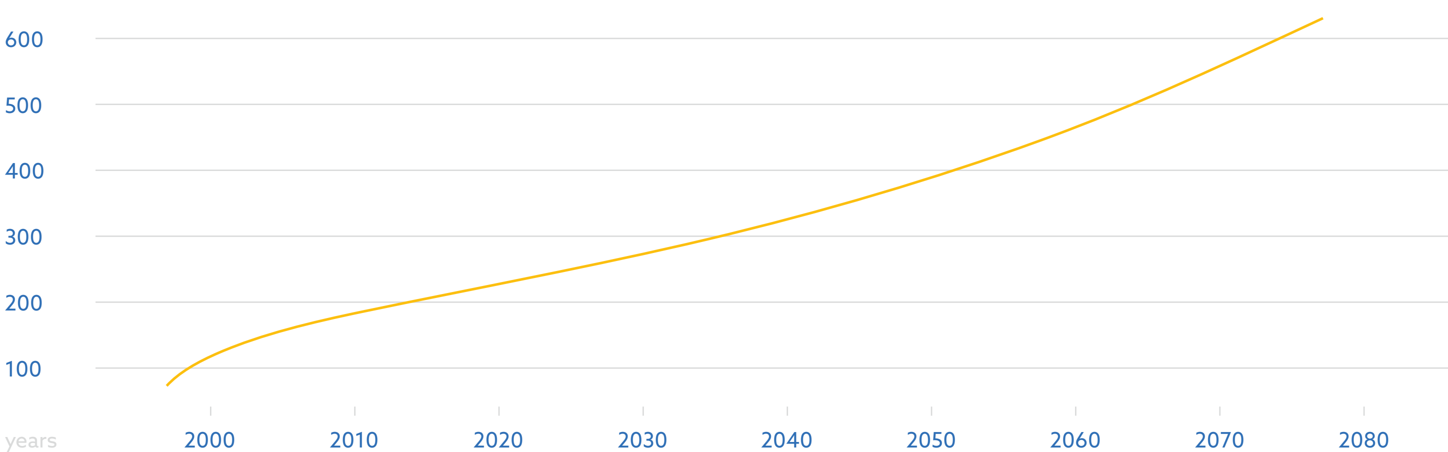


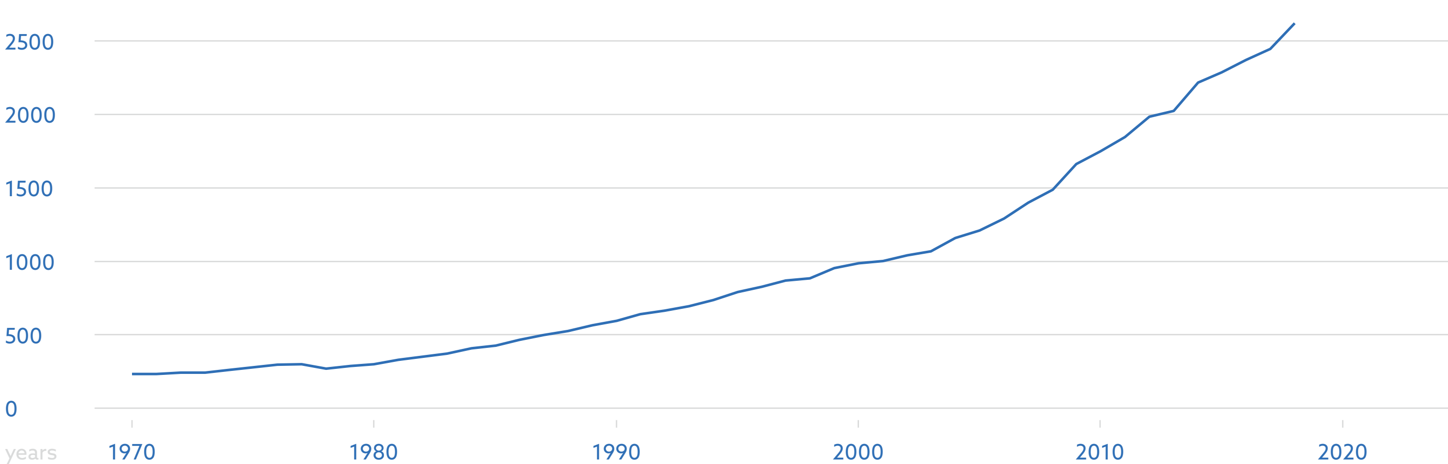


For the third category of countries, the carbon emission inflection point has not shown and is not expected to show in future (using India as an example).

Figure 4-11 India's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

India carbon emission: from 1997 (g_ω = 0.0090, ε = 0.028)



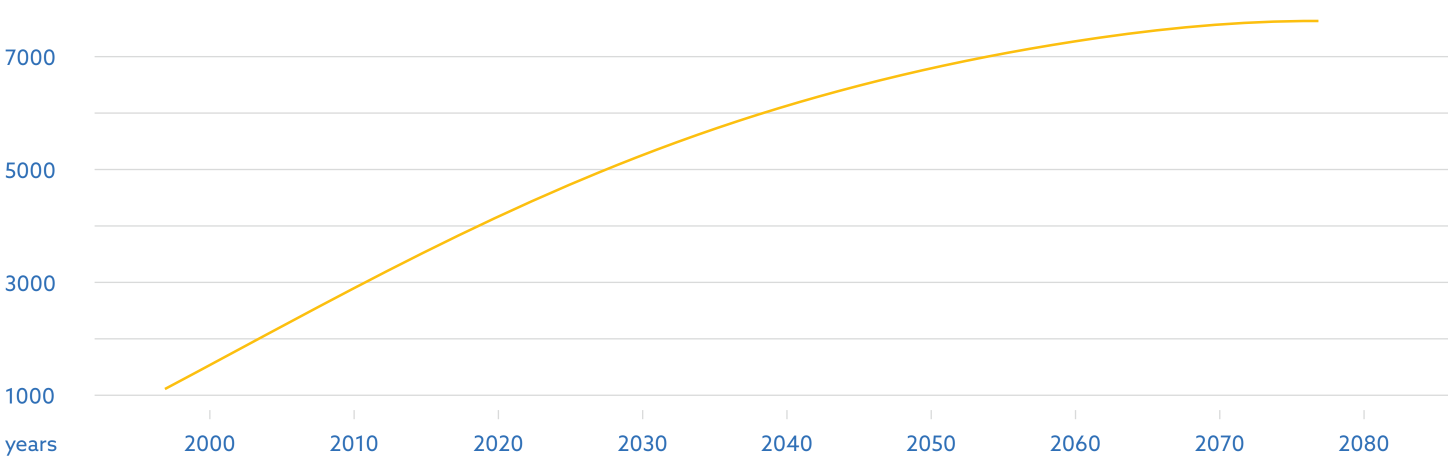


In our model, the emission reduction amount depends on three variables: the emission increase driven by economic growth, the decrease of unit emission reduction caused by emission reduction technology progress and the decrease of total emission reduction resulting from emission control scale. As known to all, India is a fast-growing economy with no signs of slowing down. In its early stage of economic development, its fast growth caused rapid carbon emission increases. Although at this time pollution control expenditures exist, India is still unable to offset the momentum of rapid carbon emission growth. In the middle and late stages of economic development, the economic development will slow down gradually, the total economic volume will still rise together with the economic growth brought by TFP and India demonstrates slow emission reduction technology progress (only 0.009, less than a quarter that of China). Therefore, its total emissions will not decrease over time but will show accelerated growth. In the qualitative analysis of our model, there will be no emission inflection point in this category of economy.

The countries that have not shown a carbon emission inflection point and are not expected to show one in the future, as per our model, demonstrate the following features: 1) most of these countries deliver rapid economic growth and high-speed economic growth is accompanied by rapid carbon emission increase; 2) the emission reduction technology progress rate is relatively low (although Brazil and some other countries show a negative value) and, thus, the emission reduction technology progress cannot offset the elevated total carbon emissions; and 3) since most are developing countries, their expenditures on pollution control are not enough to achieve the purpose of reducing carbon emissions.

Figure 4-12 Angola's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Angola carbon emission: from 1997 (g_ω = 0.0058, ε = 0.028)



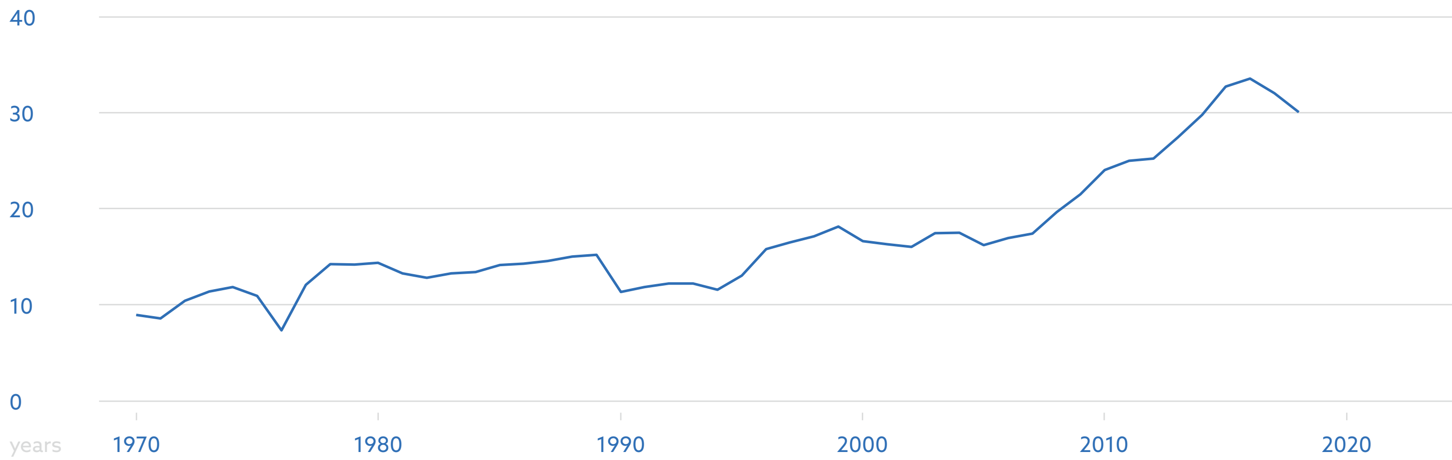
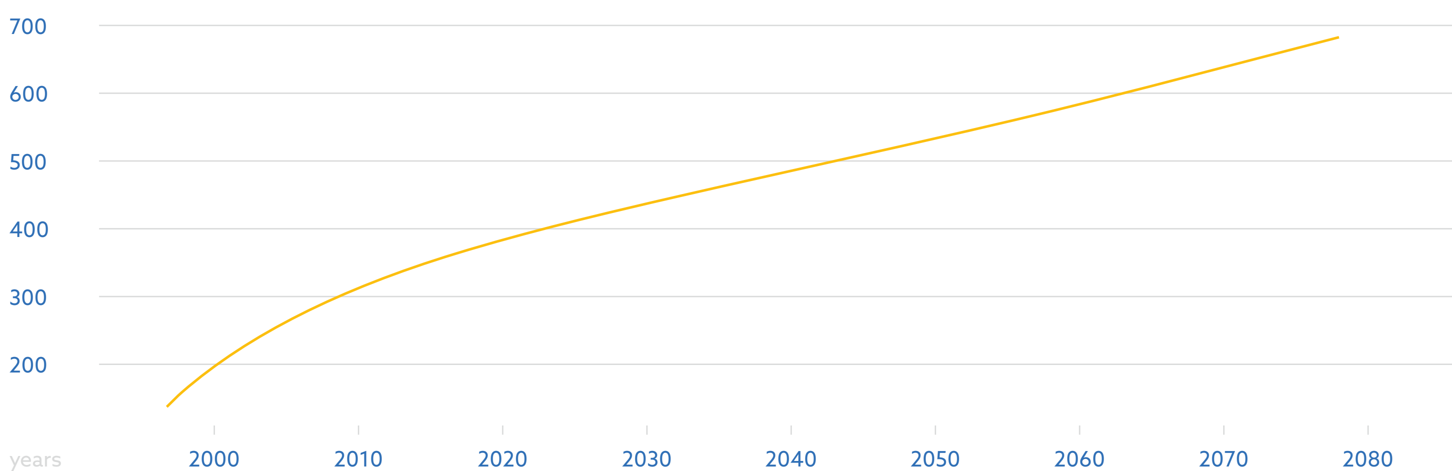


Figure 4-13 Bolivia's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Bolivia carbon emission: from 1997 (g_ω = 0.0039, ε = 0.028)



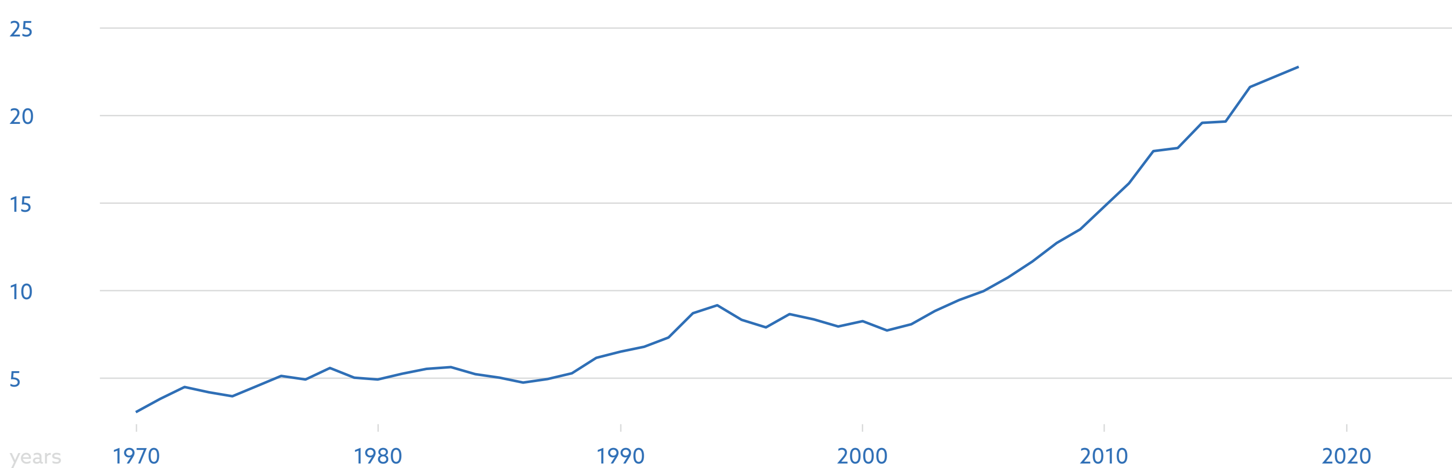


Figure 4-14 Argentina's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

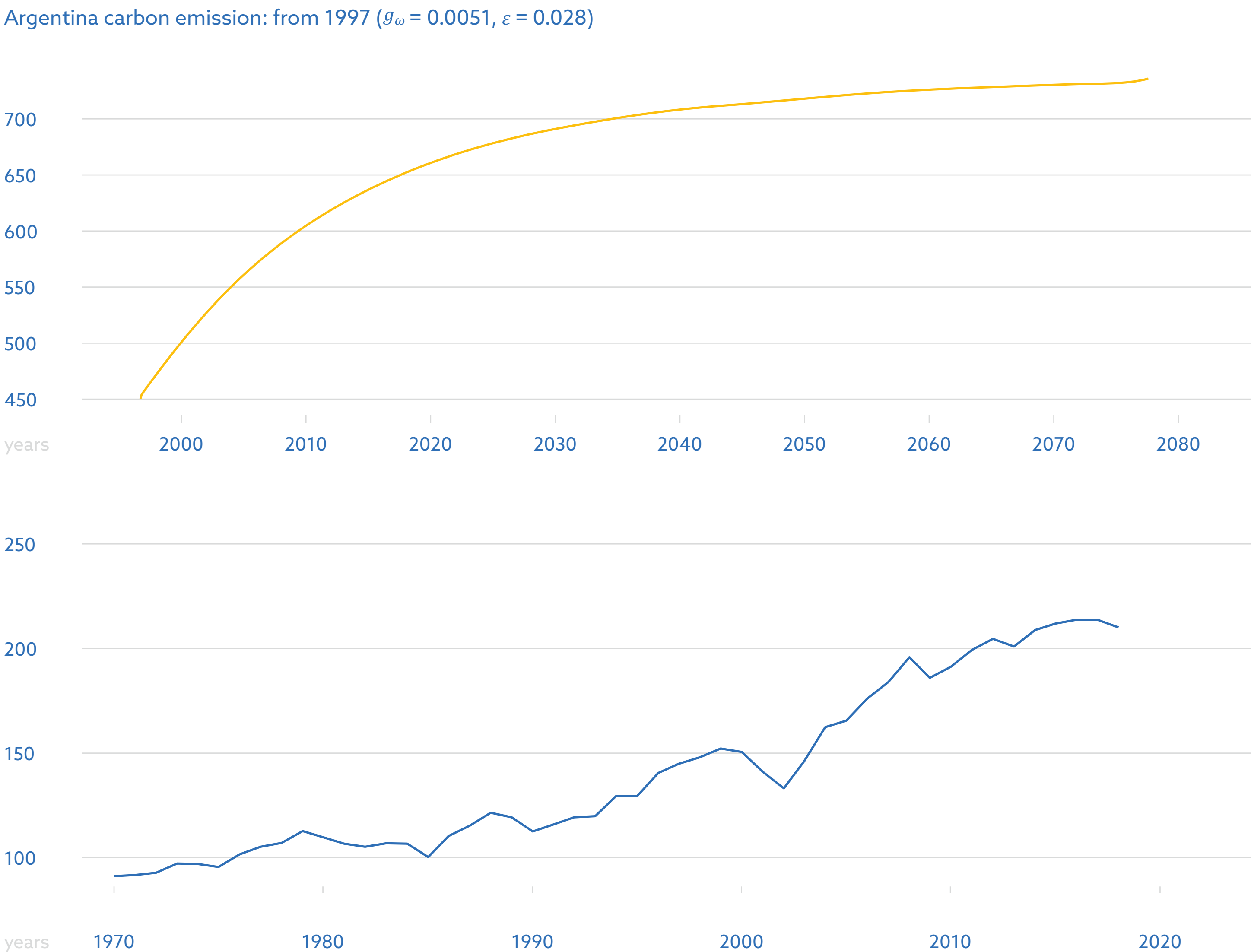
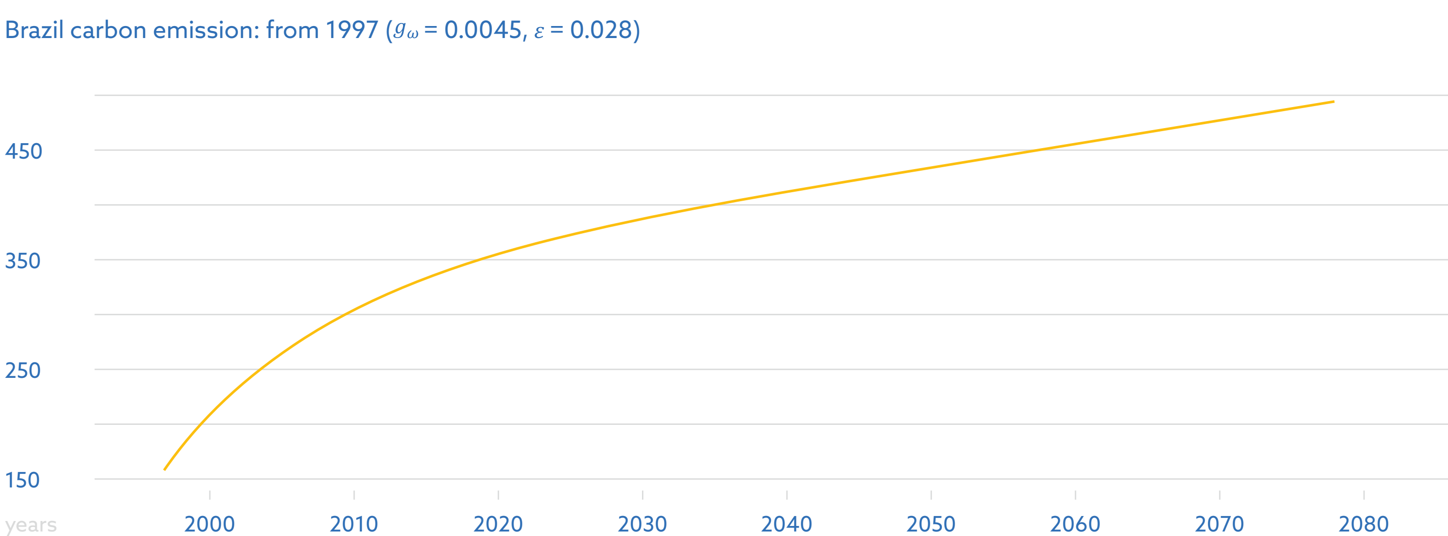


Figure 4-15 Brazil's emissions: Real-time series and projection)
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017



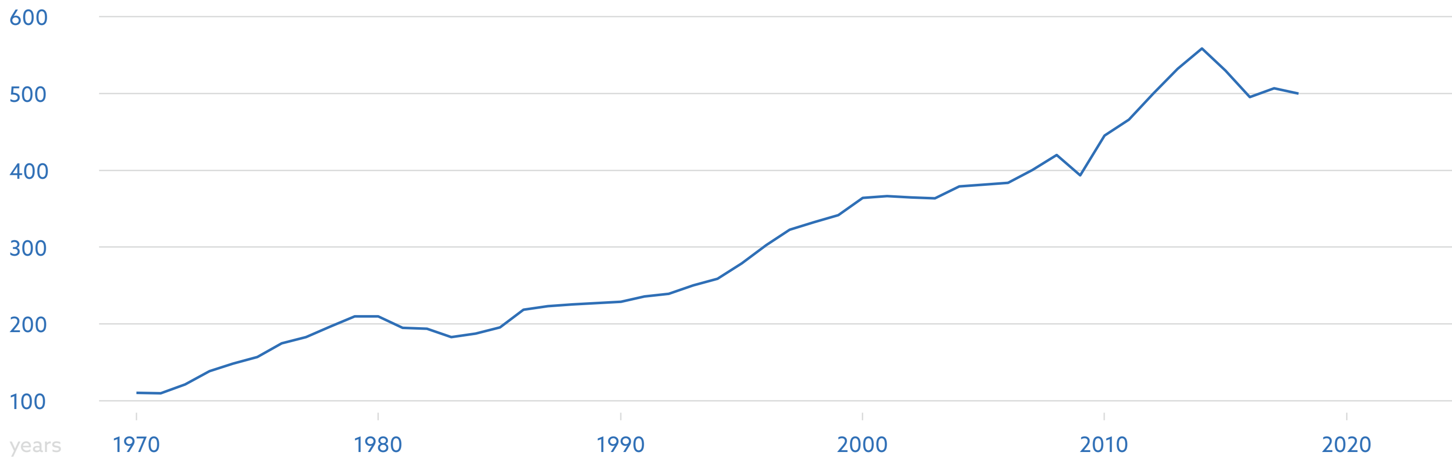
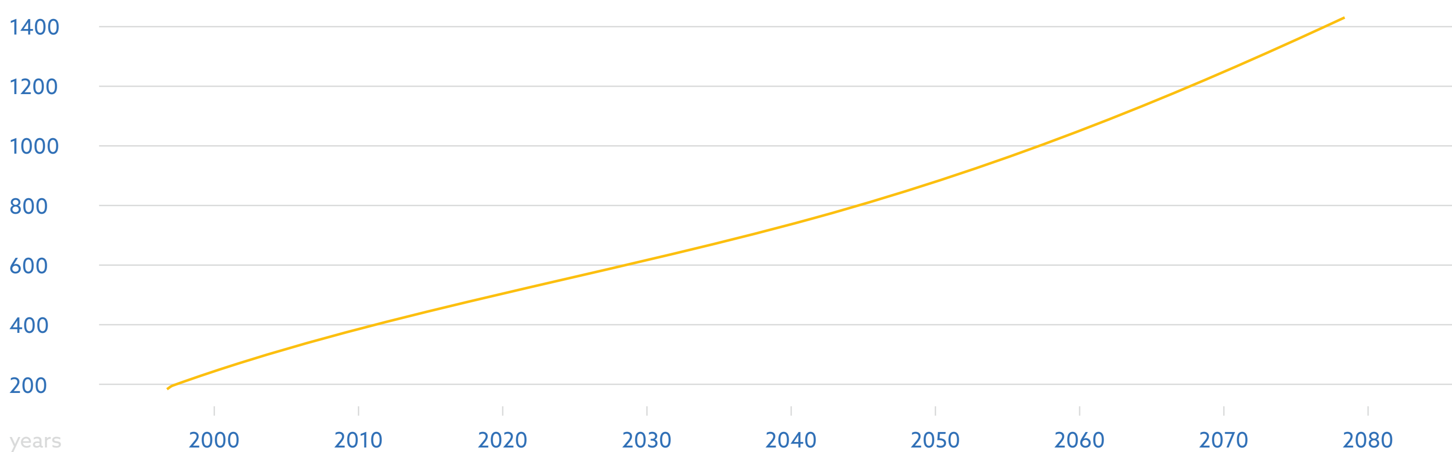


Figure 4-16 Morocco's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Morocco carbon emission: from 1997 (g_ω = 0.0015, ε = 0.028)



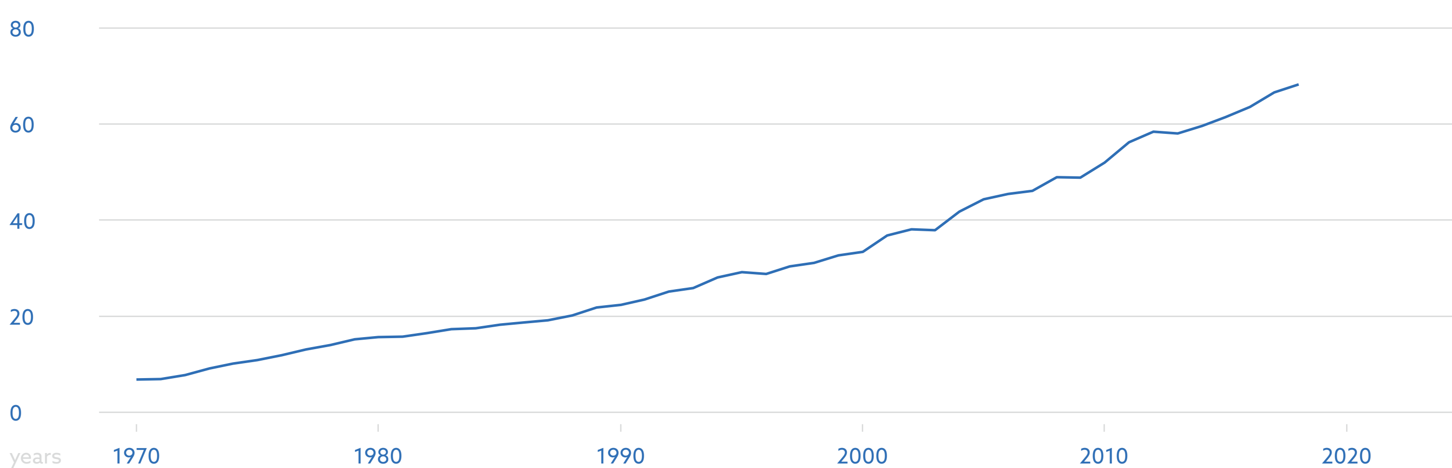


Figure 4-17 South Africa's emissions: Real-time series and projection
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

South Africa carbon emission: from 1997 ($g_\omega = 0.0003$, $\varepsilon = 0.04$)

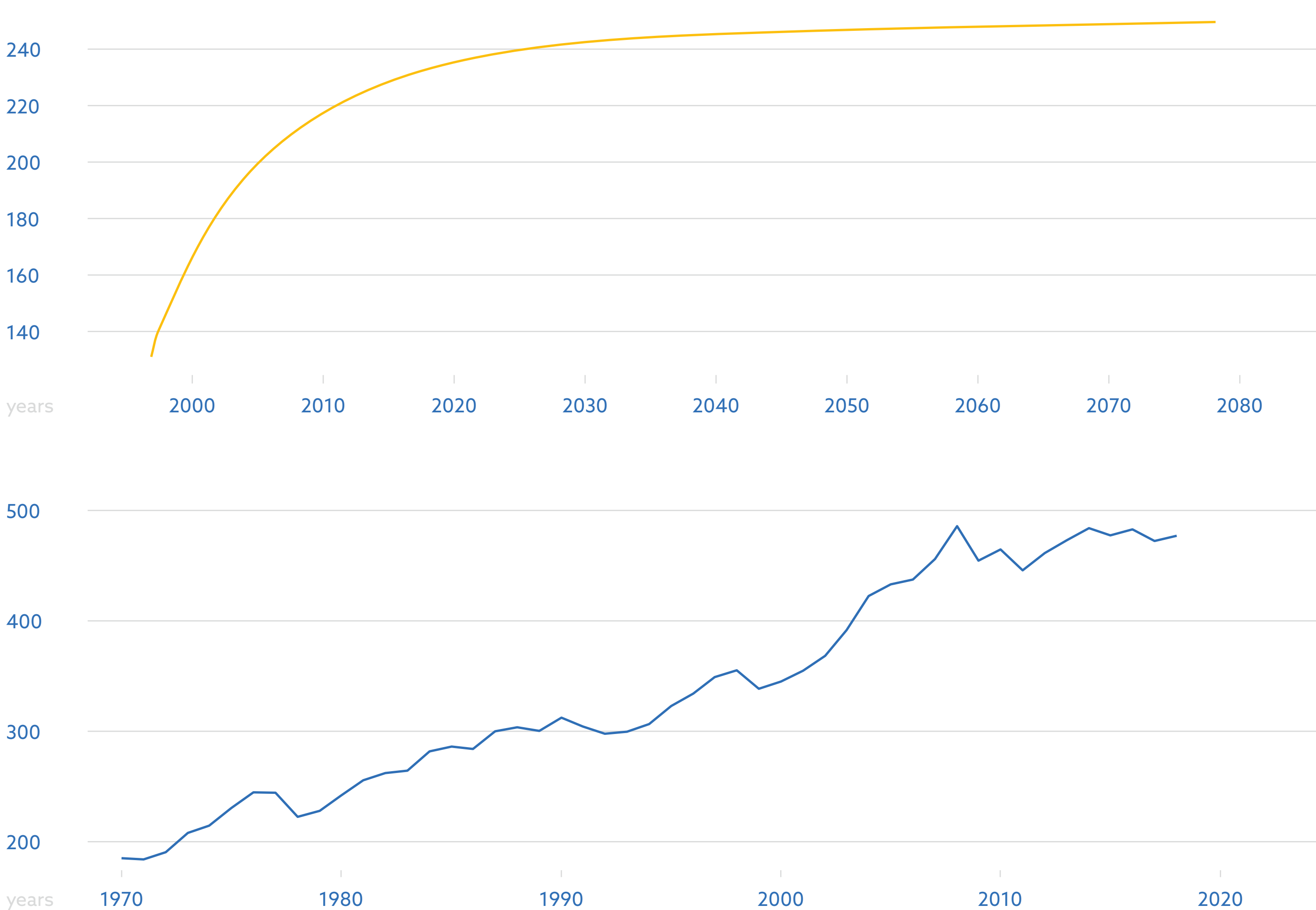
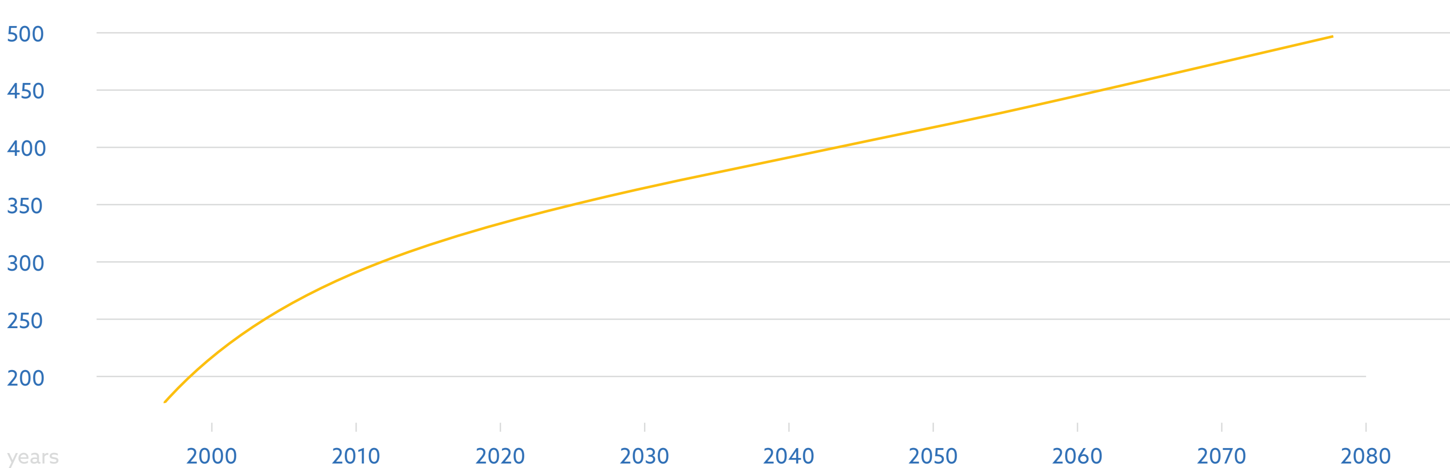
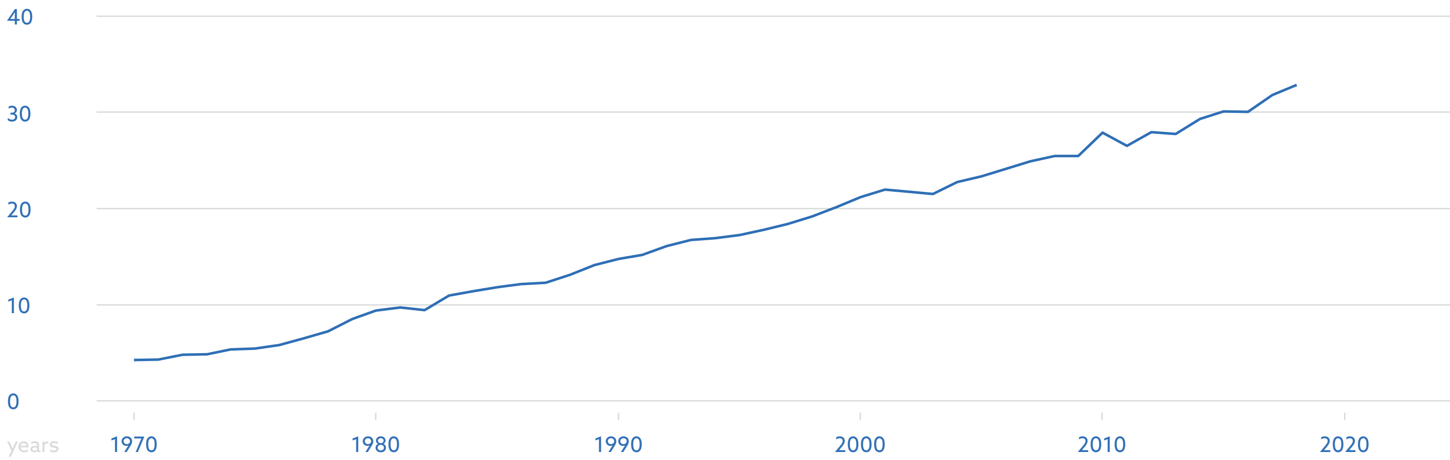


Figure 4-18 Tunisia's emissions: Real-time series and emission
(Upper panel: projection from 1997 to 2077; lower panel: real data from 1971 to 2017)

Tunisia carbon emission: from 1997 ($g_\omega = 0.0074$, $\varepsilon = 0.028$)





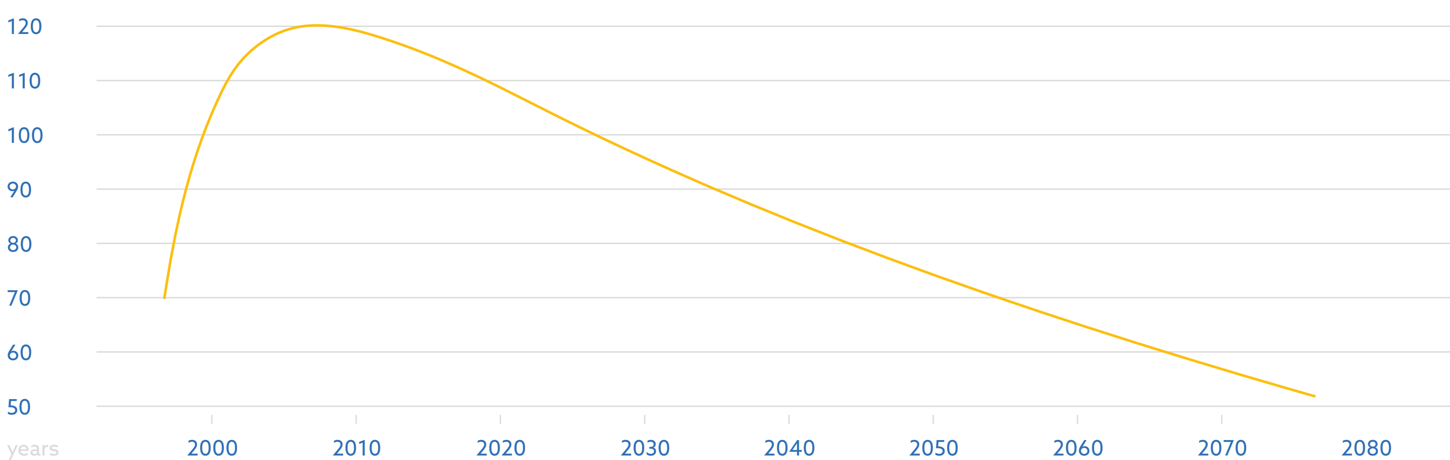
4.3 Scenario experiment by adopting more advanced emission reduction technology

Because our previous numerical simulation and projection were based entirely on the domestic emission reduction intensity of each sample country, this does not account for technology transfer and cooperation between countries. To reveal the potential of technology transfer in the emission reduction process from international cooperation and instruction, we further offer a scenario experiment for those countries belonging to the third category in the previous section, i.e., the carbon emission inflection point has not shown and is not expected to show in future, by assuming that a country can obtain the more advanced emission reduction technology of the leading (the highest g_ω) country in the same region (see Table 3-7 for the definition of regions, i.e., the "region" column).

Take India as an example. India is located in Asia, for which economic growth is rapid but progress in emission reduction technology is not evident. Let us assume India can obtain access to the emission reduction technology from China, which is the country with the largest rate of progress in emission reduction technology in the same region. The simulation of this new experimented situation is as follows.

Figure 4-19 India: experimented simulation and projection from 1997 to 2077

India carbon emission: from 1997 (g_ω = 0.0410, ε = 0.028)



The U-shaped EKC appears. We can see some results that are not the same or are not shown in the previous simulation for India (in the preceding section). In the earlier projection, India did not have an inflection point for carbon emissions, which is partly due to India's slow technological progress in reducing emissions. In the above new simulation, we see an inflection point in India's emission thanks to the borrowing of more advanced reduction technology. Although India's carbon emissions were still growing at the beginning, the turning point came early and carbon emissions began to decrease significantly.

The above exercise provides us with three important meanings. First, the total amount of carbon emissions depends not only on the total emissions but also on the progress of emission reduction technologies. When the total amount of emissions is growing rapidly, if a country has faster technological progress, the emission reduction target can still be achieved. Second, the availability of more advanced emission reduction technologies from international cooperation and instruction on environmental regulation is very important, especially for those southern countries for which it is difficult to obtain an inflection point in the EKC solely drawn from its domestic parameters. In the initial simulation in the preceding section, because countries did not share emission reduction technologies, a considerable number of countries were unable to decouple carbon emissions from economic growth. However, in our updated exercise in this section, should each country obtain the latest regional technological progress in emission reduction, the simulation results show that these countries could achieve an inflection point in the EKC, i.e., they could realize the win-win effect of economic growth and environmental sustainability at some time. Third, in the experiment, because we select the highest g_ω in the same region, this defines the largest potential benefit from international and regional cooperation and instruction on environmental regulation to that country, i.e., in reality, some extent of international cooperation may not be possible that will completely generate the scenario in the simulation and projection; however, this exercise depicts the boundary of the potential both scientifically and practically.

Applying our new simulation to other third-category countries in the preceding section, we found similar results. Further, we divide all the previous third-category countries into three groups after the new experiment, as described below.

Group I: The carbon emission inflection point will show in the future (Angola is the only country belonging to this group).

Group II: The carbon emission inflection point has already occurred (Brazil, India, Morocco, South Africa and Tunisia).[3]

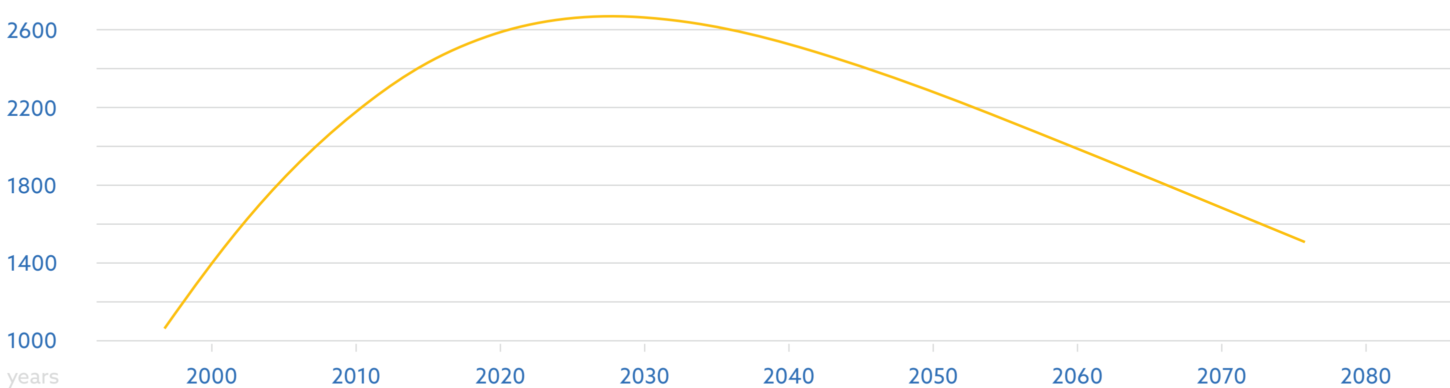
Group III: The carbon emission inflection point will still not show, but carbon emissions will become and remain stable in future (Bolivia is the only country belonging to this group).

3 Please see our abovementioned explanation: in this experiment, because we select the highest g_ω in the same region, this defines the largest potential benefit from international and regional cooperation and instruction on environmental regulation to that country, i.e., in reality, some extent of international cooperation may not be possible that will completely generate the scenario in the simulation and projection; however, this exercise depicts the boundary of the potential both scientifically and practically.

Country in Group I: Angola

Figure 4-20 Angola: Experimented simulation and projection from 1997 to 2077

Angola carbon emission: from 1997 (g_ω = 0.0267, ε = 0.028)



Countries in Group II (except India):

Figure 4-21 Brazil: Experimented simulation and projection from 1997 to 2077

Brazil carbon emission: from 1997 (g_ω = 0.00512, ε = 0.028)

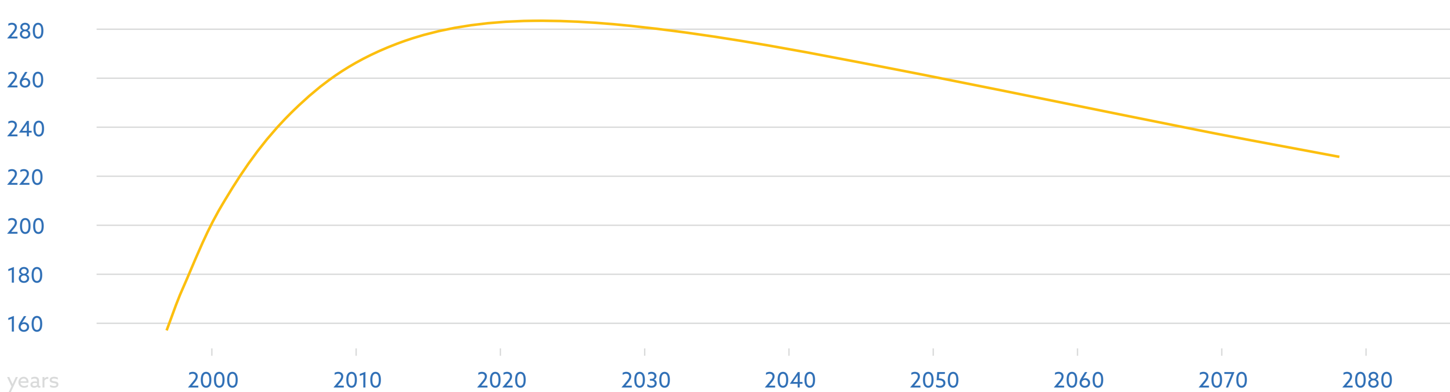


Figure 4-22 Morocco: Experimented simulation and projection from 1997 to 2077

Morocco carbon emission: from 1997 (g_ω = 0.0267, ε = 0.028)

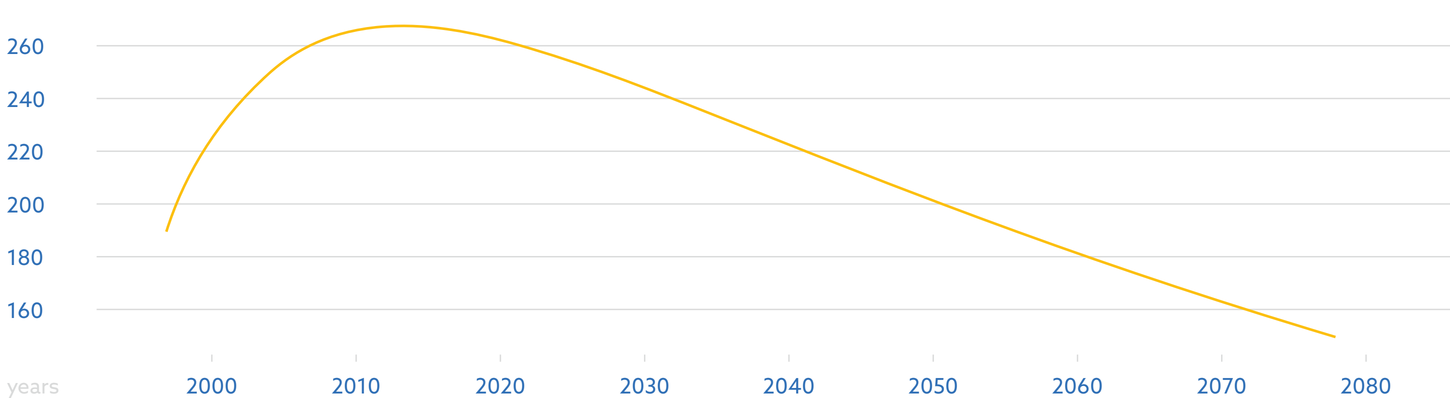


Figure 4-23 South Africa: Experimented simulation and projection from 1997 to 2077

South Africa carbon emission: from 1997 ($g_\omega = 0.0267$, $\varepsilon = 0.028$)

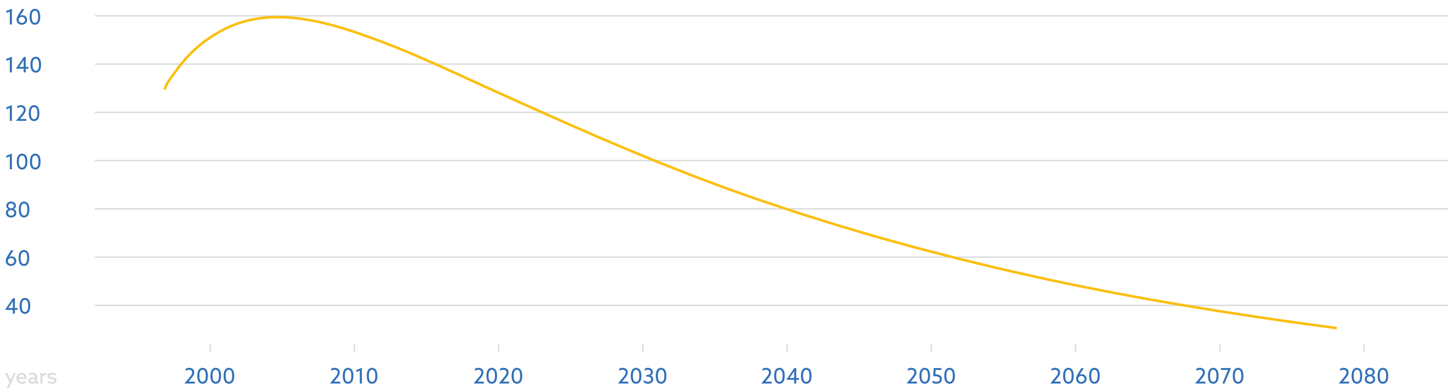
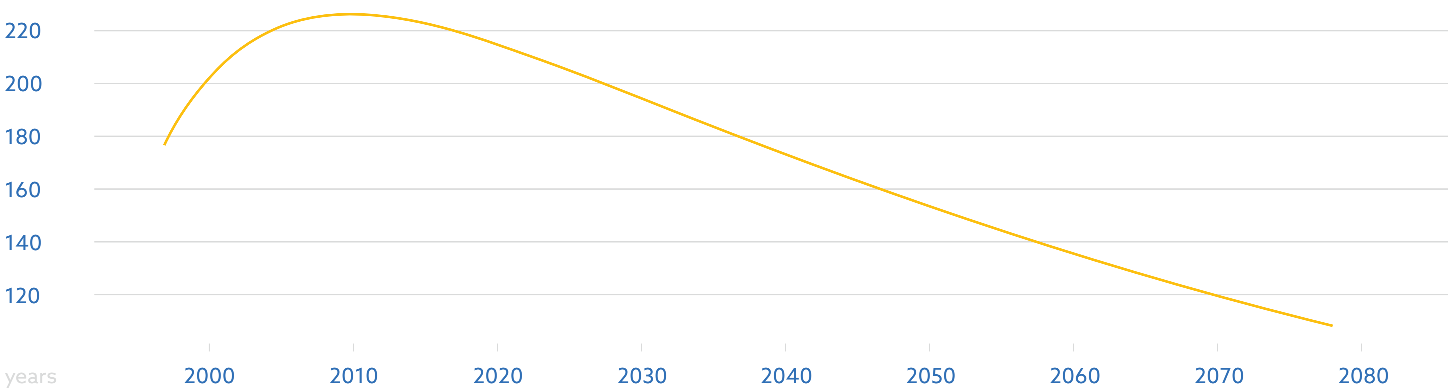


Figure 4-24 Tunisia: Experimented simulation and projection from 1997 to 2077

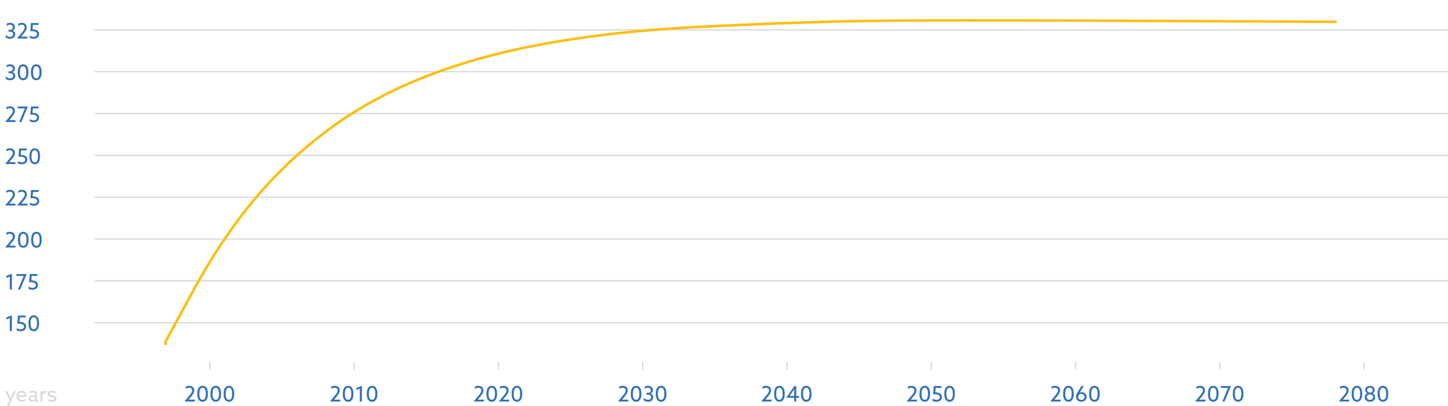
Tunisia carbon emission: from 1997 ($g_\omega = 0.0267$, $\varepsilon = 0.028$)



Country in Group III: Bolivia

Figure 4-25 Bolivia: Experimented simulation and projection from 1997 to 2077

Bolivia carbon emission: from 1997 ($g_\omega = 0.00512$, $\varepsilon = 0.028$)

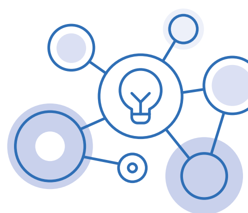


In the first two groups, all countries will sooner or later realize the win-win effect of decreasing carbon emissions and economic growth, i.e., if all countries can obtain advanced emission reduction technologies, a U-shaped EKC will appear. This gives us important policy implications: helping developing countries obtain advanced emission reduction technologies is essential to promote the realization of global emission reduction targets.

The simulation in Bolivia emphasized the importance of emission reduction technology from another aspect. Because the country with the fastest rate of technological progress in emission reduction in South America is Argentina, but its value is only 0.00512, this is a relatively slow technological progress compared to other continents. When we apply this figure to Bolivia, we will find that although the previous upward trend of total carbon emissions has been curbed, the inflection point of carbon emissions has still not yet been evident. In fact, due to the slow progress in emission reduction technology, Bolivia's total carbon emissions have reached a certain value and then become stable, which means the economic growth would not be completely decoupled from carbon emissions. To sum up, the whole region (South America) needs more advanced environmental regulation and technology aid from worldwide international instruction and intervention.

All the above means that proactive international transfer of emission reduction technologies is of great significance. Such technology transfer would facilitate countries with slow progress in carbon emission reduction to obtain more advanced technologies, which can significantly reduce the total carbon emissions of these countries and the whole southern world.

5. Concluding remarks and policy recommendations



Sharing of emission reduction technologies internationally can help especially those southern countries that initially face difficulty in obtaining a U-shaped EKC solely drawn from domestic parameters to become able to achieve an inflection point in the EKC, i.e., able to realize the win-win result of economic growth and environmental sustainability at some time.

To explore the theme "Reducing Carbon Emissions for the Economic Development of the Global South," we starting by describing the characteristics of total carbon dioxide emissions, carbon dioxide emission intensity and per capita carbon dioxide emissions in the world, and specifically in OECD countries and non-OECD countries and the BRICS countries. From this, we saw that the current non-OECD countries, including the vast majority of southern countries, have become the main global carbon dioxide emitters–especially the BRICS countries, whose carbon dioxide emissions account for more than 40 percent of the world's emissions. Therefore, it is deemed essential to study carbon dioxide emission reduction issues of southern countries in the process of economic development.

Second, based on the EKC hypothesis and "decoupling" theory, we used the data of 111 economies from 1980 to 2018 and employed ordinary least squares (OLS), fixed effects (FE), generalized method of moments (GMM) and other regression models to test the concepts. The empirical results recover a global EKC and show that when the per capita GDP of an economy exceeds $30,619.735, the double dividend effect of economic growth and carbon dioxide emission reduction can be realized. Then, we selected some representative countries based on the principles of population, GDP and per capita GDP to analyze the dynamics of decoupling elastic coefficients of these representative countries to describe the development trajectory of each country's economic development and carbon dioxide emissions.

In addition to the aforementioned basic regression and model simulation, which are solely based on a country's domestic parameters and policies, we inquired whether international economic interaction, e.g., trade, and international cooperation on environmental regulation, e.g., cross-country communication and spillover of emission reduction technology, will have an impact on the relationship between emission and economic growth and development in the southern world. Following this direction of extension, in the regression, we not only controlled the impact of the ratio of import and export trade to GDP on carbon dioxide emissions to identify the impact of international trade on environmental performance between countries, but we also decomposed trade volume into trade structure (in industry) as explanatory variables and significantly detected "carbon leakage" in the process of global manufacturing transferring, i.e., if a country's net exports of manufactures are positive, which indicates that the country is a recipient in the process of global manufacturing transferring, then its carbon dioxide emissions will increase and be higher than before.

Finally, we developed a macroeconomic model with a micro-foundation and emission decision, calibrated the parameters in the model and applied this to the simulated projection for all representative countries by which the moment of the EKC turning (inflection) point in southern countries is shown. Also, in the simulation and the projection, to exhibit and reveal the potential of technology transfer in the emission reduction process from international cooperation and instruction, we offered a scenario experiment by assuming that a country could obtain the more advanced emission reduction technology of the leading country (number one in emission reduction technology progress) in the same region. We showed that the sharing of emission reduction technologies internationally can help especially those southern countries that initially face difficulty in obtaining a U-shaped EKC solely drawn from domestic parameters to become able to achieve an inflection point in the EKC, i.e., able to realize the win-win result of economic growth and environmental sustainability at some time.

All in all, by this research, we obtained the below policy recommendations.

Policy recommendation 1

Actively explore the optimal ratio between manufacture industry and service industry and optimize the industrial structure. Either from empirical models or per analysis of representative countries, we find that sometimes a too high proportion of industrialization is not necessarily conducive to carbon emission reduction. One reason is that the existing industrial structure is biased toward high energy consumption and high carbon emissions. Another reason is that the development of the service industry, especially the production-oriented service industry, is relatively lagged, which limits its role in promoting industrial upgrading with low emissions. Thus, the overall carbon decoupling coefficient is high.

Policy recommendation 2

Moderately increase the intensity of environmental regulations and thus optimize production and energy-saving emission reduction technologies. From our previous numerical simulations of representative countries, we found that emission reduction technology is a very important parameter. Rapid economic growth does not always bring about explosive emission growth. The relative rate of technological progress in emission reduction and economic growth is particularly important for controlling pollution emissions. This means that in high economic growth countries, policymakers should seek faster technological progress in emission reduction to offset the high pollution caused by economic growth and ultimately control pollution emissions. So governments should increase investment in emission reduction technology at the same time as boosting investment for economic growth (GDP).

For policy recommendations according to the findings about the relationship between trade structure and emissions, according to the Heckshal and Ohlin (HO) trade theory, factor endowment is the basic reason and determinant of comparative advantage of each country in international trade. Therefore, each country should produce and export the relatively abundant and cheap factor-intensive products of that country and import the relatively scarce and expensive factor-intensive products. On average, southern countries have relatively abundant labour and relatively scarce capital and they have comparative advantages in developing labour-intensive industries, whereas northern countries have relatively abundant capital and relatively scarce labour and they have comparative advantages in developing capital-intensive industries. As a result, the southern countries have become the foundries of the northern countries and have produced a large amount of carbon dioxide emissions. Therefore, it is very important for the southern countries to balance economic growth and carbon dioxide emissions in the future. Below, we present two possible directions for policymakers to consider.

Policy recommendation 3

When the southern countries continue to follow their comparative advantages to develop labour-intensive industries and export to the northern countries to increase trade revenue (and carbon dioxide emissions, at the same time), they should learn from the northern countries and develop capital-intensive industries, accumulate capital, invest in production technologies and emission reduction technologies, introduce cleaner production mechanisms and reduce CO_2 emissions from export goods. The possible result is that CO_2 emissions will still increase in the short term, but the intensity of CO_2 emissions will decrease significantly in the long term and the economy will continue to develop healthily.

Policy recommendation 4

When the advanced economies transfer manufacturing to southern countries, the development stage of these countries must be considered. Northern countries should provide environmental assistance to those recipient countries. In addition, from the perspective of trade fairness, the costs of environmental protection or governance need to be included and reflected in the trade price, e.g., some international intervention or mechanism aimed at correcting environmental externality in the process of global manufacturing transferring. At the same time, the United Nations needs to play a supervisory and coordinating role and pay more attention with guidance and support to the dynamics of environment evolvement of southern countries when they are recipients of manufacture industries.

According to the findings of the scenario experiment on the technology transfer in emission reduction from international cooperation and instruction, we present the below recommendation.

Policy recommendation 5

International organizations should make full use of various means to promote countries with backward emission reduction technologies to obtain faster technological progress. In our scenario experiment of simulation and projection, when a country can obtain the emission reduction technology of the country with the fastest emission reduction rate in the same geographic region, the carbon emissions of the backward country will also be decoupled from economic growth sooner or later. This highlights the importance of international transfer of emission reduction technologies. A proactive international cooperation (e.g., initiated by the United Nations) on emission reduction technologies can help to realize the win-win result of economic growth and environmental sustainability for the whole southern world.

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