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Global carbon reduction and economic growth under autonomous economies

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ABSTRACT

The ecological and environmental issues caused by climate change have affected human health and social development. Accordingly, scientists have focused on addressing climate change. IAMs (Integrated Assessment Models) have been widely used to assess the effect of global climate governance. Since the US withdrew from the Paris Agreement and the UK broke away from the European Union, global economic development takes on an uncertain path. The worldwide trade war triggered by the US has shown that international trade may be weakened in the future. The deglobalization in global economic progress forces individual innovation within countries. Therefore, we constructed a new IAM under autonomous economies—EMRICES-E (Expanded Multi-Regional Integrated model of Climate and Economy System-Equilibrium), which contains a layered structure of national computable general equilibrium (CGE) model to describe an individual country's development and analyzes the effects of global reductions in cooperation based on the new global situation. Considering that technical progress is a significant factor in carbon reduction, we introduced endogenous technical progress in CGE. Simulation results show that developing countries/regions have large carbon emissions under the baseline scenario with their economic status increasing at the same time, climate change would lead to economic recession if there are no carbon reductions for countries/regions and the industrial structure of developing countries changes noticeably compared with developed countries.

1. Introduction

A series of agreements on climate protection quantified the reduction goal of greenhouse emissions, and national cooperation had been proven to be important for the global greenhouse emissions reduction. These efforts have promoted the global governance process on climate change(IPCC, 2014). However, there are still divergences in reduction goals and responsibilities among countries, and the reduction responsibility between developed countries and developing countries is a focus area because the implementation of emission reduction would have an uncertain effect on the economy(Hedegaard, 2011; Zhong et al., 2018). These divergences hampered the process of global climate governance. IAMs (Integrated Assessment Models), which are composed of economic systems, climatic systems and interactions between these two systems, have been widely used on evaluating the effects of global climate governance.

Since the US withdrew from the Paris Agreement and UK broke away from the European Union, global economic development has shown an uncertain path. The worldwide trade war triggered by the US has shown that national trade may be weakened in the future and the connections inside of country will be stronger than outside of countries. Regarding this new situation in the world's economy, the equilibrium within a country should be given more attention.

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Autonomous economies mean the economic relations among industries within the country are stronger than those among countries and could reflect the reverse globalization situation better. Each country reaches equilibrium within its own production while investments and economic interactions exist among countries are relatively weak.

The weak relationships among countries could be described by GDP spillover, which is described by the Mundell-Fleming model(Douven and Peeters, 1998) and reflected the economic changes resulted from other country's external shocks. Based on RICE (Regional Integrated model of Climate and the Economy), a series works has been done to improve the economic model by containing GDP spillover in RICE (Liu, 2013; Wang et al., 2000). However, there still are some places unsatisfied with the new global governance situation, such as the economic relationships within countries can't be reflected and the carbon emissions are only related to total output and carbon emission intensity. Therefore, we adjust economic model in Liu's (2013) on two aspects. On one hand, to describe the reverse globalization situation, we contain computable general equilibrium (CGE) models of some important economies to refine the economic model. On the other hand, we realize endogenous technology progress and add energy consumption structure on carbon emissions accounting process in CGE model. The new IAM is called EMRICES-E (Expanded Multi-Regional Integrated model of Climate and Economy System Equilibrium).

The remainder of this study proceeds as follows. Section 2 reviews the relevant literatures on IAMs. Section 3 discusses the methods and data preparation. Section 4 presents the results and discussion, with Section 5 provides concluding remarks, policy implications and perspectives in the future.

2. Literature review

IAMs, which contains the environmental factors and the social economic factors, are widely used in evaluating global climate governance by revealing climate policy information (Harremoës and Turner, 2001; Schneider, 1997; Van Vuuren et al., 2011). Kemfert et al. (2002) conducted an regional IAM (AIAGEM) and found that developing countries would suffer higher social welfare and economic losses under climate change. Akimoto et al. (2004) conducted an IAM (DNE21) containing improved energy systems found that the combination of different reduction strategies is necessary for global reduction. Peng et al. (2017) conducted a single-region IAM (DEMETER-CCPE) to evaluate the cost effectiveness, cost-benefit efficiency and contribution to emission reductions of China's climate policies. Ou et al. (2018) evaluated the environmental effect of low-carbon policies and found that carbon reduction would increase water demand in the US based on a national IAM. Generally, there are two developing patterns for IAMs' economic module.

The first one is optimization pattern, such as DICE, RICE and MERGE. DICE is an optimization model, which takes the whole world as an area and minimize the carbon reduction cost under the limit of Ramsey utility framework(Nordhaus, 1992). The linkages among economies are absent. To reflect regional activities, Nordhaus developed a new classical economic model—RICE, which contains climate feedback between economic and climatic systems and treats the whole world as 10 or 12 regions(Nordhaus, 2010; Nordhaus and Yang, 1996). However, there are no economic interactions among countries in RICE. These IAMs have advantage on taking climate change as a variable in the economic model while their disadvantage is lack of industrial economic effects due to the oversimplified economic mechanism. Most extend versions of RICE and DICE also have this problem, such as DICE-2007(Nordhaus, 2008), RICE-2010(Nordhaus, 2010) and DSICE(Lemoine and Traeger, 2014).

The other economic pattern is CGE model, which has an advantage on setting industrial reduction policy and reflect the industrial effect. Here come other patterns of IAMs that contains CGE model as economic module, such as FUND, WIAGEM, IMAGE. Since the algorithms of CGE is complicated, the climate model in most of these IAMs is oversimplified by a linear equation. Even though IMAGE(Bouwman et al., 2006) concerns industrial economy, there is still no inter-industrial relationships. FUND and WIAGEM only contain loss function in model and without taking temperature into production function(Ackerman and Munitz, 2012; Kemfert, 2002).

Therefore, it's better for IAMs not only contains equilibrium model as economic module but also take climate feedback into production function. CIECIA analyzed global reduction strategies under global economic integration(Wang et al., 2016). However, under the new global economic situation caused by recent policies in the US, each country declares its own economic balance prior when taking part in global governance, which requires changes in simulation under global economic integration. A series of works have been done to improve the economic module of RICE, such as the description on interregional connections (Wang et al., 2012), the industrial economic interactions under input-output equilibrium(Huang, 2014; Liu, 2013). These IAMs have play significance effects on global carbon reductions. However, there also exists some issues needed to be explored.

Firstly, the interactions within countries have been paid less attention. Under the reverse global situation, equilibrium within countries and refined industrial descriptions need to be focused. Secondly, the dynamic growth rate of technology is exogenous, which would lead to arbitrary simulations. Recent researches show technical progress driven by capital has taken larger effect during production(Brynjolfsson and McAfee, 2014; Piketty, 2014). Thirdly, the carbon emissions are determined by economic output and exogenous emission intensity, without the effect of energy consumption structure. In fact, studies have proven that reducing the energy consumption intensity that measures energy used by each country's GDP would directly cut carbon emissions and increase energy security(Chalvatzis and AlexisIoannidis, 2017; Sun et al., 2010). Different technologies will have different energy consumption structures, which will lead to changes in production structure(Tan and Lin, 2018). Therefore, it is extremely urgent to contain national CGE model and realize endogenous technical progress in IAMs.

In the context of this literature, our paper constructs a new IAM named EMRICES-E by combining CGE models of some important economies with climatic model. We implement endogenous technology progress and add energy consumption structure when accounting carbon emissions in CGE model.

3. Model and data

EMRICES-E divides the world into China, the US, Japan, the EU, India, Russia, high-income countries, upper-middle-income countries, lower-middle-income countries, and low-income countries based on the classification of World Bank. The economic module, carbon-cycle module, land surface temperature module and their interactions in EMRICES-E are shown in Fig. 1. The economic relations are described by GDP spillover model.

The economic core of EMRICES-E is national industrial general equilibrium model or regional macroeconomic growth model. To simulate the activity of the major economies in the world, the economies of China, the US, Japan, India and Russia are constructed by the CGEs, and the economic model of other regions is still a macroeconomic growth model due to lack of data. The whole world's equilibrium is described by the GDP spillover model. The

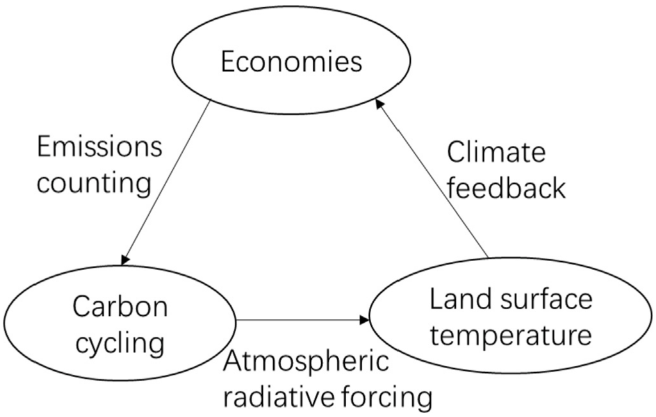

Fig. 1. Flowchart of EMRICES-E.

global carbon-cycle model adopts the single-layer carbon-cycle model(Nordhaus and Yang, 1996). In the climatic feedback process, all countries' carbon emissions make up the input of the climatic system and affect land surface temperature by atmospheric radiative forcing, the temperature affects the production in the economic system in turn.

3.1. Economic model

Autonomous economies in EMRICES-E mean the equilibrium within countries is prior to global equilibrium. The main assumptions about autonomous economies are as follows: capital and labour moves freely among the industries in the same country without flows among countries; national development demand is prior to global needs. EMRICES-E employs Cobb-Douglas production functions to describe the production of industries in China, the US, Japan, India and Russia.

$$VA_{ij} = A_{ij} L_{ij}^{\alpha_{ij}} K_{ij}^{1-\alpha_{ij}} \tag{1}$$

$$X_{ij} = VA_{ij} + II_{ij} + TX_{ij} \tag{2}$$

The value added of industry j in country i depends on total factor productivity A, labour $L$and capital K. The total output of industry j in country i is consist of value added, total intermediate inputs and net production taxes.

Endogenous technological changes assume knowledge as capital goods in production (Romer, 1990; Van der Zwaan et al., 2002), total factor productivity is decided by total capital:

$$A_{i,t} = a_i \ln\left(\sum_j K_{i,j,t}\right) + b_i \tag{3}$$

where a and b are parameters fitting by history data.

For the EU, high-income countries, upper-middle-income countries, lower-middle-income countries, and low-income countries, macroeconomic growth functions are applied. Total output $X$for each region is determined by technology T, labour L, financial capital $K$and knowledge capital Z:

$$X_i(t) = T_i(t) Z_i(t)^{\beta} K_i(t)^{\gamma} L_i(t)^{1-\gamma} \tag{4}$$

where β is the elastic coefficient of knowledge capital, $\gamma$is the elastic coefficient of financial capital.

Regions are linked by GDP spillover model, which means fiscal or monetary policies in one region could affect other regions' economic variables by market making, trade promotion and technological diffusion(Douven and Peeters, 1998):

$$\ln X_i(t+1) - \ln X_i(t) = \sum_j v_j^i \left(\ln X_i(t+1) - \ln X_i(t)\right) + g_i(t) \tag{5}$$

where v_j^i represents country i's coefficient relative to country j, g_i is economic growth rate of country i.

3.2. Emissions counting

Energy consumption structure and industrial technical progress are considered when we calculate the carbon emissions. The energy used in production is supplied by the energy industry to ensure that the supply and demand of energy are in equilibrium.

On the supply side, energy industries contain mining, coke, petroleum and nuclear fuel industry, and electricity, gas and water supply. On the demand side, energy consumption contains coal, oil, gas and non-fossil energy with proportions described as follows:

$$S_{i,t} = (C_{i,t}, P_{i,t}, G_{i,t}, NF_{i,t}), S_{i,0} = (C_{i,0}, P_{i,0}, G_{i,0}, NF_{i,0}) \tag{6}$$

where i denotes industry, t denotes year and 0 denotes base year.

The energy consumption is described as follows:

$$E_{i,t}^j = a_{E,j,i,t} X_{i,t}^j \tag{7}$$

where $E_{i,t}^j$ represents the energy consumption of industry i of country j in year t, $a_{E,j,i,t}$ is the consumption coefficient, and $X_{i,t}^j$is the industry's output. The industrial carbon emissions can be calculated by the following:

$$C_{k,t} = \sum_{H=C,P,G} En_t^H \beta_H = \sum_{H=C,P,G} En_t S_t \beta_H \tag{8}$$

where β_H is the emission coefficient of each kind of energy.

We assume that each industry's energy consumption coefficient is affected by process technical progress by randomly stochastic shock(Gu and Wang, 2017). Under planned economics, each industry would reduce energy intensity with technical progress, as described in equations (9) and (10). The new consumption coefficient is adopted after every shock if the new energy intensity is lower than the old, and vice-versa. Each step includes 1000 times shocks.

$$\ln(a_{i,t}) = \ln(a_{i,t-1}) + \psi_{i,t},\ \psi_{i,t} \sim N(0;\lambda) \tag{9}$$

$$\varsigma_{i,t} = \begin{cases} \varsigma'_{i,t} & if \quad \varsigma'_{i,t} < \varsigma_{i,t} \\ \varsigma_{i,t-1} & if \quad \varsigma'_{i,t} > \varsigma_{i,t} \end{cases} \tag{10}$$

where $a_{i,t}$ is energy demand coefficient of industry i at time t, $\psi_{i,t}$ is the random normal distribution shock and decreased with time, which indicates the improvement in energy intensity fading along with the decrease in energy intensity. $\varsigma_{i,t}$is industry i's energy intensity at time t. $\varsigma'_{i,t}$means the industry i's temporary energy intensity at time t since we conducted 1000 shocks.

3.3. Climate feedback

EMRICES-E measures the interactions between economic development and climate change. On one hand, the CO_2 from economic production would lead increasement of atmospheric temperature; on the other hand, the increasement of atmospheric temperature would have negative effect on economic production.

The single-layer carbon-cycle model means CO_2 only circulative accumulated in atmosphere. The CO_2 concentration in atmosphere would have a positive effect on atmospheric radiation, which would lead to increase on atmospheric temperature.

Nordhaus climate feedback model(Nordhaus and Yang, 1996) is adopted to reflect the global warming's economic effects $\Omega^N_{i,j,t}$:

$$\Omega^N_{i,j,t} = \frac{1 - b_{1,j}\mu^j_t}{1 + \left(\frac{D_{0,j}}{9}\right)T^2_t} \tag{11}$$

where $b_{1,j}$ is country j's damage coefficient of production, μ^j_t is country j's reduction control rate, $D_{0,j}$ is the economic loss from 3 °C of global warming of country j, T_t is the surface temperature in year t.

3.4. Data

The base year is 2009 in EMRICES-E. One reason is to avoid the effect of economic crisis in 2008, the other reason is supplying enough simulation results to compare with the real data, which are necessary to evaluate the accuracy of the simulation results. The simulation step is 1 year, and the end year is 2100, which is the goal year in the Paris Agreement. The CGE model data, energy consumption at the base year and emission coefficient are from the World Input-Output Database (WIOD) and each country's statistical yearbook. Other data needed in the model refer to previous studies(Huang, 2014; Liu, 2013).

4. Results and discussions

4.1. Base scenario

The base scenario reflects the world's economic development and carbon emissions in future based on trajectory for now. Parameters under base scenario should be tested to make sure the economic development is approximate to real world. To verify fitting degree under the base scenario, correlation analysis, mean analysis (Z-test) and one-way analysis of variance (ANOVA) are adopted to test the consistency, correlation and significant difference between the simulation emissions/GDP and real data from 2009 to 2014. The results are listed in Table 1. Based on the standardized normal distribution Z-test, we deduced the probability of variance and estimated the discrepancy of two mean values, which was applicable when the number of samples is larger than 30(Wu, 2008). The real data are from World Bank.[1] Results show that the simulation results are highly correlated with the reality with no significant differences, indicating the simulation results could reflect the reality exactly.

Table 1
Verifies the base scenario.

	Regression analysis	Z-test	Variance analysis	
	Correlation coefficient	Z-value	F-value	P-value
GDP	0.9952	0.2661	0.0708	0.7872
Carbon emission	0.9959	0.1963	0.0385	0.8451

Fig. 2 shows every region's GDP trends from 2010 to 2100 under the base scenario. China's GDP increases dramatically during this period, exceeds the EU and the US in 2046 and 2051, respectively, and would become the largest economy in the world in 2100 while accounting for 21.16% of the world's economy. India's GDP ranks fourth in the world with a high increasing rate, which is approximate to China, accounting for 11.96% of the entire economy. The lower-middle-income countries become the third economy in 2100, accounting for 12.84% of the entire economy. The GDP increasing rate of higher-middle-income countries is close to Russia and is larger than the US and EU. The GDP increasing rate of the US, the high-income countries and the EU are slow during the simulation and become the second, seventh and the fifth in the global economy at the end of simulation. Japan's increasing rate is smallest among all regions, which is related with its decreasing labour predicted by the United Nations. The low-income countries' economy is the last one in the global economy at first and become the eighth in global economy. The GDP increasing rate of the low-income countries is largest among all regions. Compared with the situation under global economic equilibrium(Gu and Wang, 2017), China's economic status maintains increasing while India's GDP increasing rate is lower under autonomous economies.

Fig. 3 shows every region's carbon emissions trends from 2010 to 2100 under the base scenario. Global carbon emissions first increase and then decrease at the end of the period. China's carbon emissions peak at 2033 (3.82 GtC) under base scenario. That means China need to take reduction actions to peak carbon emissions by 2030 that proposed by the China-US joint statement on climate change. China's carbon emissions in 2100 are smaller than that in 2010 with annual decreasing rate of 1.02%. The EU's carbon emissions peak at 2028 and the carbon emissions in 2100 are smaller than that in 2010 with annual decreasing rate of 0.60%. Russia's carbon emissions peak at 2072 and the emissions in 2100 are larger than that in 2010 by 0.11 GtC. India's carbon emissions peak at 2059 and the emissions in 2100 are larger than that in 2010 by 0.66 GtC. The carbon emissions of upper-middle-income countries, lower-middle-income countries, high-income countries all increase at first and peak in 2057, 2076 and 2036, respectively. Low-income countries' carbon emissions keep increasing at the annual rate of 1.79%, which is largest among all countries/regions during the simulation. The carbon emissions of the US and Japan decrease all the time with the rate of 1.55% and 0.42%, respectively. At the end of the century, low-income countries, upper-middle-income countries, lower-middle-income countries, India and China have large carbon emissions, accounting for almost 80% of the global emissions. Under global economic equilibrium (Gu and Wang, 2017), China's carbon emissions peaks at 2032 which is similar with our results, India's carbon emissions continue to increase and the emissions are larger than our research. India would assume more responsibility for developed countries under global equilibrium than under autonomous economies.

Structural changes of China, the US, Japan, India and Russia are discussed in this section. Generally, China's three main industries change slightly. The ratio of agriculture decreases to 3.45% in 2100. The ratio of secondary industry increases to 48.16% in 2051 and decreases to 47.81% in 2100. The ratio of tertiary industry increases to 48.82% in 2090s and then decreases to 48.74% in 2100. For different industries, the ratios of food processing industry, heavy industry, transportation industry, finance and insurance industry, commercial retail industry, energy industry and chemical industry increase during the simulation, while the ratio of light industry increases at first and decreases at last. The ratio of finance and insurance industry increases largest among all the industries. The industrial structure changes obviously from 2010 to 2050 and begins to flatten after 2050 except for the finance and insurance industry and transportation industry. In 2100, the ratios of finance and insurance industry, commercial retail industry and heavy

[1] The real emissions data of India and Russia in 2012 are missing, so we excluded these data.

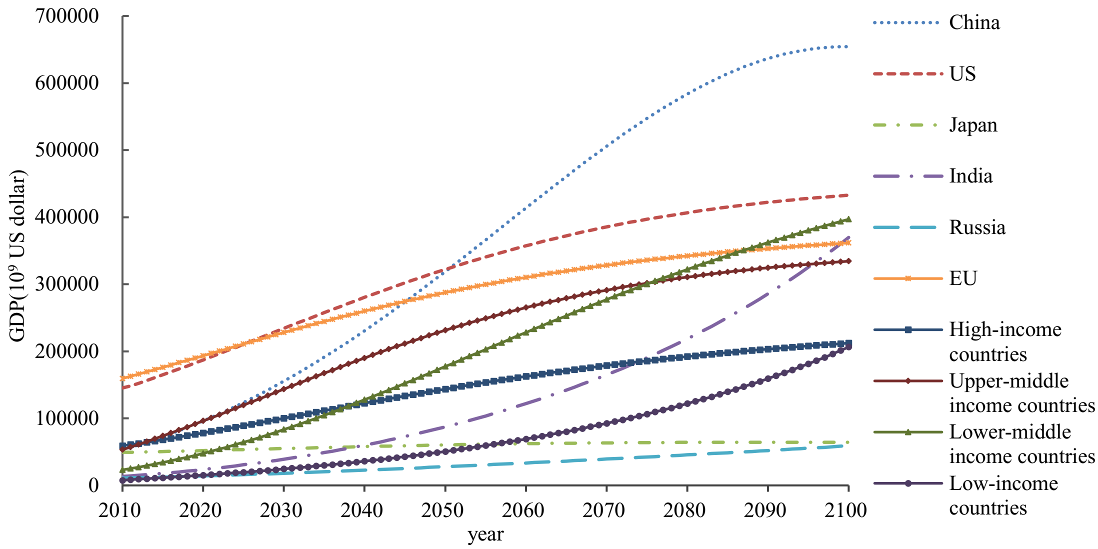

Fig. 2. GDP of all countries and regions from 2010 to 2100 under the base scenario.

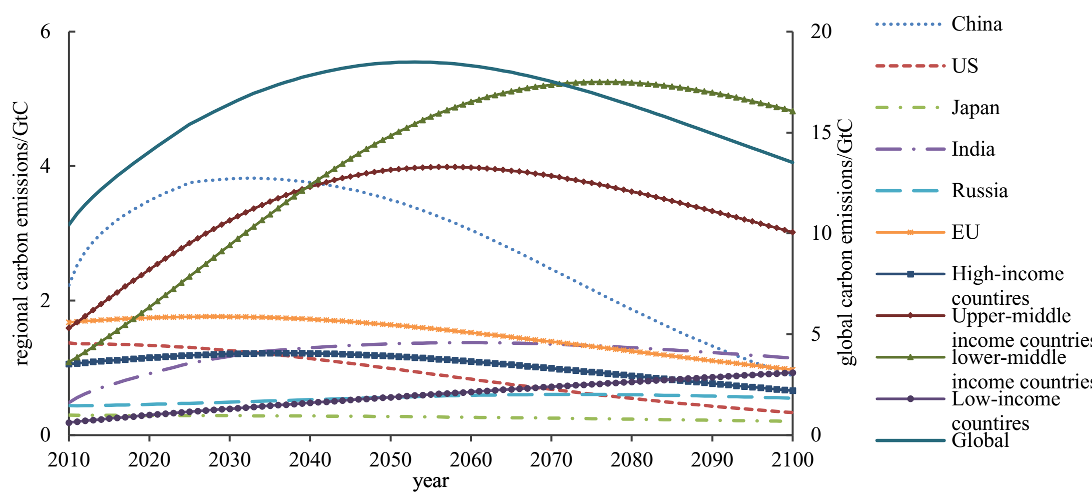

Fig. 3. Carbon emissions of all countries/regions from 2010 to 2100 under the base scenario.

industry are in the top. For the perspective of economic development, service industry especially finance and insurance industry and transportation industry will be main forces of China's economy.

The US's industrial structure changes slightly during the simulation. The ratios of agriculture and tertiary industry increase and the ratio of secondary industry decreases. From industrial perspective, the ratios of finance and insurance industry and energy industry have modest increase relatively. The ratios of commercial retail industry and construction have slight decrease relatively. In general, along with the shift to developing countries, the ratio of tertiary industry would maintain around 80%. For Japan, the ratio of agriculture increases after a short decrease at first. The ratio of secondary industry takes on similar trend with agriculture. The ratio of tertiary industry decreases during the simulation. The ratios of construction and other service industry have relatively modest increase, while the ratios of finance and insurance industry and commercial retail industry increase relatively.

For India, the ratios of agriculture and tertiary industry decrease while the ratio of secondary industry keeps rising during the simulation. That means the advantages of India's secondary industry would keep under autonomous equilibrium. From industrial perspective, the ratios of heavy industry and energy industry have sharp increase and the ratios of commercial retail industry and construction have substantial decrease. For Russia, the ratio of agriculture decreases after a slight increase, while the ratio of tertiary industry decreases during the simulation. The ratio of secondary industry takes on a steady rising trend. For the secondary industry, it is better under autonomous equilibrium than global equilibrium. The ratios of energy industry and transportation industry increase obviously while the ratios of commercial retail industry, construction and other service industry decreases. In general, the ratio of secondary increases in China, India and Russia. At the end of simulation, the ratio of India's secondary industry is larger than Russia's. Even though the ratio of India's secondary industry is smaller than China's, the rising speed in India (0.64%) is higher than China (0.03%). That gives a clue that India would become manufacturing center in the future.

Compared with changes of industrial structure results under global equilibrium(Gu and Wang, 2017), the ratios of China's, India's and Russia's agriculture have similar trend and all decrease during both simulation, and the ratio of Japan's secondary industry have an increasing trend at the end of simulation. There are some different trends from situations under global equilibrium. In our simulation, the ratio of China's secondary industry decreases later. The ratio of India's and Russia's secondary industry increases gradually, and India's increasing speed is higher than China and Russia. The ratios of the US's secondary and tertiary industry take on repetitive movements under global equilibrium.

The global surface temperature increases by 3.37 °C in 2100 compared to the pre-industrial level and is 2.61 times larger than that in 2010. This result is consistent with the scope (1.9C-4.0 °C) described by IPCC-AR4 (2007) and cannot meet the control goal (2 °C) proposed by Paris Agreement. The CO_2 density also increased under the baseline scenario, reaching 644.42 ppmv in 2100 and exceeding the international control density (450–500 ppmv).

4.2. No technical progress on carbon reduction scenario

No technical progress on carbon reduction scenario means free emissions without any technical progress on each country's reduction technology and is called Scenario 1 for short. Under this condition, every region's technology maintains the 2009 level until 2100, with no technical energy innovation and no reduction policies and attempting to illustrate the situation when countries stop applying reduction policies. The energy consumption matrix of each country during the simulation remain the same as in 2009.

The global GDP's increasing rates are 3.07% (2010–2030), 2.19% (2030–2050), 0.76% (2050–2100) and 1.59% over the whole period. These are smaller compared with the base scenario. Each region's GDP trends are shown in Fig. 4. The total GDP in 2100 would be ordered by China, the lower-middle-income countries, the EU, the upper-middle-income countries, the US, India, the high-income countries, the low-income countries, Russia and Japan. One important phenomenon is that some regions' GDP decline in this simulation compared with base scenario, such as the GDP of Japan, the US, the EU, China and the middle-income countries decline since 2054, 2074, 2082, 2087 and 2088, respectively. The production is affected by climatic feedback for the reason that there are no controls on carbon emissions. That means this recession is related to the feedback of the climatic system. This result is quite important for policy makers, that climatic governance is useful not only for global climate change but also for their own economic development. Considering the time when the economic recession appears, the US's GDP recession occurs earlier than most other regions in this situation. For the increasing rate of GDP, the low-income countries have the largest increasing rate, Japan has the smallest increasing rate, the increasing rates of the US and the EU are similar, and India and China have similar increasing rates. The economic recession coincides with findings of previous research, such as climate change would make 77% of countries poor in per capita(Burke et al., 2015), the increase in global economic loss if the global temperature increase exceeds 2 °C, and the per-capita GDP declines by 30% compared with that in 2100 when the global temperature increase reaches 4 °C(Burke et al., 2018). It should be noted that the economic recession of the US occurs earlier than China, which means that the climate skeptics about China proposed by Trump is incorrect. This finding also illustrates that carbon reduction is beneficial for the economy. The purpose of maintaining the US's economic profit by withdrawing from Paris Agreement may not come true in the long run. Similar economic loss has been found in US based on "bottom-up" micro-founded estimations(Hsiang et al., 2017).

The carbon emissions' trends are shown in Fig. 5. The global carbon emissions increase from 10.29GtC (in 2010) to 58.80GtC (in 2097) and decrease to 58.75GtC (in 2100). The peaking year is 44 years later than that under base scenario and the emissions are larger. For each region, the carbon emissions of low-income countries, Russia and India increase all the time. Other regions' carbon emissions all increase a period and decrease at the end of simulation. The carbon emissions' trends of the US and Japan are different from base scenario, with peaking at 2073 and 2053. It should be noticed that there is no technical progress on carbon reduction, that means their carbon emissions decline are mostly related to the recession on GDP. China's carbon emissions peak at 2086, that is quite later than base scenario. The trends of high-income countries, upper-middle income countries, lower-middle income countries and the EU is close to these under base scenario.

The trends of energy use are similar with carbon emissions. China's total energy use peaks in 2086 with 1394.74 MTJ, which is later and larger compared with base scenario. At the end of simulation, China's total energy use is 9.56 times larger than that in 2010 and decreases by 10.50% than the peak emission. This indicates China's energy consumption structure in 2009 is quite rugged. Japan's energy use peaks in 2053 and the energy use in 2100 decreases by 19.02% compared with the peak emission. The US's energy use peaks in 2073 and the energy use in 2100 decreases by

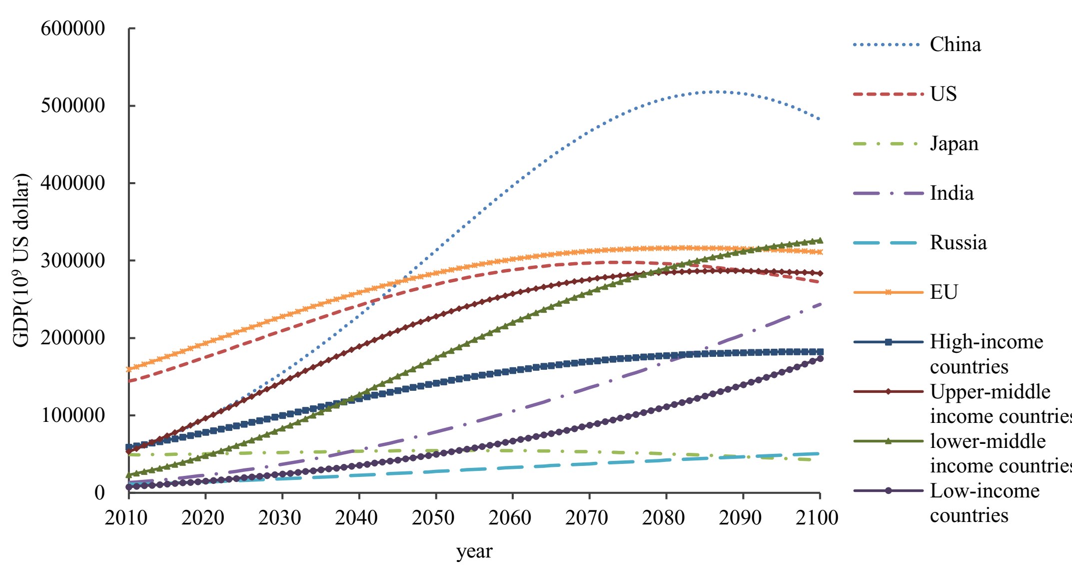

Fig. 4. GDP from 2010 to 2100 under scenario 1.

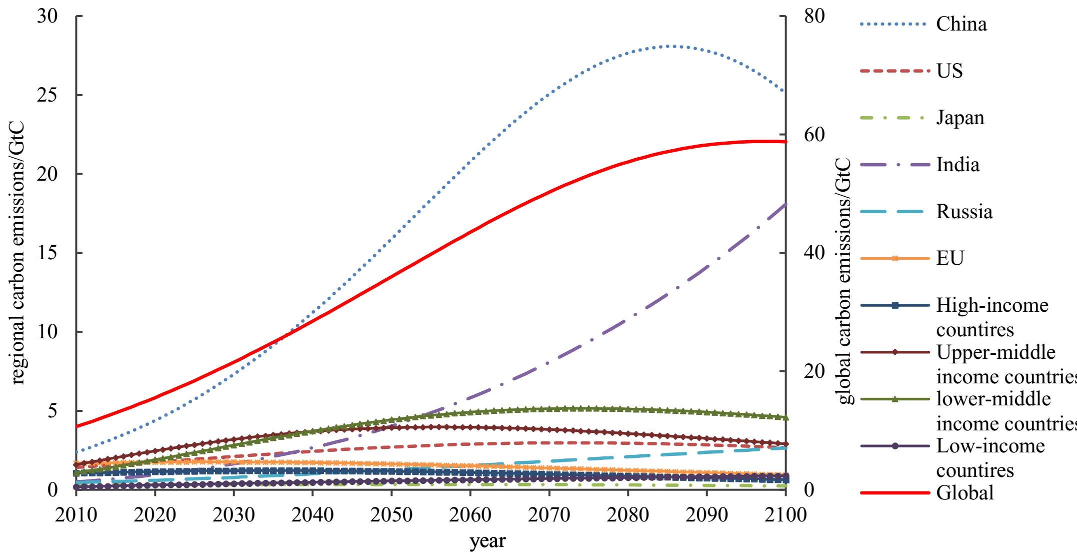

Fig. 5. Carbon emissions from 2010 to 2100 under Scenario 1.

10.07% compared to the peak emission. Compared with the energy use in 2010, India's energy use increases by 33.83 times and is close to China, while Russia's energy use increases by 4.69 times in 2100.

From 2010 to 2100, global cumulative carbon emissions reach 3484.93GtC and are 2008.70GtC higher than base scenario. China has the largest cumulative carbon emissions, followed by India, the lower-middle-income countries, the upper-middle-income countries, the US, the EU, high-income countries, low-income countries and Japan. Compared with base scenario, China's cumulative carbon emissions increase most among all regions, followed by India, while the US and Russia show a little increase.

Considering the industrial cumulative energy use in each country (Table 2), the energy industries account for almost half of the total cumulative energy use in China, the US, Japan, India and Russia. India's energy industries' cumulative energy use takes the largest part (69.06%), followed by Russia (67.65%). The heavy industry's cumulative energy use also takes large part of the total cumulative energy use and the rate of China is the largest.

From the industrial perspective, most industries in China have the largest cumulative energy use except the food processing industry, commercial retail industry and finance & insurance industry. The cumulative energy use for the heavy industry in China accounting for 72.46% of the total. The cumulative energy uses of agriculture, the energy industry and the chemical industry in China take 58.47%, 51.20% and 47.23% part of the total of these five countries, respectively. The US's commercial retail industry and the finance & insurance industry have largest cumulative energy use among countries, accounting for 39.46% and 66.04% of the total, respectively. India's food processing industry has the largest cumulative energy use among all countries.

The global surface temperature increases gradually compared with pre-industrial level, and the rising temperature in 2100 would be 4.92 °C, which is 4.46 times greater than that in 2010 and has exceeded the upper limit required by IPCC-AR4 (4.0 °C). Compared with base scenario, the temperature change is 1.55 °C larger.

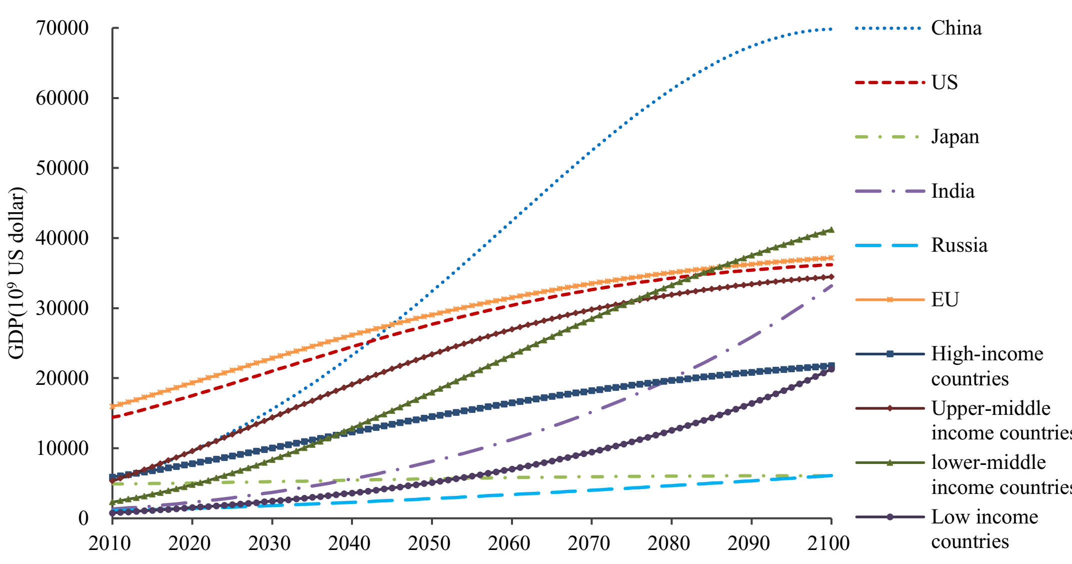

Fig. 6. GDP from 2010 to 2100 under scenario 2.

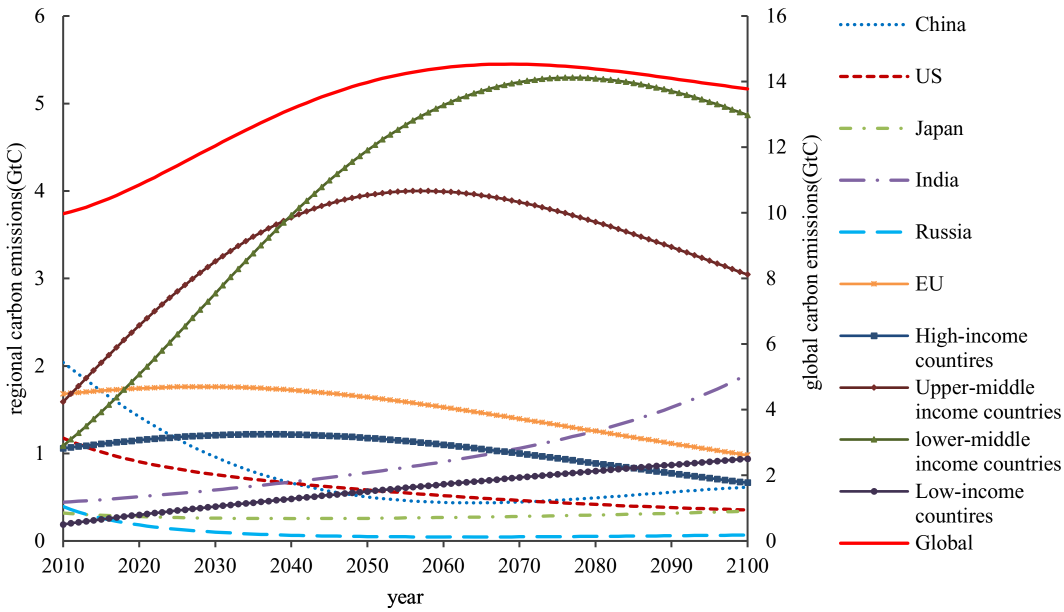

Fig. 7. Carbon emissions from 2010 to 2100 under Scenario 2.

Table 2
Industrial cumulative energy use for countries (EJ).

Industries	China	US	Japan	India	Russia
Agriculture	2126.88	181.11	27.23	1083.53	218.64
Food processing industry	728.16	232.37	23.42	993.07	39.70
Energy industry	47204.77	11552.74	1452.02	24871.68	7113.69
Light industry	944.11	317.06	24.86	498.16	45.90
Chemical industry	4187.14	1193.87	252.28	2102.41	1128.93
High industry	15922.98	731.90	241.92	4092.70	984.74
Construction	1453.77	373.46	61.96	927.68	126.14
Commercial retail industry	630.52	798.60	103.27	380.32	111.18
Transportation industry	2946.03	1299.56	195.18	907.11	554.73
Finance & insurance industry	399.11	1289.49	105.96	77.31	80.59
Other service	921.40	670.87	82.69	81.83	111.71

4.3. *Exogenous technical progress on carbon reduction scenario*

Under this scenario, technical progress on technology in the future is exogenous and determined by data-fitting using historical energy use. This scenario is called scenario 2 for short. The future energy consumption matrixes are fitted by energy consumption matrices from 1995 to 2009.

Under scenario 2, the annual increasing rate of global GDP is 1.88%. China still would be the largest economy, accounting for 22.72% of the world's GDP in 2100 (see Fig.6). China's increasing rate of GDP in scenario 2 (2.90%) is little higher than base scenario (2.82%) and scenario 1 (2.47%). Lower-middle income countries would be the second largest economy, accounting for 13.40% of the world's GDP in 2100. The EU and the US have similar increasing rate and would be the third and fourth economy in 2100. The US's increasing rate of GDP in scenario 2 (1.03%) is little higher than scenario 1 (0.71%) and lower than base scenario (1.22%). The upper-middle-income countries would be the fifth economy in 2100 with the increasing rate of 2.10%. India has the second largest increasing rate among all regions and would be the sixth economy in 2100. High-income countries are next to India in 2100. Low-income countries have the largest increasing rate among all regions and exceed Russia and Japan in the middle of simulation. Japan has the lowest increasing rate among all regions and takes the last place in global economy. Russia's increasing rate is close to high-income countries and would be the last but one economy due to the small economy at the beginning of simulation.

Under scenario 2, the global carbon emissions increase from 2010 to 2069 by the rate of 0.88% and decrease to 13.78GtC in 2100. The carbon emissions of countries/regions rank by upper-middle income countries, lower-middle income countries, India, EU, low-income countries, high-income countries, China, the US, Japan and Russia (see Fig.7). Low-income countries' and India's carbon emissions increase and the US's while Russia's carbon emissions decrease during the period. The carbon emissions' trends of high-income countries, upper-middle income countries, lower-middle income countries and the EU are similar, peaking at 2036, 2057, 2077 and 2028 respectively. It should be noticed China's and Japan's carbon emissions increase slightly at the end of simulation. The reason is that there is no structural optimization during data fitting, which lead some industries' emission intensity increase the whole period if their history data is high energy demand. That indicates data fitting is not suitable in long term simulation.

The global surface temperature and the CO_2 density decline compared with base scenario. The global surface temperature would increase by 3.06 °C in 2100, which is 0.31 °C lower than the base scenario. Even though, the mitigation goal of 2 °C cannot be realized under this scenario.

5. Conclusions and perspectives

5.1. Conclusions and policy implications

Global climate change and its economic effects have received more attention in present. Considering recent economic situation, such as UK withdraws from the EU and the US quitted from Paris Agreement, we constructed a new IAM named EMRICES-E to predict global economic growth and carbon emissions under autonomous economies, which means preferential equilibrium at country scale, and evaluate the effects of different technical progress on carbon reduction. The economic growth, carbon emissions, industrial structure, energy use and temperature change are main indicators. We considered endogenous technical progress in EMRICES-E when counting the carbon emissions and proved that the data fitting on technical progress is not suitable for long-time forecasting.

Under the base scenario, the economic status of developing countries/regions (such as China and India) rise gradually since their economies grow faster than developed regions (such as the US, the EU) during the simulation. The carbon emissions of developing countries/regions (such as upper-middle income countries and lower-middle income countries) also increase dramatically and hold large part of the total world's carbon emissions. The reduction task for developing countries/regions is a long way to go based on development trajectories for now. Even some countries/regions' carbon emissions have peak emissions, such as China's and India's carbon emissions would peak in 2033 and 2059, that's not enough to realize the reduction goal in 2100 for the whole world.

As for changes on industrial structure, the ratios of different industries in developing countries changes noticeably compared with developed countries. Compared with the situation under globalization, the secondary industries in developing countries show distinct development trajectory under autonomous economies. India would become the world's manufacture center with high increasing speed on the ratio of secondary industry. Developed countries need push on carbon reductions on technology and capital while supply technical and capital aid to developing countries.

If all the regions stop applying reduction policies, the global surface temperature would increase by 4.92 °C in 2100. What's worse, climate change would bring negative effects on regional production and even result economic recession if there are no controlling measures on carbon emissions. Not only low-income countries would suffer economic loss predicted by IMF(IMF, 2017), developed countries' economy also would decrease due to the negative feedback of increasing temperature.

For China, the US, India, Japan and Russia, energy and heavy industries consume large part of energy. Improving energy efficiency on energy and heavy industries would be focused to decrease the energy use for whole region. From industrial perspective, developing countries takes more energy use compared with developed countries in most industries, except for commercial retail industry and finance & insurance industry. Developing countries should make progress on secondary industrial carbon reductions, including carbon capture, utilization and storage (CCUS).

5.2. Research limitations and perspectives

Due to data limitation, the EMRICES-E only improved the economic model of China, the US, Japan, India and Russia, more delicate data are needed to realize the improvement on other regions' economic model. The CGE model used in EMRICES-E is a "top-down" economic model without description on micro-scale. That resulted lack of analysis on innovation impetus and high leverage on micro-scale. We adopted the industrial energy consumption structure contains coal, oil, gas and non-fossil energy due to the supply and demand of energy should be equal under CGE model. In fact, the detailed energy consumption forms would be better on reflecting the energy consumption structure. As for energy technology, future work should consider alternative cost among different energy forms, such as different power generation technology.

Results in this paper show the mitigation goal of the global surface temperature increasing by 2 °C in 2100 is a tough work for all countries. More attention should be taken on effects of carbon policies in the future. For now, more than 190 regions have submitted their intended national determined contributions (INDCs). Future work should focus on the effects of carbon reduction under NDCs and the ways to realize their NDCs. Differentiated carbon tax among countries and economic effect should be considered since levying a carbon tax is usually for carbon reductions.

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