SYSTEM DYNAMIC ANALYSIS OF GREENHOUSE EFFECT BASED ON CARBON CYCLE AND PREDICTION OF CARBON EMISSIONS

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Abstract. With the intensification of greenhouse effect, the global average temperature gradually increases, and the atmospheric CO_2 concentration has exceeded 400 ppm. It has been a global consensus to reduce carbon emissions and the impact of the greenhouse effect. However, researches are rare on how to develop a reasonable emission reduction target and distribute funds in maintaining sustainable development. Based on the system dynamics method in the environmental system, we took a macro approach to simulate the trends of CO_2 amount, CO_2 concentration and temperature change in the next 5 decades. Through sensitivity analysis, we found anthropogenic CO_2 emissions as the major factor influencing the above trends. The iteration result at the step size of -0.4% showed that the -3.2% CO_2 emission reduction rate can achieve the Paris Agreement goal. On this foundation, we calculated the future amount of global CO_2 emission reduction and its investment and depict the latter, which provides reference for relevant sectors to formulate CO_2 emission reduction policies.
Keywords: *global warming, CO_2, emission reduction, investment path, policies*

Introduction

Reducing carbon emissions and slowing down the greenhouse effect has become the consensus across the globe, as countries around the world have signed several climate agreements to mitigate the greenhouse effect. As early as 1992 (Tu, 2005), the United Nations Conference on Environment Development formulated a convention on climate change in Rio de Janeiro, Brazil. In 1997, 149 countries adopted the Kyoto Protocol, which set the goal of limiting the average temperature rise below 2 °C by the end of the 20th century (Meinshausen et al., 2009). The year of 2015 witnessed the signing of the Paris Agreement among representatives from more than 200 countries. According to it, the rise in global temperature should not exceed 2 °C or if it can be achieved 1.5 °C compared to the value before industrialization (Li, 2017; Ogle et al., 2018); the countries and regions around the world should achieve the peak carbon emissions as soon as possible and meet the goal of zero CO_2 emission in the second half of the 21st century (Chen and Chen, 2016; Marino et al., 2017).

To ensure that the temperature rise is not higher than 2 °C, the equivalent of anthropogenic CO_2 should not exceed 450 ppm (which used to be 280 ppm before industrialization) (Elzen and Höhne, 2008). IPCC experts concluded that the 2020 emission volume of developed countries should be reduced by 25-40% compared to the 1990 one, which is 15-30% for developing countries (Elzen and Höhne, 2010). The results of a variety of studies show with a higher than 66% probability, that if we want the total anthropogenic temperature rise at the end of the century not to exceed the temperature of the 1861-1880 period by more than 2 °C, countries should keep the amount of CO2 emissions accumulated since 1870 below 2,900 Gt, and yet it was already 1,900 Gt by 2011 (Magazzino, 2016). In June 30, 2015, our country submitted the document of Intended Nationally Determined Contribution (INDC), committing to reach the peak carbon emissions roughly by 2030, drop the carbon intensity by 60%-65% than 2005, and occupy around 20% accumulated carbon emissions quota of the total according to the equity requirements in the effort-sharing scheme (Cui et al., 2016). Most of the current researches are concentrated on total amount control, focusing little on the annual amount and allocation of investments on carbon dioxide emission reduction. The fragmented CO_2 emission goal-settings among countries are disadvantageous to unifying CO_2 emission reduction paths (Sikharulidze et al., 2016; Huang et al., 2016; Gotovsky et al., 2018). In this study, the system dynamics model was used to predict the temperature change trend and carbon dioxide emission trend in the next 50 years. By analyzing the influence of different emission strategies on the greenhouse effect, the optimal emission strategy was finally determined. The research can provide a reference for the country to formulate a reasonable carbon emissions policy.

Material and methods

Carbon cycle model and greenhouse effect

The land and sea on the surface of the earth will absorb the short-wave radiation from the sun and convert it into heat which returns to the outer space in the form of long-wave radiation. This circulation helps balance the terrestrial temperature. However, CO_2, CH_4 and other greenhouse gases are active in reflecting long-wave radiation off the atmosphere, causing the “greenhouse effect” as the temperature on the earth surface rises (Frolking et al., 2006; Köhler et al., 2017). Greenhouse effect is a natural phenomenon caused by the emission of large amounts of greenhouse gas due to the rapid economic development in recent years. In this scenario, the atmospheric and marine temperatures will ultimately increase, and the glacial sheet in the Polar Regions will melt down, causing the rise in sea levels and the change of climate patterns (Cloy, 2018; Perry et al., 2012; Shao et al., 2016).

The main measure to control the greenhouse effect are to control carbon emissions, mainly due to the recent high contribution of CO_2 84% to atmospheric radiation (Levin, 2012). Therefore, it is necessary to study on the global carbon cycle model. In doing so, there are mainly two approaches: dynamic simulation and statistics (Bayer et al., 2015). The latter method is simple but physically blurred. With the analysis of historical data, this method can directly establish the model of carbon cycle law to show the past and future development trend. However, it fails to illustrate the system dynamics behaviors of carbon cycle to climate change, and the source and integrity of known data limits the precision of the model. The statistical method can be combined with the dynamics model to achieve good effect (Isacs et al., 2016). The system dynamics method includes the radiation convection mode, energy balance mode, and atmospheric circulation mode (Li and Tan, 2000). They will be analyzed in the following part, so that we can choose the most suitable mode for this study.

Radiation convection: By studying the effect of greenhouse gas on the solar radiant energy and the terrestrial and atmospheric radiation, we can use this method to calculate

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the potential contributions of different green gases to global warming and the atmospheric contours when the radiations reach a balanced state. Also, by considering the atmosphere as a column, this mode allows the establishment of a greenhouse effect model with clear physical meanings and simple calculations (Inamdar and Ramanathan, 1994). Nevertheless, as the influence of atmospheric circulation is excluded, this method is insufficient for the biosphere analysis and the carbon cycle effect research in a large scale.

Atmospheric circulation: through the study of carbon cycle law of the ocean, the atmosphere and the terrestrial biosphere under global warming, this mode includes the marine factors of water content, heat and chemical effect and the terrestrial factors of plant photosynthesis and respiration in analyzing carbon cycle (Babič, 2017; Chen et al., 2015; Xu and Shang, 2016; Zhang et a., 2018). As the description of the physical process of carbon cycle in the atmosphere, this mode fits well for long-lasting, large-scale issues with highly precise outcomes. However, the error of research results can be high due to the large data pool and the complicated calculation procedures.

Energy balance: this mode is mainly based on the energy balance model established under the law of conservation of energy. The energy balance equation is *Equation 1*:

$$C\frac{dT}{dt} = R\downarrow - R\uparrow \quad \text{(Eq.1)}$$

where:
C: the thermal inertia of land, ocean and the atmosphere,
R↓: incoming radiation,
R↑: outgoing radiation.
Equation 1 can be converted into *Equation 2*:

$$C\frac{\partial T}{\partial t} = Q(1-\alpha) - \Delta I - dvi(\mathrm{F}) \quad \text{(Eq.2)}$$

where:
Q: solar radiation,
α: reflectivity,
ΔI: outgoing long-wave radiation,
dvi (F): net energy flux along the circle of latitude.

This method takes into account the carbon cycle system and the influence of biosphere on atmospheric temperature increased. It can reflect the physical processes and the sensitivity of different indicators to climate change in a clear and simple way (Pugh et al., 2016). In this study, the energy balance model will be used in line with the data obtained from the atmospheric circulation mode and the radiation convective mode to establish a system dynamics model of the greenhouse effect.

Relationship between CO_2 concentration and temperature increase

According to the present study, the atmospheric CO_2 concentration is correlated with the increase in atmospheric temperature. By collating the average terrestrial temperature data statistics from the NASA Goddard Institute for Space Research (*Fig. 1*), we find that the average temperature of the earth has increased annually since 1958, rising by 1 °C in 2015. Furthermore, we fit the equation of temperature increase (ΔT) at the R^2

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value of 0.8875, as shown in *Equation 3*. The reliability of these data should be high as they conform to the statistical principle.

$$\Delta T = 0.0001Y^2 + 0.0086Y - 0.0914 \quad \text{(Eq.3)}$$

where Y: the difference of temperature between the calculation year and the year of 1958.

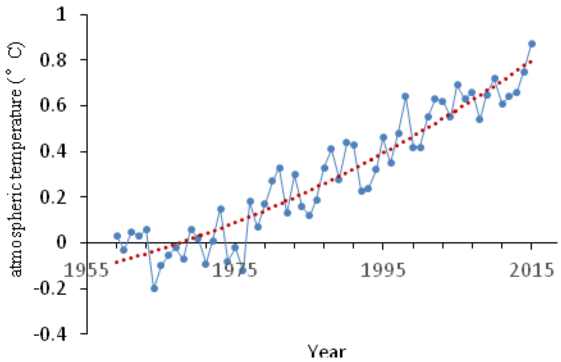

Figure 1. *The broken line of annual temperature increase since 1958*

According to *Equation 3*, it can be calculated that the temperature increase at the end of this century will reach 3.15 °C without considering the increase in CO_2 emissions from social development or human intervention. This value is far higher than the ideal value of the Kyoto Protocol. Actually, due to social development and economic boom, the CO_2 emissions will inevitably increase.

Figure 2 is the environmental monitoring data from the American Earth System Research Lab. The atmospheric CO_2 concentration has increased from 315 ppm in 1958 to the current 406 ppm, which is only 44 ppm lower than the threshold of 450 ppm. With these data, the CO_2 concentration equation can be obtained, as shown in *Equation 4*:

$$C_{CO2} = 0.0123Y^2 + 0.8119Y + 314.47 \quad \text{(Eq.4)}$$

where Y: the difference of CO_2 concentration between the calculation year and the year of 1958.

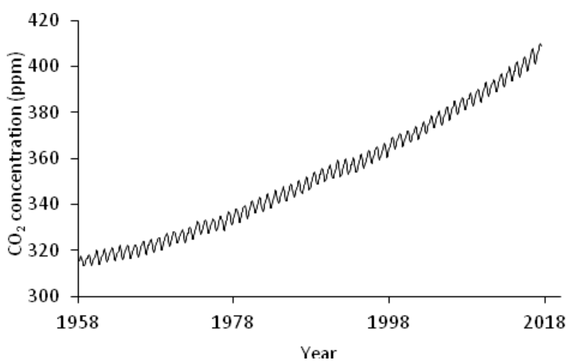

Figure 2. *Changes in atmospheric CO_2 concentration since 1958*

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According to the average annual data, we obtain the average annual growth line of atmospheric CO_2 concentration after 1958. It can be seen from *Figure 3* that the average annual growth rate of CO_2 concentration increases from 0.75 ppm in 1958 to the current value of 2.98 ppm, indicating a fast speed of growth.

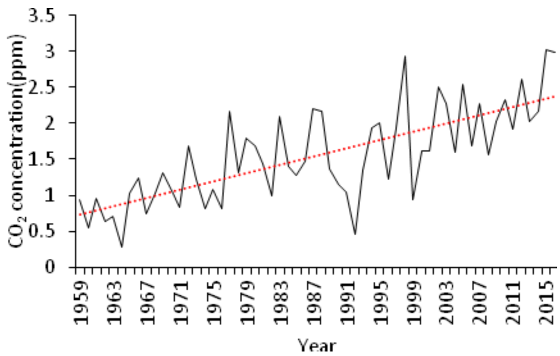

Figure 3. *The average annual growth line of CO_2 concentration since 1958*

The CO_2 concentration (C_{CO2}) and atmospheric temperature increase (ΔT) are fitted into a relationship line, as in *Figure 4*. With another fitting, we obtain the relationship formula between CO_2 concentration and atmospheric temperature increase (ΔT), as shown in *Equation 5*:

$$\Delta T = 8\times10^{-5} C_{CO2}{}^{2} - 0.0472 C_{CO2} + 6.777 \quad \text{(Eq.5)}$$

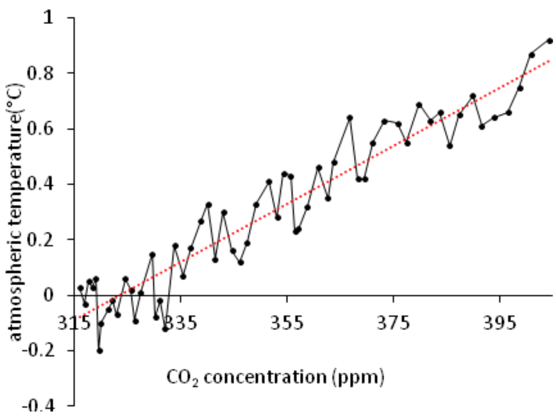

Figure 4. *The relationship line of CO_2 concentration and atmospheric temperature growth trend*

Establishment of the system dynamics model of greenhouse effect

Greenhouse effects in the global carbon cycle

The main source of greenhouse gases in the atmosphere are anthropogenic emissions, the respiration of plants and animals, and the release of dissolved permafrost. Greenhouse gases are adsorbed mainly by dissolving in ocean and plant photosynthesis (Albergel, et al., 2010; Stark et al., 2018), as shown in *Figure 5*.

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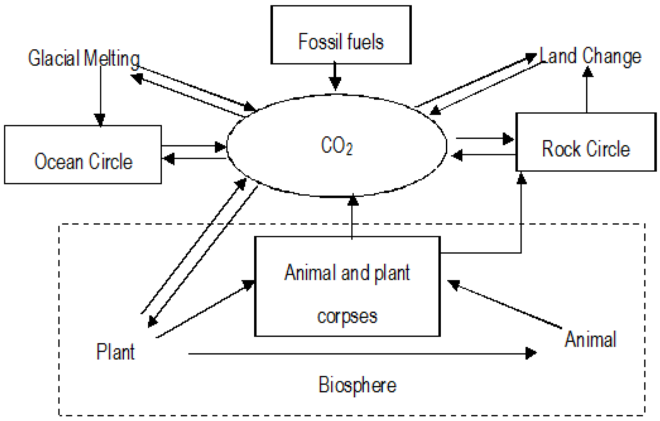

Figure 5. *Global carbon cycle flow char*

As can be seen from *Figure 5*, human production life needs to consume fossil fuels. The resultant large amount of CO_2 is discharged into the atmosphere and, through atmospheric circulation, partly dissolved into sea water and accumulated in the form of carbonate while partly absorbed by plants through photosynthesis. If plants are eaten by animals, some of the carbon will stay in the animal body and not released in the form of CO_2 until the animal is dead and the dead body is under microbial decomposition; the other carbons will exist in soil layers and turn into the carbon component of rock after a long time. In this process, those that cannot be fixed will circulate in the atmosphere and generate the greenhouse effect. As a result, the atmospheric temperature will rise, melting glaciers and thawing permafrosts. Consequently, the CO_2 that used to accumulate in glaciers and permafrosts will be released to the air, which intensifies the greenhouse effect. The atmospheric CO_2 equilibrium equation is as follows (*Eq. 6*) (Shi and Guo, 1997):

$$\frac{dn_a}{dt} = p_{fos} + p_{bio} + k_{ma}(\mathrm{N_m} + \xi_{\mathrm{nm}}) - \mathrm{k_{am}}(\mathrm{N_a} + \mathrm{n_a}) + \mathrm{F_{bi,a}} + \mathrm{F_{a,bi}} + \mathrm{F_{h,a}} \quad \text{(Eq.6)}$$

where:

P_{fos}: CO_2 release rate of fossil fuels,
P_{bio}: the rate of CO_2 release due to land use change,
K_{ma}: ocean atmosphere exchange coefficient,
$K_{am:}$ atmosphere ocean exchange coefficient,
N_m: total carbon in the ocean,
N_a: total carbon in the atmosphere,
n_a: atmospheric carbon increment,
ξ_{nm}: ocean buffer factor,
$F_{bi, a}$: CO_2 exchange flux from land to the atmosphere,
$F_{a, bi}$: CO_2 exchange flux from the atmosphere to land,
$F_{h, a}$: CO_2 exchange flux from soil humus to the atmosphere.

System dynamics principles

System Dynamics (short for "SD") is an approach to understanding the dynamic behaviour of complex systems over time created by Professor Jay W. Forrester of the

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Massachusetts Institute of Technology (Alirezaei et al., 2017). It is based on the theory of feedback control and computer simulation technology in studying the relationship between the structure, function and dynamic behavior of complex systems. The system dynamics emphasizes the system as a whole, understand the composition of the system and the interaction of system components, and can carry on the dynamic system simulation experiment to examine the system dynamic change behavior and trend when the different parameters or strategic factors are inputted. In this way, decision-makers can take different measures and observe the simulation results in different scenarios.

The system dynamics model is a causal mechanism model. It emphasizes the decisive role of system inherent mechanism played in system behaviors, performing well in addressing long-term and periodic issues. In the case of insufficient data and unquantized parameters, feedback loops are also usable in some researches. The system dynamics model is good at handling high-order, non-linear, time-varying complex problems. Because of the unparalleled advantages of system dynamics in the study of complex nonlinear systems, it has been widely used in many fields such as society, economy, management, resources and environment.

System dynamics model in the global carbon cycle

The greenhouse effect model was established in Vensim according to the principle of the carbon cycle and the equations summarized above, as shown in *Figure 6*. Based on the 2015 report of the United Nations Environment Program, the CO_2 concentration reaches 400.21 ppm, the atmospheric CO_2 content is 1,965 Gt, and the global anthropogenic CO_2 emission is 36.3 Gt with the total atmospheric CO_2 amount as the variable of integration. By measuring World Bank statistics, the annual CO_2 emission in recent years grows at the rate of 0.82%. The CO_2 produced by the change in land used is about 9.47% of anthropogenic emission (Bergamaschi et al, 2013), while the CO_2 equivalent released annually from the global permafrost is about 1.84 GT. The ocean absorbs about 35% of anthropogenic CO_2 per year, and the proportion is 20% to the biosphere.

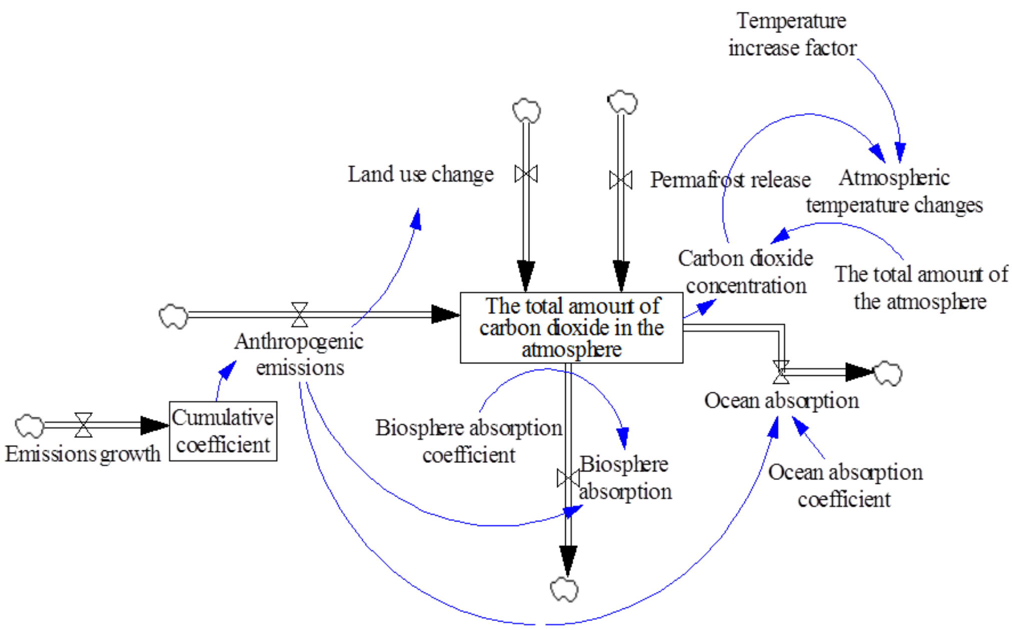

Figure 6. *Global carbon cycle and greenhouse effect model*

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Results and discussion

With 50 years as the data boundary, these data are inputted into the model for simulation analysis without taking any carbon reduction measures.

The total amount of CO_2 in the atmosphere is analyzed and shown in *Figure 7*. The figure shows the constant increase in total atmospheric CO_2 amount from the 1,964 Gt in 2015 to the final 3,581.85 Gt, rising by 82.38%. The initial CO_2 concentration of 404 ppm grows to 736.92 ppm by the fifth decade, which far exceeds the warning line of 450 ppm.

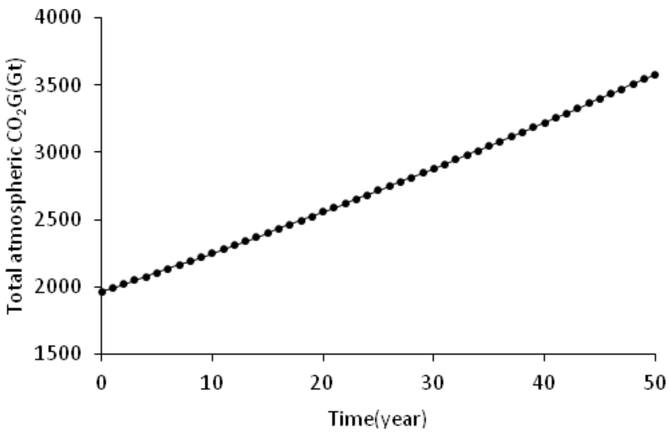

Figure 7. *Total atmospheric CO_2 amount*

The impact of anthropogenic emissions growth rate on key indicators

The anthropogenic emissions are mainly determined by the emission growth rate (Van den Bergh and Botzen, 2015). By adjusting the emission growth rate, the impact of the emission growth rate on the atmospheric index can be found, providing an intuitive way for determining the reasonable emission amount on which basis the goals of the upper limit and reduction amount of emitted CO_2 can be formulated.

The current annual emission growth rate is 0.82%, and we set the decline in growth rate to 0.4%, as shown in *Figure 8*. With the decrease of the CO_2 emission growth rate, the anthropogenic CO_2 emission line begins to tilt down. When the emission growth rate drops to -2%, the anthropogenic emissions will become zero in 50 years. As the emission growth rate continues to decrease, the time required for reaching zero carbon emissions will be shortened gradually. When the emission growth rate is -3.2%, the zero carbon emissions will be achieved in 28 years. However, the lower the emission growth rate is, the more challenges the technologies will be posed to. After a comprehensive thought, we will discuss what the reasonable decline amount of growth rate should be below.

To obtain the reasonable decline amount in growth rate, we re-simulate the model in terms of the CO_2 concentration in the atmosphere at different emission rates, as shown in *Figure 9*. The figure shows that the CO_2 concentration line becomes inverse parabolas with peaks. The peak value gradually decreases as the decline in growth rate is enlarged. When the growth rate becomes -3.2%, the sole peak will emerge in the 22th year at the value of 453.99 ppm. The calculated result complies with the result of INDC.

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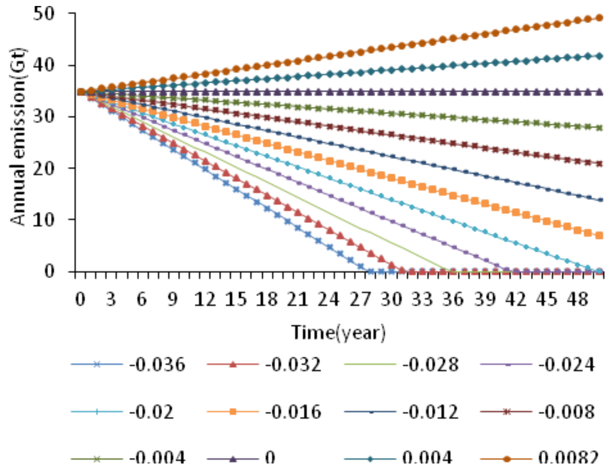

Figure 8. *Annual emission amounts at varying emission growth rates*

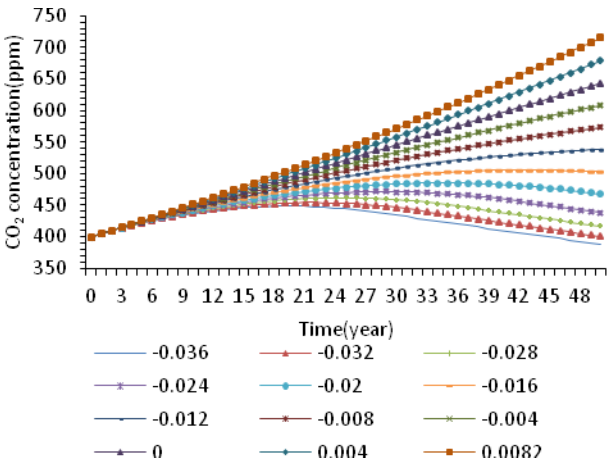

Figure 9. *CO_2 concentration in the atmosphere at different emission rates*

We continue to simulate the model to analyze the average atmospheric temperature changing with the CO_2 emission growth rate, as shown in *Figure 10*. As can be seen from the figure, if the emission growth rate remains unchanged, the atmospheric temperature change curve will go up exponentially, which will bring disastrous consequences to the environment. When the CO_2 emission growth rate declines to -0.8%, the average atmospheric heating curve will present the form of inverse parabola. When the CO_2 emission growth rate declines to -2.8%, the peak temperature becomes 2.029 °C. When the CO_2 emission growth rate declines to -3.2%, the peak temperature becomes 1.836 °C, which meets the requirements of CO_2 concentration. Therefore, -3.2% is the reasonable decline value of CO_2 emission growth rate in order to address the greenhouse effect.

Emission reductions and emission reduction investments

The emission reduction amounts are calculated according to the emission growth rate, and then we draw them in lines in *Figure 11*. It can be seen that there is an

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inflection point in the 31th year, indicating the realization of zero-emission. This result can be basically equated with the Paris Agreement goal of realizing zero-emission in the second half century. In the next 5 decades, the global carbon emissions reduction amount should increase from the initial 1.4 GT p.a. to the final value of 49.16 GT p.a., and the total emission reduction amount is 1,580 GT, China needs to bear 20% of the total emission reduction amount, which is about 316 GT.

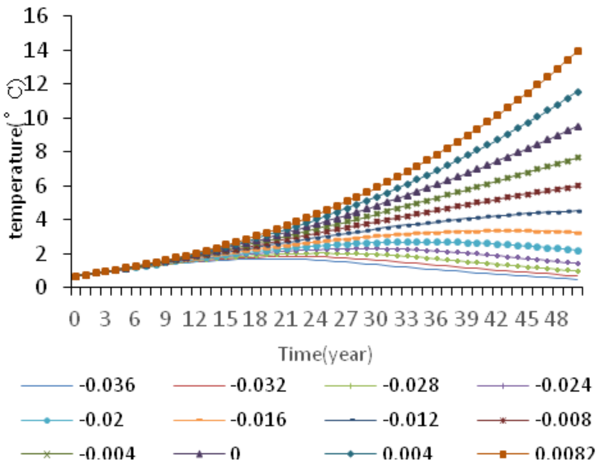

Figure 10. *The average atmospheric heating curves at different emission rates*

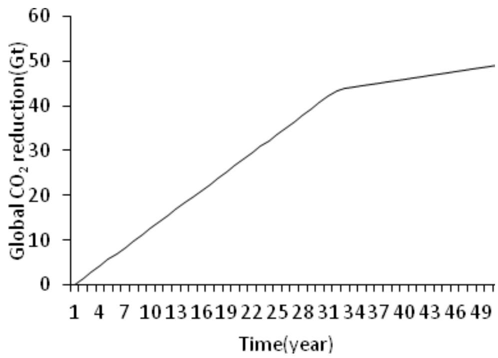

Figure 11. *Global CO_2 reduction line in the next 50 years*

Some scholars have measured the macroeconomic cost of CO_2 emission reduction, which ranges between US \$456/t and US \$592/t (Fan et al., 2010). We take the average of US \$524/t to calculate the future global investment on carbon emissions (see *Fig. 12*). The figure shows that it is necessary to constantly increase investments on carbon emissions in the future 50 years until the annual investment value rise to US \$2.57 trillion. The total sum of investments should reach US \$82.81 trillion across the globe.

Taking China as an example, in formulating investment policies, the investment on CO_2 emission reduction in the next 50 years can be calculated on the premise that China bears the 20% of global carbon emissions reduction amount. And the related data is shown in *Figure 13*. To address climate change, China should continuously increase

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investments on carbon emissions reduction in the future 5 decades until the annual investment amount reaches US $0.514 trillion. The total sum of Chinese investments on carbon emissions reduction should be US $16.56 trillion and the total carbon emissions reduction amount should be 316 GT.

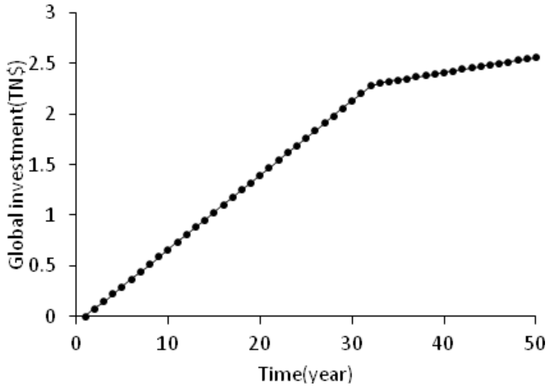

Figure 12. *Global investment line on CO_2 emission reduction in the next 50 years*

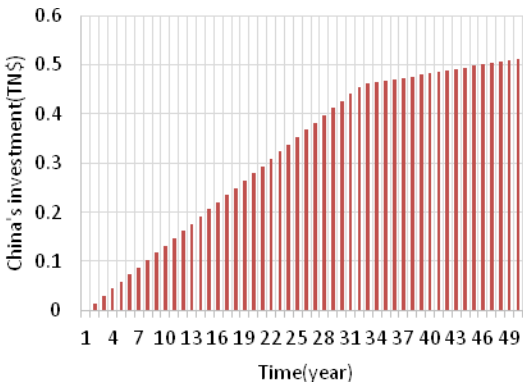

Figure 13. *China's investment on CO_2 emission reduction in the next 50 years*

Conclusion

The greenhouse effect is an environmental phenomenon that triggers global climate change and has attracted the attention of all countries in the world. Although countries are committed to reducing carbon emissions, related goals can only be realized by them setting emission reduction targets according to scientific calculations and investing a reasonable amount of funds on the targets. Reduce carbon emissions, and gradually weaken the impact of greenhouse effect. Through the macro-data based system dynamics analysis, we can see that the task of global CO_2 emission reduction is still arduous. Only by settling the CO_2 emission reduction funds can a country achieves the objectives specified in the Paris Agreement. With certain responsibilities, countries and regions need to make reasonable investments to help reduce global CO_2 concentrations, so as to avoid the unpredicted and uncontrollable consequences brought by the otherwise intensified greenhouse effects. In future research, it is necessary to strengthen the accumulation of basic data, study the relationship between different industrial development and carbon emissions, improve the accuracy of carbon emissions

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prediction model, and timely adjust the carbon emissions strategy through more accurate model.

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