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Pareto improving Climate Policies for the Main CO2 Emitting Countries/Regions

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Abstract in Norwegian:

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Pareto improving Climate Policies for the Main CO2 Emitting Countries/Regions
Shan Jiang thesis for the Masterdegree

The Paris Climate Change Conference, som ble avholdt i desember 2015, vedtok Paris-avtalen, som offisielt sluttet seg til målet om å begrense den globale oppvarmingen til under 2°C over førindustrielt nivå. Ingen obligatoriske kvantitative utslippstiltak eller fordeling av utslippskutt er gitt i denne avtalen. Det ble heller ikke gjort klart om partene kan nå de foreslåtte tiltakene kjent som "Intended Nationally Determined Contributions" (INDCs). Min avhandling fokuserer på to aspekter, utslippsreduksjoner og fordeling av utslippskutt, for de viktigste CO_2-emitterende land og regioner, som Kina, Europeiske Union (EU) og USA (US).

En paretoforbedring er en endring til en annen allokering som gjør at minst én person får det bedre uten at noen andre får det verre. Dette konseptet er innført for å redusere konfliktene rundt fordeling av utslippskutt mellom land/regioner og generasjoner. RICE-2010-modellen som brukes til de numeriske simuleringene, er en global modell som strukturerer verden inn i 12 regioner og 60 tiår. Hvordan utslippsreduksjoner fordeles mellom land/regioner og generasjoner vil bli presentert under ulike scenarier, og de vil bli sammenlignet med INDCs. Alle de numeriske simuleringene er utført av CONOPT løsningsprogram i GAMS (General Algebraic Modeling System).

Studien finner at under Paretoforbedring, går temperaturtrender over "2°C-målet" med ubegrensede consumoverføringer. Studien gir mer håp om å nå "2°C-målet" når det ikke er noen overføringer. I ikke-overføringstilfellet, er karbonutslippstrendene mer sannsynlig å være på banen for å nå "karbonbudsjett" enn de beregnede karbonutslippsnivåene fra INDCs. For de tre viktigste CO_2-utslippsland/regioner, er de estimerte karbonutslippsnivåene fra Kinas INDC ganske nær den estimerte utslippsutviklingen når Kinas velferd er maksimert. De estimerte karbonutslippsnivåene fra USAs INDC er nærmere karbonutslippstrender når velferden av de to andre land/regioner er maksimert. Dette er også tilfellet for EUs INDC. Dette tyder på at EU og USA viser mer altruisme enn Kina når de velger sine INDCs. Dette kan også være på grunn av at de teknologiske mulighetene for de utviklede landene blir bedre enn beskrevet av modellen. Dessuten viser simuleringene i sensitivitetsanalysen for å maksimere forskjellige perioder at det er alltid lavere trender for global gjennomsnittstemperatur når man maksimerer med hensyn til fremtidige perioder enn i forhold til de foreliggende periodene.

Pareto improving Climate Policies for the Main CO$_2$ Emitting Countries/Regions

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II

Abstract

The Paris Climate Change Conference held in December 2015, adopted the Paris Agreement, which officially endorsed the target of limiting global warming to well below 2°C above pre-industrial levels. No compulsory quantitative abatement task or abatement allocation is provided in this agreement. Moreover, whether the "Intended Nationally Determined Contributions" (INDCs) submitted by parties involved in this agreement can meet the "2°C target" was also left to be discussed. My thesis focuses on two aspects, the abatement level and the abatement allocation, for the main CO_2 emitting countries/regions, such as China, United States (US) and Europe Union (EU).

Pareto improvement is a change to a different allocation that makes at least one individual better off without making any other individual worse off. This conception is introduced to reduce the conflicts for abatement allocation among countries/regions and generations. The RICE-2010 model is used for the numerical simulations, which is a global model structuring the world into 12 regions and 60 decades. How the abatement is allocated among countries/regions and generations will be presented under different scenarios, and they will be compared to the INDCs as well. All the numerical simulations are conducted by the CONOPT solution program in GAMS (General Algebraic Modeling System).

The study finds that under Pareto improvement, the temperature trends go beyond the "2°C target" with unlimited consumption transfers. However, they are more promising about reaching the "2°C target" when there are no transfers. In the no transfer case, the carbon emissions trends are more likely to be on the path of reaching the "carbon budget" than the estimated carbon emission levels from the INDCs. For the three main CO_2 emitting countries/regions, the estimated carbon emission levels from China's INDC are quite close to the emission trends when its welfare is maximized. While the estimated carbon emission levels from US' INDC is closer to the carbon emissions trends when the welfare of the other two countries/regions are maximized. This is also the case for EU's INDC. This indicates that EU and US display more altruism than China when choosing their INDCs. This may also be due to the technological options for the developed countries being better than described by the model. Besides, the simulations in the sensitive analysis for maximizing different periods show that there are always lower trends for global mean temperature, when maximizing with respect to the future periods than with respect to the present periods.

Preface

This thesis is made as a completion of the Master of Philosophy in Economics at the University of Oslo. I am very thankful to people and the institution that have assisted me in the process of writing this thesis.

First of all, I would like to express my sincere gratitude to my supervisor, Director of the Oslo Centre for Research on Environmentally friendly Energy (CREE), Senior Research Fellow, Snorre Kverndokk, for giving me the opportunity to investigate Pareto improving climate policy. Your broad knowledge, outstanding guidance, valuable comments and timely input during the writing of this thesis have been invaluable. I am also very grateful to Deputy Director, Senior Research Fellow, Sverre A. C. Kittelsen, for all your support and guidance.

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Contents

List of Figures

List of Tables

1 Introduction

The climate is important for the natural environment and for the survival and welfare of humans. It is also a very important factor of the sustainable development for the world economy. However, due to the interaction of nature and human activities, the global climate system is experiencing a significant change, featured by global warming. The melting of glaciers, the rise of sea level, the increasing temperatures and extreme climate phenomena caused by global warming have increasingly affected humans and the environment humans need for survival (Walther et al. (2002); Haines et al. (2006)), and global warming also leads to direct and indirect economic damages (Ayres & Walter (1991)). As a result, facing the climate change is now becoming a global sustainable development problem, which is connected with humans survival and safety, as well as countries' development opportunities and economic growths (Acaravci & Ozturk (2010); Govindaraju & Tang (2013)).

Global warming, or the greenhouse effect, is mainly caused by the greenhouse gases (GHGs) emitted from the economic activities, such as the combustion of fossil fuels (coal, natural gas and oil) for energy and transportation. The GHGs abatement is a crucial debate when facing the climate change, which needs the efforts and cooperation from all the countries/regions of the world.

1.1 "Abatement debate"

As we know, the Paris Climate Change Conference (COP21) was held in December 2015. *"195 countries adopted the first-ever universal, legally binding global climate deal"*, commented in the Climate Action News of European Commission (Historic Climate Deal (12 December 2015)). It describes that *"The agreement sets out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2°C"*. Specifically, the governments signed the Paris Agreement agreed that *"(1) a long-term goal of keeping the increase in global average temperature to well below 2°C above pre-industrial levels; (2) to aim to limit the increase to 1.5°C, since this would significantly reduce risks and the impacts of climate change; (3) on the need for global emissions to peak as soon as possible, recognizing that this will take longer for developing countries; (4) to undertake rapid reductions thereafter in accordance with the best available science."*(Paris Agreement (2015))

1

It is no doubt that COP21 was successful, and the "Paris Agreement" is the most important achievement of global climate change negotiations. However, there is no compulsory and accurate quantitative abatement task or abatement allocation provided in this agreement. Instead, it gives the options of emission allocations to every country/region involved in this agreement through *"Intended Nationally Determined Contributions"* (INDCs)[1], and indirectly uses an increase in the *"global average temperature"* as a control target. Although the global temperature control target seems more result oriented, and INDCs provide more flexibility in the execution procedure regarding each country/region's actual abatement ability, it cannot be denied that the compulsory strength of INDCs is weaker than a direct allocation for the emission reduction targets, and there is still a distance from the "Paris Agreement" to a real "abatement agreement".

Until now, the Kyoto Protocol is the only climate change document that specifies compulsory abatement. We can see the huge challenges to reach an agreement for all the countries/regions, and to meet the abatement targets for the involved parties in the procedures of signing and implementing the Kyoto Protocol. Questions from a national level mainly concern two aspects: the proper abatement level and abatement allocation. My thesis will focus on the two aspects with respect to the main CO_2 emitting countries/regions, whose behaviors can affect global carbon emission much more than the small parties.

1.2 Emissions and INDCs of the main CO_2 emitting countries/regions

According to the report from PBL Netherlands Environmental Assessment Agency (Olivier et al. (December 2014)), global CO_2 emissions from fossil fuel combustion and from the industrial process have summed up to a new record of 35.3 billion tonnes in 2013 as the use of energy increases in the past decade. The top three emitting countries/regions are China, United States (US) and Europe Union (EU). Figure 1 shows that the top three emitting countries/regions, China, US and EU together account for more than half (55%) of the total global CO_2 emissions in 2013, and their percentages are 29%, 15% and 11% respectively.

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[1]See "decision 1/CP.19". Retrieved from http://unfccc.int/focus/indc_portal/items/8766.php

Figure 1: The percentages of the top three CO_2 emitting countries/regions in 2013
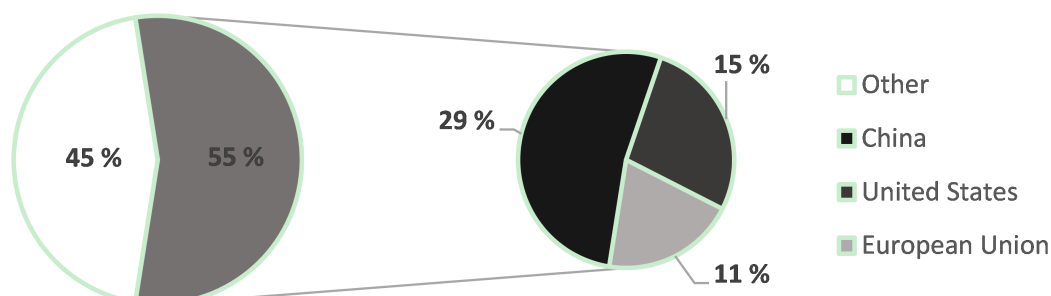
Data Source: PBL Netherlands Environmental Assessment Agency (2014)

Actually, the three countries/regions also have a large GHGs[2] emissions from a historical view. Table 1 illustrates the GHGs and CO_2 inventory amounts of these countries/regions from the statistical data by United Nations Framework Convention on Climate Change (UNFCCC). As the mitigation of climate change can be achieved through activities in the land use, land-use change and forestry (LULUCF/LUCF) sector[3], I only use the data of emissions excluding LULUCF/LUCF, which can represent the direct emissions more accurately. From Table 1, we can see that CO_2 is the most important GHG for the three countries/regions, which accounts for approximately 80% of the total GHGs. Also, we can see that only EU decreased its GHG emission from 1990 to 2005, while for the other two countries, GHG emissions increased during the similar period. Furthermore, China was the lowest GHG emitting country of the three in 1990s, but it became the highest in 2005 due to its fast economic developing.

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[2]According to the statistical range for GHGs by UN, GHGs includes CO_2, CH_4, N_2O, HFCs, PFCs, SF6 and F-gases, among which CO_2 is the key GHG.

[3]According to the measurement of UN for the GHGs emissions, the land use, land-use change and forestry (LU-LUCF/LUCF) sector can increase the removals of the GHGs from the atmosphere or decrease emissions by sources leading to an accumulation of carbon stocks, so the data including LULUCF/LUCF will offset part of the GHGs emissions.

Table 1: Summary of the GHGs and CO_2 Inventory Data
for the Main CO_2 Emitting Countries/Regions

Year	1990		2005	
Countries/Regions	Total GHG emissions excluding LULUCF/LUCF	Total CO2 emissions excluding LULUCF/LUCF	Total GHG emissions excluding LULUCF/LUCF	Total CO2 emissions excluding LULUCF/LUCF
China	4,057.62	3,073.47	7,465.86	5,975.57
United State of America	6,219.52	5,100.61	7,228.29	6,103.29
European Union	5,626.26	4,437.03	5,178.20	4,262.34

Data Source: The United Nations website[4]

Note: China's data in column "1990" is from the year 1994, because the data from 1990 is not available on the UN website.

As one of the most important preparation works for COP21, all parties needed to *"initiate or intensify"*[5] their INDCs and submit them to the secretariat of the United Nations (UN), which is towards achieving the objective of the convention that set out in the agreement. A country's INDC not only indicates its determination to take actions for the climate change, but also shows its expectation of the actions from other countries and the government's cognition for climate change. Before the start of COP21, 160 countries had submitted their INDCs. Table 2 is a brief summary of the INDCs for the three main CO_2 emitting countries/regions, showing that different countries/regions put forward different abatement schemes and targets.

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[4]The "GHGs Inventory Data - Detailed data by party" can be checked by the link
`http://unfccc.int/di/DetailedByParty.do`
[5]*"Intended Nationally Determined Contributions (INDCs)"*, line 2, the United Nations website.
Retrieved from `http://unfccc.int/focus/indc_portal/items/8766.php`

Table 2: A brief summary of the INDCs for the main CO_2 emitting countries/regions

Countries/Regions	INDCs
China	By 2020 will lower carbon dioxide emissions per unit of GDP by 40% to 45% from the 2005 level; To lower carbon dioxide emissions per unit of GDP by 60% to 65% from the 2005 level by 2030
United States	Reducing its greenhouse gas emissions by 26-28 per cent below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28%
Europe Union	A binding target of an at least 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990

Data Source: The United Nations website[6]

1.3 Are INDCs the goal?

Most of the countries/regions involved in the agreement have submitted their INDCs, but can evidence be found showing that the global average temperature control target can be achieved by these policies? *"How ambitious must the Paris agreement be to decisively support such a trajectory?"* Rockström (25 November 2015) described, *"To meet the 2°C limit, the world must cut carbon emissions at about 6% per year."* Also, one working paper from LSE Research Online (Boyd et al. (2015)) found that the current ambitions and plans of countries are inconsistent with the international goal of avoiding global warming of more than 2°C. It concluded that *"There is a gap between the emissions pathway that would result from current ambitions and plans, including those goals outlined by the submitted INDCs, and a pathway that is consistent with a reasonable chance of limiting the rise in global average temperature to no more than 2°C above pre-industrial levels"*. Moreover, a recent report (Sterman et al. (29 November 2015)) from MIT and Climate Interactive looked at how national pledges would have to increase gradually between now and 2030 to stay below 2°C of warming. The assumptions of the "Ratchet Success" scenario from the report are illustrated by Table 3. We can see that the countries/regions listed below would have to do much more than the current climate policies to achieve the temperature control target.

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[6]The INDCs that have been submitted to the secretariat of the UNFCCC are published at
http://www4.unfccc.int/submissions/indc/Submission\%20Pages/submissions.aspx

Table 3: Summary of "Ratchet Success" pathway assumptions

	(Current INDC)	Improvement for 2030	2030-2050
EU	40% below 1990 levels by 2030 (45% below 2005)	47% below 1990 levels by 2030	80% below 2005 by 2050
U.S.	26% below 2005 levels by 2025	45% below 2005 levels by 2030	80% below 2005 by 2050
Other Developed	3.5% decrease below 2005 emissions by 2030*	45% below 2005 levels by 2030 (or 50% below 1990 levels)	80% below 2005 by 2050
China	Peak CO2 by 2030	Peak by 2025	Reduce 2% per year through 2040 and 4% per year after
Other Developing	10% below BAU by 2030*	Peak by 2027	Reduce 2% per year through 2040 and 4% per year after

*Level of ambition of the aggregate of individual INDCs within this group.

Source: Sterman et al. (29 November 2015)

The discussions above indicates that is doubtful whether the abatement targets mentioned in the INDCs can guarantee the international goal of avoiding global warming of more than 2°C. To say the least, even though the proper abatement level is specified in the INDCs, which means the first aspect of the allocation problem mentioned in the beginning is solved, how to allocate abatement properly among countries/regions to prevent a recurrence like the Kyoto Protocol situation, is still left to be answered.

In fact, many abatement allocation principles have been proposed in the past few decades, pursuing a proper way to allocate abatement. As early as 1993, Welsch (1993) suggested an appropriate cost-share equilibrium to the allocation of public cost according to the benefit approach, which leads to an efficient result. Benestad (1994) pointed out that a country's abatement should be consistent with the energy it demands, and presented an "equal burden" formula. Bohm & Larsen (1994) revealed that the equalization of net costs per GDP is a fair treatment in the research for the area of West Europe and the former Soviet Union. Kverndokk (1995) advised that emission permits should be allocated based on the population, the way that can take both justice and political feasibility into account. Rose et al. (1998) provided that distinguishing equity or not between the industrialized and developing countries has the same welfare outcomes.

After the Kyoto Protocol was signed, researchers began to work on the quantitative

abatement schemes. Global abatement schemes include Sørensen (2008), Garnaut (2008), Stern (2008), Chakravarty et al. (2009) etc. There are also abatement schemes put up by institutes, like the UNDP[7] in 2007, the GDRs[8] in 2008, the UNEP[9] in 2010, the OECD[10] in 2012, as well as the IPCC[11] in 2007 and 2013.

Unfortunately, until now there is no abatement allocation scheme that can be widely accepted by most of countries/regions yet. It is still a task left to the researchers to find an allocation method that can help the world to reach a consensus. The controversies regarding the abatement schemes are about the proper abatement level and the abatement allocation. Here, I will suggest Pareto improvement and using a theoretically based model to solve the proper abatement and the abatement allocation problems for the three main CO_2 emitting countries/regions, which will be introduced in detail in the following sections.

1.4   Why Pareto improvement?

In this thesis, I use Pareto improvement to reduce the conflicts for abatement allocation among countries/regions and suggest climates policies for the main CO_2 emitting countries/regions. Pareto optimality, or Pareto efficiency, is *"a resource allocation for which it is impossible to make some individual better off without making another worse off"* (Tisdell & Hartley (2008), pp.25), while Pareto improvement is *"given an initial allocation of goods among a set of individuals, a change to a different allocation that makes at least one individual better off without making any other individual worse off"* (Stiglitz et al. (2013)). The relationship between the two definitions is described as *"An allocation is Pareto efficient when no Pareto improvements are possible"* (Gerber & Patashnik (2007), pp.24). Thus, this thesis focuses on Pareto efficient outcomes which are also Pareto improvements, and under these Pareto improvements, no individuals are worse off and at least one individual is better off compared to the initial allocation. Pareto improvements is meaningful in climate change negotiations, since nobody will lose and everybody will

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[7]"Human Development Report 2007/8" by the United Nations Development Programme (UNDP). Retrieved from `http://hdr.undp.org/en/content/human-development-report-20078`

[8]"The Greenhouse Development Rights (GDRs) framework", by the Stockholm Environment Institute. Retrieved from `http://www.ecoequity.org/wp-content/uploads/2009/02/gdrs_execsummary.pdf`

[9]"The Emissions Gap Report", by the United Nations Environment Programme (UNEP). Retrieved from `http://www.unep.org/publications/ebooks/emissionsgapreport/`

[10]"OECD Environmental Outlook To 2050", by Organisation for Economic Co-operation and Development (OECD). Retrieved from `http://www.oecd.org/env/indicators-modelling-outlooks/oecdenvironmentaloutlookto2050theconsequencesofinaction.htm`

[11]The Fourth and Fifth Assessment Report, by the Intergovernmental Panel on Climate Change (IPCC). Retrieved from `http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml`

be at least as well off as in "business as usual" by Pareto improving abatement allocation, i.e., maximizing the welfare of one country/region subjected to the constraints that the welfare for other countries/regions will not be worse off.

Pareto improvement can help to reduce the conflicts among countries/regions, since it can lead the allocation of abatement to an efficient and "win-win" state in a multiparty situation, and create a cooperative environment. The INDCs are on the other hand based on the voluntary contributions to abatement, and may not ensure the efficiency of the abatement allocation and the protection for the other countries/regions' welfare. They are likely to be set in a non-cooperative environment as in the model by Helm (2003). Moreover, Pareto improvement can help us to reallocate welfare across generations, avoiding the situation that the present generation grasps its benefit as sacrificing the welfare of the future generation.

The thesis uses the model RICE-2010, developed by Nordhaus (2010). It is a regionalized version of the Dynamic Integrated model of Climate and the Economy (DICE), which is also developed by Nordhaus (2008). It differs in some respects from the DICE model, especially in the dimension of time and countries. The RICE-2010 model structures the world into 12 regions and 60 decades from 2000 to 2600. It provides a numerical support in solving the proper abatement level problem, and will illustrate how Pareto improving agreements can look like.

Hoel et al. (2015) has used the RICE-2010 model to suggest Pareto improving climate policies, which focuses on distributing the benefits across four generations and two regions, and ensures that every region in each period will maximize its utility. In my analysis, the RICE-2010 model will be aggregated into four countries/regions, i.e., China, US, EU and the rest of the world (ROW). The Pareto improving scenarios for these countries/regions will be calculated to obtain the Pareto improving climate policies. Afterwards, the estimated effects of the aggregated INDCs and of each country/region's INDC will be compared to the simulations. All the numerical simulations are conducted by the CONOPT solution program in GAMS (General Algebraic Modeling System).

The rest of the thesis is organized as follows: In Section 2, I will introduce the model RICE-2010. The major equations of the model, the related variables as well as the related parameters will be presented. In Section 3, a four-country/region model will be presented and described in detail. Then the Pareto improving scenarios for global mean temperature and carbon emissions trends will be derived using the RICE-2010 model, and these trends

8

will also be derived for the three main CO_2 emitting countries/regions separately. In addition, the baseline and social optimum line will be calculated as benchmarks. In Section 4, the Pareto improving scenarios, the baselines and the social optimal solutions will be compared to the INDCs and discussed. In Section 5, I will perform sensitivity analysis, and differences in the trends will be compared and discussed. Section 6 concludes with the main findings of this thesis.

2   The RICE-2010 model

In this section, I present an overview of the equilibrium model used in my thesis: the RICE-2010 model.

2.1   Description of the model

The RICE-2010 model brought the climate factors into the framework of economic growth. In the Ramsey model (Ramsey (1928)), people can invest in capital markets and consume goods, as well as reduce the consumption of today in order to increase future consumption. The RICE-2010 model modifies the Ramsey model to include climate investment, and thus the capital stock includes the investment for the environment ("natural capital", Jansson (1994)). In other words, abatement is a kind of the environmental investment. The GHGs can be taken as "negative natural capital", and abatement can decrease the "negative natural capital".

The economic sector of the model assumes that each country produces a single commodity, which can be used for consumption, investment and abatement. Every region is endowed with an initial capital stock, labor and technology level. Population data are from the UN, updated through 2009, with projections using the UN estimates to 2300. Output is measured as standard GDP in constant prices, which are converted into constant US international prices using Purchasing Power Parities (PPP) exchange rates. The output data through 2009 are from the World Bank and the International Monetary Fund (IMF), with projections to 2014 from the IMF. CO_2 emissions data are from the US Energy Information Administration and Carbon Dioxide Information Analysis Center (Dixon & Jorgenson (2012)).

The geophysical sector of the model includes several relationships, which connect these different factors that affect the climate and the economy. These relationships include the carbon cycle and climate change equations etc. In the RICE-2010 models, the only greenhouse gas that is subject to controls is industrial CO_2. Other greenhouse gases are included as exogenous trends in radiative forcing. The climate changes are presented by the mean of the global surface temperatures. The climate equations are calibrated with large-scale general circulation models of the atmosphere and ocean systems from the IPCC Fourth Assessment Report (IPCC Fourth (2007)). The RICE-2010 model also

10

includes an annual sea-level rise (SLR) calculation module with temperature trails. Furthermore, the RICE-2010 provides an estimation approach for the damages. The functions include damages from the temperature change, SLR and the impacts of CO_2 concentrations.

2.2 Equations of the model

RICE-2010 divides the world into 12 regions, including US, EU, China, Japan, Russia, India etc. Some are large countries, like US and China, while others are large multinational regions, like EU and Latin America. There is a social welfare function for each country/region, by which every region optimizes its consumption, investment and climate policies over time. It contains 60 decades from 2000 to 2600. The general preference function is a Bergson-Samuelson social welfare function

$$W = W(U^1, ...U^k, ...U^{12}) \tag{1}$$

where U^k is the preference function of the kth region. The model uses the Negishi approach, in which regions are aggregated using time- and region-specific weights subject to budget constraints, yielding

$$W = \sum_{k=1}^{12} \sum_{t=1}^{Tmax} \left(\varphi_{kt} U[c^k(t), L^k(t)] R(t) \right) \tag{2}$$

where φ_{kt} is the "Negishi wights" for each region and each time period. The Negishi algorithm in the RICE model sets each weight so that the consumption marginal utility is the same in each region and each time period.

Besides equation (2) mentioned above, i.e., the welfare equation, the rest of the 19 major model equations are as below. Some unimportant equations are omitted, such as initial conditions.

Discount factor:

$$R(t) = (1 + \varrho)^{-t} \tag{3}$$

Utility function:

$$U[c^k(t), L^k(t)] = L^k(t)[c^k(t)^{1-\alpha}/(1-\alpha)] \tag{4}$$

Output before damages and abatement:

$$Y^k(t) = A^k(t)K^k(t)^\gamma L^k(t)^{1-\gamma} \tag{5}$$

Abatement cost as fraction of output:

$$\Lambda^k(t) = Y^t(t)\theta_1(t)\mu^k(t)^{\theta_2} \tag{6}$$

Climate damages as fraction of output:

$$\Omega^k(t) = g^t[T(t), SLR(t), M_{AT}(t)] / \left(1 + g^k[T(t), SLR(t), M_{AT}(t)]\right) \tag{7}$$

Output after damages and abatement:

$$Q^k(t) = \Omega^k(t)[1 - \Lambda^k(t)]Y^k(t) \tag{8}$$

Composition of output:

$$Q^k(t) = C^k(t) + I^k(t) \tag{9}$$

Per capita consumption:

$$c^k(t) = C^k(t)/L^k(t) \tag{10}$$

Law of motion of capital stock:

$$K^k(t) = I^k(t) - \delta_K K^k(t-1) \tag{11}$$

Industrial emissions:

$$E_{Ind}^k(t) = \sigma^k(t)[1 - \mu^k(t)]Y^k(t) \tag{12}$$

Carbon fuel limitations:

$$CC_{um} \geq \sum_{t=1}^{Tmax} \left[\sum_{k=1}^{12} E_{Ind}^k(t) \right] \tag{13}$$

Total carbon emissions:

$$E^k(t) = E_{Ind}^k(t) + E_{Land}^k(t) \tag{14}$$

Dynamics of atmospheric carbon concentrations:

$$M_{AT}(t) = E(t) + \phi_{11}M_{AT}(t-1) + \phi_{21}M_{UP}(t-1) \tag{15}$$

Dynamics of carbon concentrations in biosphere and upper oceans:

$$M_{UP}(t) = \phi_{12}M_{AT}(t-1) + \phi_{22}M_{UP}t - 1 + \phi_{32}M_{LO}(t-1) \tag{16}$$

Dynamics of carbon concentrations in lower oceans:

$$M_{LO}(t) = \phi_{23} M_{up}(t-1) + \phi_{33} M_{LO}(t-1) \tag{17}$$

Radiative forcings:

$$F(t) = \eta\{log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t) \tag{18}$$

Global mean surface temperature:

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\} \tag{19}$$

Temperature lower oceans:

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4\{T_{AT}(t-1) - T_{LO}(t-1)]\} \tag{20}$$

Sea level rise (thermal expansion, glaciers, ice sheets):

$$SLR(t) = SLR(t-1) + \Big[\sum_{j=1}^{5} \pi_{1,j} + \pi_{2,j} T_{AT}(t-1) + \pi_{2,j}[T_{AT}(t-1) - \overline{T}^j_{AT}]\Big] \tag{21}$$

The definitions for the variables and parameters follow below. Note that endogenous variables are marked with asterisks, and the regional subscripts or superscripts are omitted for brevity.

Variables definitions and units:
$A(t)$ = total factor productivity (productivity units)
$*c(t)$ = per capita consumption of goods and services (2005 U.S. dollars per person)
$*C(t)$ = consumption of goods and services (trillions of 2005 U.S. dollars)
$*D(t)$ = damages from climate change (trillions of 2005 U.S. dollars)
$E_{Land}(t)$= emissions of carbon from land use (billions of metric tons Carbon per period)
$*E_{Ind}(t)$ = industrial carbon emissions (billion metric tons Carbon per period)
$*E(t)$ = total carbon emissions (billion metric tons Carbon per period)
$*F(t), F_{EX}(t)$ = total and exogenous radiative forcing (watts per square meter from 1900)
$*g_k[T(t), SLR(t), M_{AT}(t)]$ = damage function
$*I(t)$ = investment (trillions of 2005 U.S. dollars)
$*K(t)$ = capital stock (trillions of 2005 U.S. dollars)
$L(t)$ = population and proportional to labor inputs (millions)
$*\Lambda(t)$ = abatement cost as fraction of output
$*M_{AT}(t), M_{UP}(t), M_{LO}(t)$ = mass of carbon in reservoir for atmosphere, upper oceans,

and lower oceans (billions of metric tons Carbon, beginning of period)

$*\mu(t)$ = emissions-control rate (fraction of uncontrolled emissions)

$\sigma(t)$ = ratio of uncontrolled industrial emissions to output (metric tons Carbon per output in 2005 prices)

$*\Omega(t)$ = damage function (climate damages as fraction of regional output)

$*\Lambda(t)$ = abatement cost function (abatement costs as fraction of regional output)

$*Q(t)$ = output of goods and services, net of abatement and damages (trillions of 2005 U.S. international dollars)

$SLR(t)$ = sea level rise (relative to 1990), meters

t = time (decades from 2001-2010, 2011-2020,)

$*T_{AT}(t), T_{LO}(t)$ = global mean surface temperature, temperature upper oceans, temperature lower oceans (°C from 1900)

$*U[c(t), L(t)]$ = instantaneous utility function (utility per period)

$*W$ = objective function in present value of utility (utility units)

$*Y(t)$ = output of goods and services, gross of abatement and damages (trillions of 2005 U.S. dollars)

Parameters:

α = elasticity of marginal utility of consumption (pure number)

$CCum$ = maximum consumption of fossil fuels (billions metric tons carbon)

γ = elasticity of output with respect to capita (pure number)

δ_K = rate of depreciation of capital (per period)

η = temperature-forcing parameter (°C per watts per meter squared)

$\phi_{11}, \phi_{21}, \phi_{22}, \phi_{32}, \phi_{12}, \phi_{33}, \phi_{23}$ = parameters of the carbon cycle (flows per period)

$\xi_1, \xi_2, \xi_3, \xi_4$ = parameters of climate equations (flows per period)

ψ_1, ψ_2 = parameters of damage function

ρ = pure rate of social time preference (per year)

$R(t)$ = social time preference discount factor (per time period)

$Tmax$ = length of estimate period for model (60 periods = 600 years for most variables)

$\overline{T}^j_{AT}(t)$ = threshold temperatures for ice sheets in SLR equation (°C)

$\theta_1(t), \theta_2$ = parameters of the abatement cost function

φ_{kt} = Negishi parameters of the social welfare function

The saving rate is constant from the year 2125, and the initial price for the backstop technology is high but decreases after 2250, so that emissions decline rapidly after 2250. The population growth rate is exogenous for each country in the model. The utility discount rate, or social rate of time preference, is set to be 1.5% per year in the model. The

elasticity of marginal utility of consumption is 1.5. The rate of depreciation per year is 10%.

3   Pareto improving simulations

3.1   Settings in a four-country/region model

As mentioned, I choose China, US and EU as my study targets, since the CO_2 emissions of these countries/regions account for a large percentage of the worldwide CO_2 emissions. Thus, the model is aggregated into four countries/regions, i.e., China, US, EU and ROW. ROW consists of Japan, Russia, other high income countries (OHI), Eurasia, India, Middle East, Africa, Latin America and other non-OECD Asia. As the countries/regions included in the fourth region are very heterogeneous, the analysis will focus on the three main CO_2 emitting countries/regions: China, US and EU.

For the time settings, it should be noticed that the UNFCCC suggests the INDCs *"contain a time frame up to 2030"*[12]. In order to keep consistent with the time frame of the INDCs, I use this as a period (t0) in the model. The time line is aggregated into four periods as follow for the optimization:

  - t0: 2001-2030

  - t1: 2031-2100

  - t2: 2101-2200

  - t3: 2201-2600

where *t0* represents the *present period* and *t2* represents the *future period*. The analysis will concern about the welfare of the two periods or generations: present and future.

According to the RICE-2010 model, the initial price for the backstop technology is high but decreases after 2250. However, the Paris Agreement is likely to decrease the price of the backstop technology even more. In my study, the innovation effects of the Paris Agreement will not be taken into account.

A few adjustments in the simulations should be noticed. A region has two ways to affect the output of the future periods, the GHG emissions and investments. The GHG emis-

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[12] *"Adoption of the Paris agreement"* (pp. 4). Retrieved from the link:
`https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf`

sions have an impact on future damage and therefore the future output, while investments increase future capital stocks and production possibilities. In the model, investments are decided by the saving rates, i.e., the share of the net output that is not consumed and used for investments. Thus, the saving rates are endogenous before 2170. For technical reasons, the saving rates are exogenous from 2170 in the simulations.

The utility discount rate is set to 1.5% per annum in the RICE model. As the rate has been criticized by a number of authors (e.g. Stern (2007)), here I first use 0.5% per annum in the base runs. The case for a higher discount rate will be studied in the sensitivity analysis section.

It should also be noticed that transfers are the only way to affect other countries/regions within one period, since there is no trade or other interactions between them in the RICE-2010 model. In our model, time periods are aggregated and cover several decades, so other countries/regions within the same period can be affected by the GHG emissions as well.

3.2   The different scenarios

I first work with the "Business As Usual" (BAU) scenario and the social optimum (OPT) scenario. The two scenarios are the standard scenarios used in the assessment literature. There is no abatement in the BAU scenario, while abatement is allowed in the OPT scenario, and the target is to maximize the total welfare in the OPT scenario.

- *BAU: Business as usual*

- *OPT: Social optimum*

Then the constrained optima is derived for the concerned three countries/regions under the periods "present" and "future", in which no one will lose welfare compared to the BAU scenario. Each country/region maximizes its utility in the present period or future period under the constrained optima.

- *China0: Maximize the utility of China at present*

- *China2: Maximize the utility of China in the future*

- US0: Maximize the utility of US at present

- US2: Maximize the utility of US in the future

- EU0: Maximize the utility of EU at present

- EU2: Maximize the utility of EU in the future

In the standard setup of the RICE-2010 model, climate change will reduce the output available to the consumers. In these scenarios, I first assume consumption transfers are allowed, as transfers, or climate finance, are part of the Paris Agreement.

3.3   Pareto improvement

Now we have four defined periods, *t0* to *t3*, and we have four defined regions, i.e., China, US, EU and ROW. Hence there are 16 combinations of different periods and regions. The utility of one region in one period is maximized, while the utilities of other 15 combinations of the periods and the regions are kept unchanged, which means that these combinations should not be worse off than the BAU scenario. The maximizing problem is similar to the social optimal problem that maximizes the total welfare by equation (2), except that the utility levels of the other 15 combinations are kept at their BAU levels. Thus under Pareto improvements, there will be 15 additional constraints for the utility maximizing problem of each country/region.

A further explanation of the Pareto improvement approach can be given. In this case, the utility possibility frontier, or Pareto efficiency frontier, is a 16-dimensional hyperplane. The BAU scenario is a point that lies inside the Pareto efficiency frontier, not on the Pareto efficiency frontier itself, since the BAU scenario is not a Pareto efficient state. The OPT scenario is a point on the Pareto efficiency frontier, where the total social welfare is maximized. The Pareto improving scenarios are also points on the Pareto efficiency frontier, but the Pareto improving scenarios may be different from the social optimum.

I use Figure 2 to illustrate the Pareto improving state in a two-dimensional case. The point lying inside the Pareto efficiency frontier is the BAU scenario. There are many ways to optimize and move from BAU to the Pareto efficiency frontier. But only under Pareto improvements, it will follow a path that maximizes a party's utility and avoids hurting the

benefit of the other party. If we hold country 1's utility at BAU and maximize country 2's utility, it gives us point P. Similarly, if we hold country 2's utility at BAU and maximize country 1's utility, it gives us point Q. When moving from BAU to any points between P and Q, both U_1 and U_2 will increase and the total welfare is higher. Thus, the points between P and Q on the Pareto efficiency frontier are Pareto improving scenarios, since an increase in U_1 does not decrease U_2 compared to BAU, and vice versa.

Figure 2: An illustration of the relationship between social optimum and Pareto improving scenarios
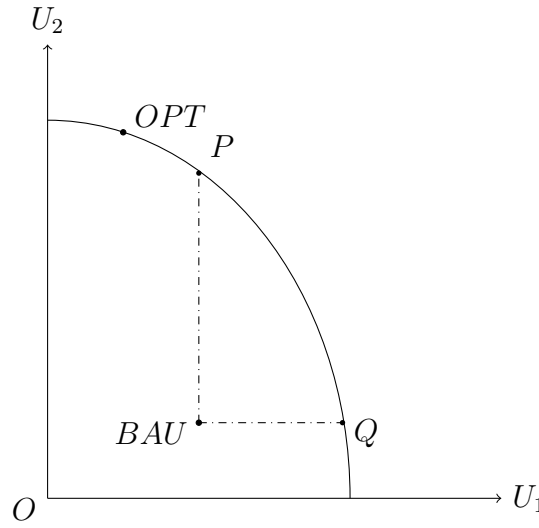
The OPT scenario is also a point on Pareto efficiency frontier. From the figure we can see that the OPT scenario may be not a Pareto improving scenario. When we move from BAU to OPT, U_1 decreases as U_2 increases. In other words, the social optimum is not necessarily a Pareto improvement. Besides, Pareto improving policies may have higher emissions than the OPT scenario (Hoel et al. (2015)), which will be confirmed in the numerical analysis below.

3.4   Simulation results

In this section, I will present the simulation results by using the temperature and the carbon emissions trends. The global temperature will be presented, as well as the global carbon emissions and the carbon emissions of three main CO_2 emitting countries/regions, i.e., China, US and EU.

3.4.1 Temperature trends

With consumption transfers, the optimizing country/region, i.e., China, US or EU at present or in the future, maximizes its utility level, given that the other three regions at present and in the future should not be worse off than their BAU scenarios. The temperature trends from 2000 to 2250 in the different scenarios using the RICE-2010 model are shown in Figure 3.

Figure 3: The global mean temperature under different scenarios
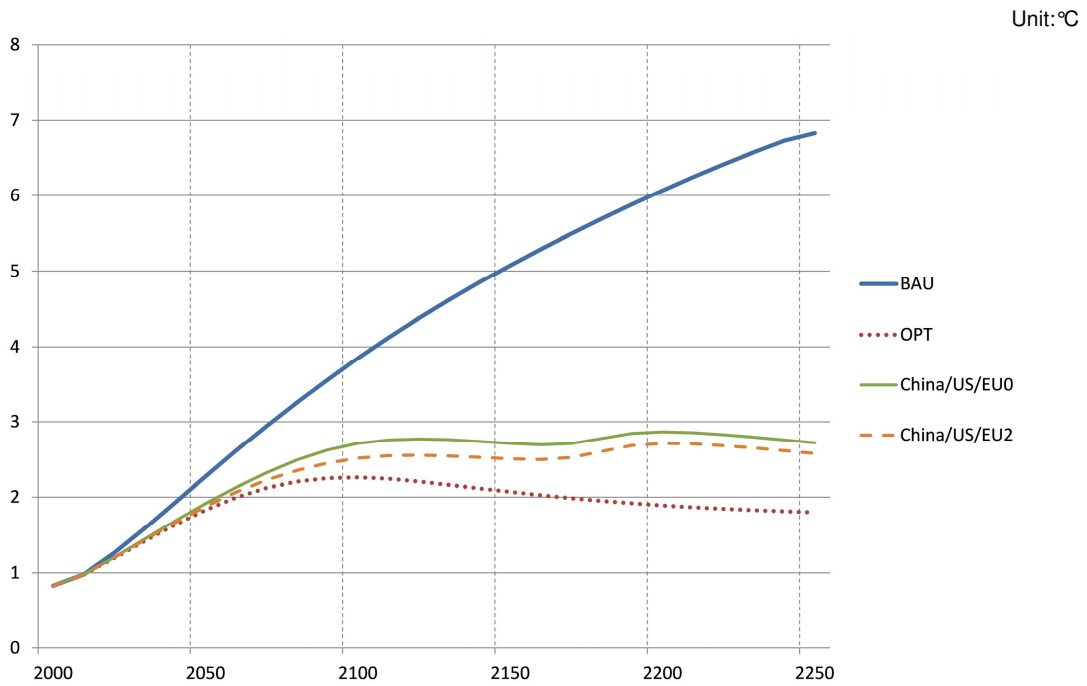
Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

Figure 3 illustrates the temperature under the BAU, the OPT and the Pareto improving scenarios (marked with *"China/US/EU0"* and *"China/US/EU2"*) separately. As we expected, the temperature under the BAU scenario is the highest, since no abatement is allowed. The temperature is out of control and keeps increasing. Not surprisingly, the temperature under OPT scenario is the lowest, since there is no Pareto improving constraints and all countries/regions do their best to maximize the total utility, even by sacrificing their benefits to increase the utility for other countries/regions, which is not realistic without large side payments. For the Pareto improving scenarios, abatement is allowed and there are Pareto improving constraints, so the temperature is in the middle[13].

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[13]The small convexities on the curves (yellow and green) for the Pareto improving scenarios between 2150 and 2200

This indicates that the BAU scenario and the social optimum are not Pareto improving scenarios, and the welfare of one country/region or some countries/regions will be worse off under social optimum.

It should be noticed that abatement and temperature only depend on the generation, present (China/US/EU0) or future (China/US/EU2), that we are maximizing with respect to. The reason is that transfers make it optimal to maximize the total consumption in one period for a given total consumption in the other period, so the results are the same for abatement and temperature no matter which country/region we are maximizing with respect to. The total consumption levels are allocated by appropriate transfers.

The peak temperature in the OPT scenario is 2.3°C approximately, and will go below 2°C around 2175, while the temperature under the Pareto improving scenarios is well below 3°C over the periods. For the present generation, the peak temperature is 2.9°C approximately, and it goes to 2.7°C in 2250. For the future generation of Pareto improving scenario, the peak temperature is 2.7°C approximately, and reduces to 2.6°C in 2250. According to the simulation results, the global temperature trends are not on the path to achieve the "2°C target" from the Paris Agreement under Pareto improvements by the end of the century when there are consumption transfers.

From Figure 3 we also notice that in the simulated outcomes, the temperature for the present generations (China/US/EU0) is higher than the future generations (China/US/EU2) under Pareto improvements. This is due to the fact that climate change matters more for the future generations than the present generations, and thus the future generations have more incentive for abatement. The present generations are more "shortsighted" when optimizing, and only do the necessary abatement to make the future generations no worse off.

3.4.2 Carbon emissions

The global carbon emissions

Besides global mean temperature, the RICE-2010 model can also help us to simulate the carbon emissions under Pareto improvements. Figure 4 shows global annual industrial carbon emissions from 2000 to 2100 when the welfares of the three main CO_2 emitting

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in Figure 3 are due to the fact that the saving rates are not endogenous any more from 2170, which is mentioned in Subsection 3.1.

countries/regions are maximized.

Figure 4: The global carbon emissions under different scenarios

Unit: Billion metric tons carbon per period
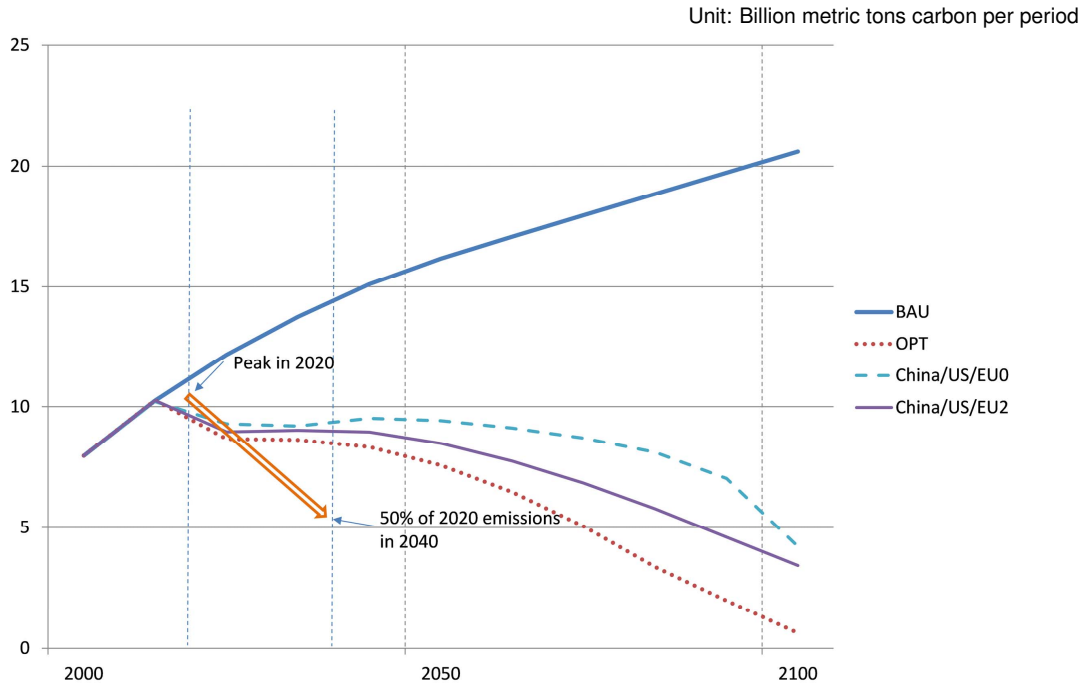
Transfer type and discount rate: Consumption transfers.ρ=0.5 p.a.

From Figure 4 we can see that the emissions under the BAU scenario is completely different from under the OPT scenario, one keeping increasing, while the other keeping decreasing. The BAU scenario is the highest over the periods and the OPT scenario is the lowest. As for the temperature in Figure 3, the carbon emissions for the Pareto improving scenarios are in the middle.

The global carbon emissions are approximately 16 Gt[14] under the BAU scenario, and 7.5 Gt under the OPT scenario in the year 2050. For the Pareto improving scenarios, the global emissions are well below 10 Gt after 2015, and reach the peak 9.5 Gt around 2050 for the present generation and 8.5 Gt for the future generation before declining towards the end of the century. This is consistent with the temperature trends in Figure 3, since higher carbon emissions lead to more increase in temperature.

It should be noticed that the global carbon emissions under Pareto improvements are the same for the present and future period respectively, no matter which country/region's

[14]Gt Carbon: Gigatonnes of carbon, 1 Gt Carbon = 10^9 metric tons Carbon = 3.67 Gt carbon dioxide = 3670 Tg carbon dioxide), IPCC, retrieved from `http://www.ipcc.ch/ipccreports/tar/wg3/index.php?idp=477`

welfare is maximized. It is because the total consumption levels are allocated by appropriate transfers, and transfers make it optimal to maximize the total consumption in one period for a given total consumption in the other period. At the same time, carbon taxes will be equalized across countries/regions with consumption transfers. As a result, the levels of the global carbon emissions only depend on the generation that maximizes.

In 2008, IPCC identified the world's "carbon budget", and specified that *"to best ensure we are able to limit warming to 2°C, it is essential that annual global emissions peak by the year 2020"* around 10 Gt carbon, and *"are reduced steeply"* afterwards, with only *"50% of 2020 emissions"* in the year 2040[15]. The orange arrow in Figure 4 shows the emissions under the "carbon budget" constraint. Compared to "carbon budget", Pareto improving trends have an earlier peak and decline more moderately afterwards. A further discussion about this will be found in Subsections 5.1 and 5.2.

The three main CO_2 emitting countries/regions' carbon emissions

Figures 5-7 show the annual industrial carbon emissions of the three main CO_2 emitting countries/regions respectively. The carbon emissions for all the three countries/regions have the same feature as the global carbon emissions in Figure 4, i.e., the emissions under the BAU scenario are the highest, and the carbon emissions for the OPT scenario are the lowest for all the three countries/regions. For the Pareto improving scenarios, the emissions are in the middle.

As seen from Figure 5, the carbon emissions for China, under Pareto improvements are around 2.3 Gt for the present period, and 2.2 Gt for the future period in 2030, and they keep decreasing towards the end of the century. The carbon emissions are approximately 3.5 Gt under the BAU scenario in 2030, and keep increasing afterwards. They are about 2.1 Gt under the OPT scenario in 2030, and keep declining. As in Figure 4, the results are the same for China's emission levels, no matter which country/region's welfare is maximized.

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[15]The cited words are from *"INFOGRAPHIC: The Global Carbon Budget"*, World Resources Institute, and the numbers are from the graph in the same page. Retrieved from `http://www.wri.org/ipcc-infographics`

Figure 5: The carbon emissions of China under different scenarios
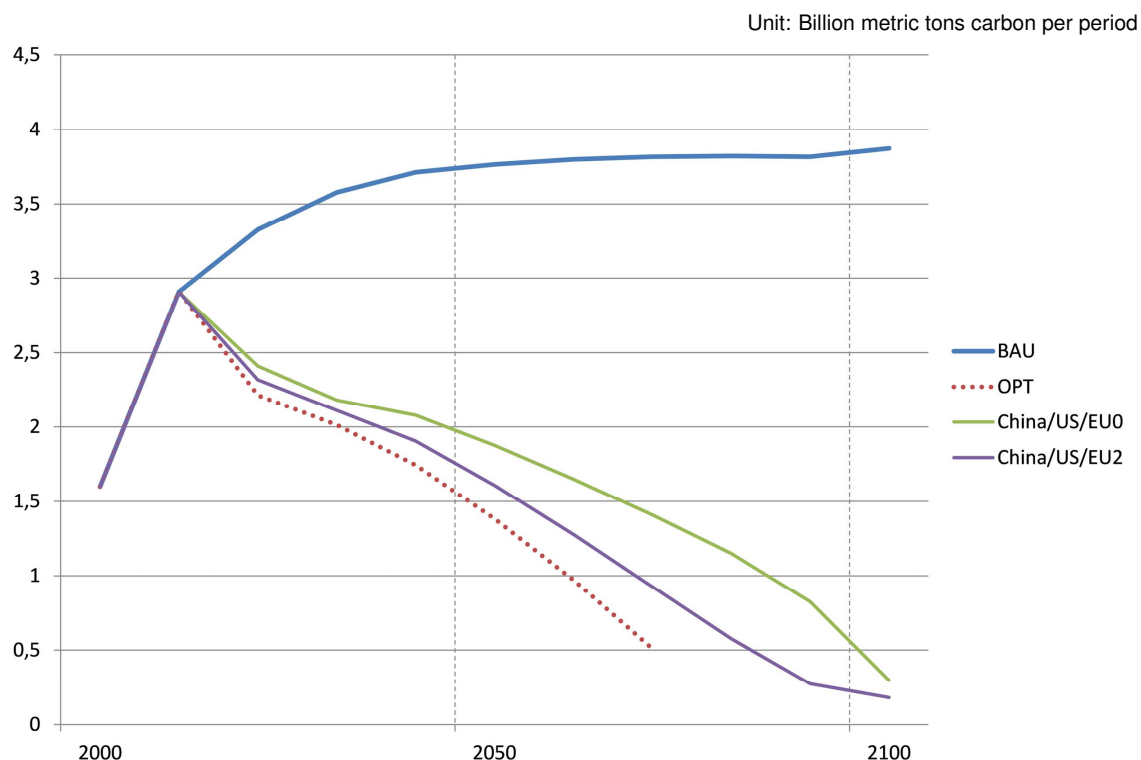
Transfer type and discount rate: Consumption transfers.ρ=0.5 p.a.

For US, Figure 6 shows that carbon emissions under the BAU scenario, the OPT scenario and the Pareto improving scenarios are similar to those for China, i.e., the BAU scenario is the highest, the OPT scenario the lowest, and the Pareto improving scenarios in the middle. With consumption transfers, the emission levels of US under Pareto improvements only depend on the generation that maximizes.

The carbon emissions under Pareto improvements are around 1.35 Gt for US' present period, and 1.30 Gt for the future period in 2030, and they keep decreasing towards the end of the century. Carbon emissions are approximately 1.9 Gt under the BAU scenario in 2030, and keep increasing, while they are about 1.28 Gt under the OPT scenario in 2030, and keep declining.

Figure 6: The carbon emissions of US under different scenarios

Unit: Billion metric tons carbon per period
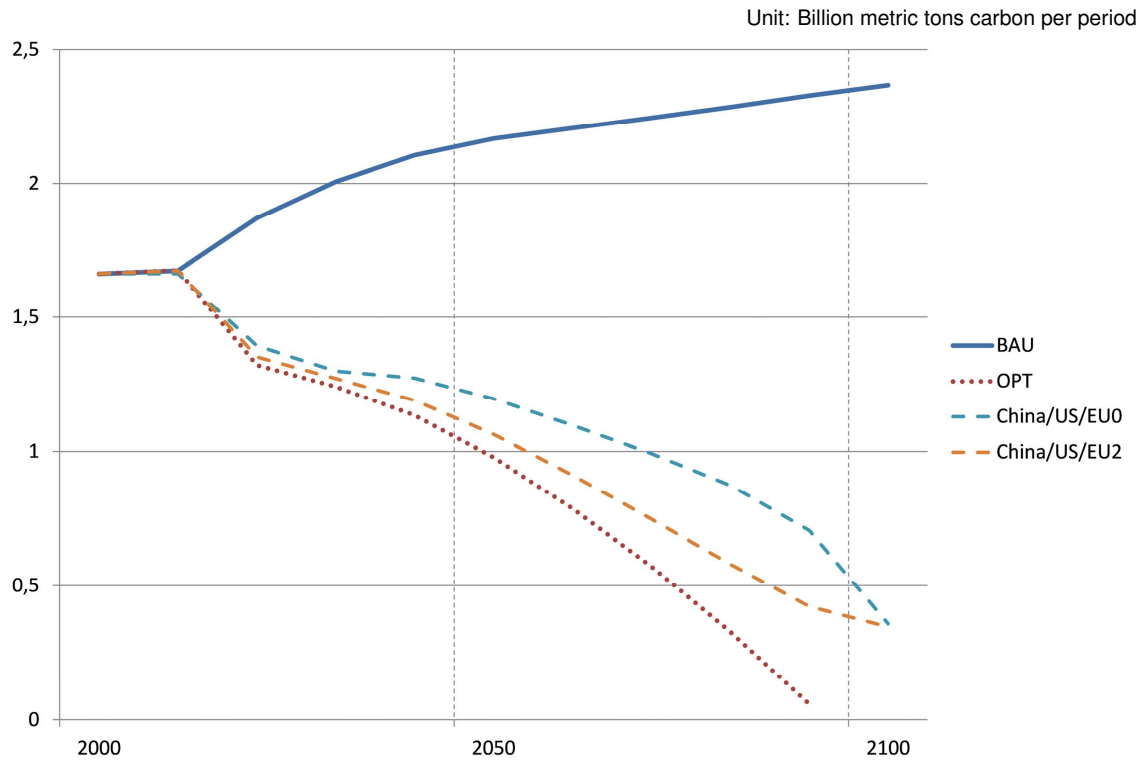
Transfer type and discount rate: Consumption transfers.ρ=0.5 p.a.

The carbon emissions under the BAU scenario, the OPT scenario and the Pareto improving scenarios for EU are shown in Figure 7, which are similar to those for China and US, i.e., the BAU scenario is the highest, the OPT the lowest, and the Pareto improving scenarios in the middle.

The carbon emissions under Pareto improvements are around 0.9 Gt for EU's present period, and 0.87 Gt for the future period in 2030, and they keep decreasing towards the end of the century. The carbon emissions are approximately 1.15 Gt under the BAU scenario in 2030, and are about 0.86 Gt under the OPT scenario.

Figure 7: The carbon emissions of EU under different scenarios

Unit: Billion metric tons carbon per period
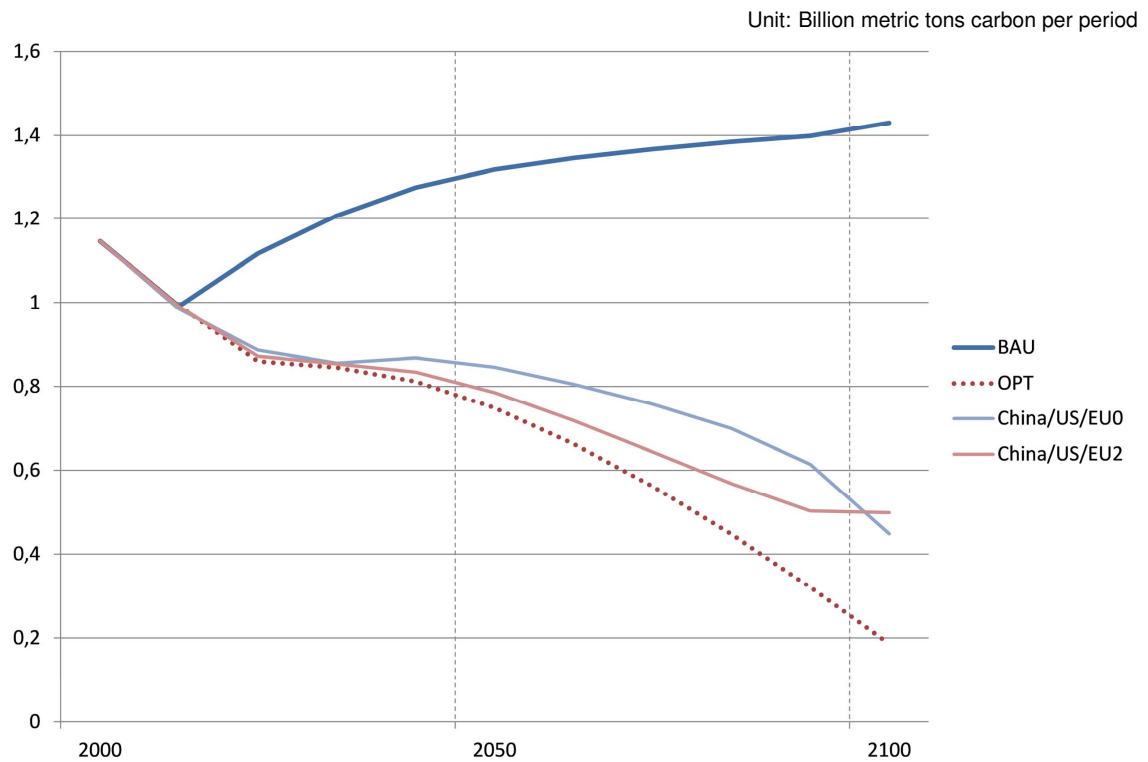
Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

4 Comparisons with the INDCs

In this section, I make comparisons between the simulation results and the INDCs for temperature and carbon emissions. The global temperature will be compared and discussed, in addition to global carbon emissions. Emissions for the three main CO_2 emitting countries/regions, i.e., China, US and EU, will also be compared and discussed separately. As the results are simulated with consumption transfers, the related consumption transfer amounts will be presented and discussed at the end of this section.

4.1 Temperature comparison

Above, we have derived the different temperature under the BAU scenario, the OPT scenario and the Pareto improving scenarios from the RICE-2010 model. What about the assessed implications for temperature change under the INDCs? A synthesis report (UNFCCC (October 2015)) on the aggregate effect of the INDCs was issued by UNFCCC. 119 INDCs communicated by 147 Parties have responded and included in the report, accounting for 75% of all Parties to the UNFCCC. Estimates of the aggregate GHG emission levels in 2025 and 2030 resulting from the implementation of those INDCs are provided by this report. The report has confirmed that INDCs will *"not be sufficient to reverse by 2025 and 2030 the upward trend of global emissions. Furthermore, estimated annual aggregate emission levels resulting from their implementation do not fall within least-cost 2°C scenarios levels."* Although the report does not give a direct assessment for temperature under the INDCs, a newsletter issued by UNFCCC has mentioned that *"other independent analyses have, based on a range of assumptions, methodologies and data sources, attempted to estimate the impact of the INDCs on temperature leading to a range of average estimates below, at or above 3°C"*[16] by the end of the century. Figure 7 illustrates global mean temperature under the different scenarios derived from the RICE-2010 model and the estimated temperature from the INDCs.

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[16] *"Global Response to Climate Change Keeps Door Open to 2 Degree C Temperature Limit - New UN Report Synthesizes National Climate Plans from 146 Countries."* Retrieved from `http://newsroom.unfccc.int/unfccc-newsroom/indc-synthesis-report-press-release/`

Figure 8: The global mean temperature under different scenarios comparing with the INDCs
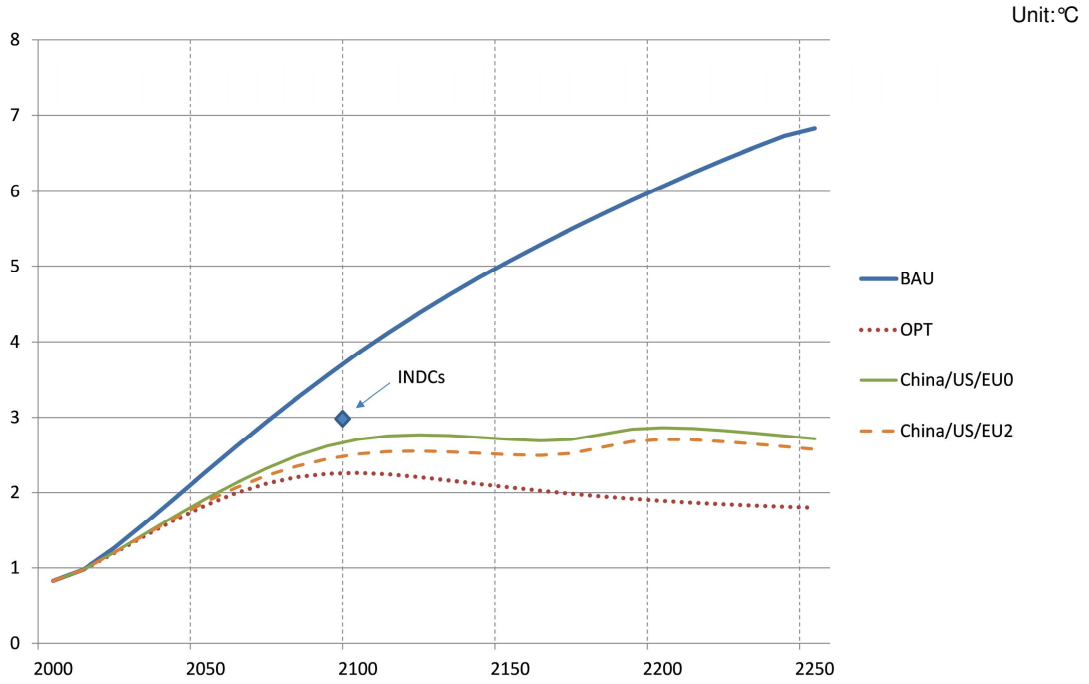
Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

In our model, the increase in temperature can be controlled below 2.7°C when the welfare of the present period (China/US/EU0) is maximized, and below 2.5°C when the welfare of the future period (China/US/EU2) is maximized by 2100 under Pareto improvements. As a result, we can rank the temperature from Figure 6 as below:

$$BAU > INDCs > Pareto\,0 > Pareto\,2 > OPT \tag{22}$$

where *"Pareto 0"* stands for the global mean temperature trend when maximizing the welfare of the present period under Pareto improvements, and *"Pareto 2"* stands for the global mean temperature trend when maximizing the welfare of the future period under Pareto improvements. From the results, we expect that the emission trends under these different scenarios and the INDCs will also follow the same ranking, since higher carbon emissions lead to more increase in temperature. This will be confirmed in Subsection 4.2.

4.2 Carbon emissions comparison

The global carbon emissions comparison

According to the synthesis report (UNFCCC (October 2015)), *"the implementation of the communicated INDCs is estimated to result in aggregate global emission levels of 55.2 (52.0 to 56.9) Gt CO_2 eq in 2025 and 56.7 (53.1 to 58.6) Gt CO_2 eq in 2030"*[17], i.e., 11.73 (11.05 to 12.09) Gt carbon in 2025 and 12.05 (11.29 to 12.45) Gt carbon in 2030[18]. In Section 3, we have obtained the different carbon emissions under the BAU scenario, the OPT scenario and the Pareto improving scenarios from the RICE-2010 model. By the end of 2030, the carbon emissions will be approximately 13 Gt, 8.6 Gt and 9 Gt for the three different scenarios respectively. Figure 9 illustrates the carbon emissions under the different scenarios derived from the RICE-2010 model and the estimated carbon emission levels from the INDCs.

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[17]The numbers in the brackets are ranges indicate 20 to 80 percent ranges and single values indicate medians. And the reported emission levels include emissions from land-use change.

[18]It should be noticed that the emissions calculated from the RICE-2010 model are only industrial carbon emissions, which account for around 80% of the total GHGs if converted into CO_2 as mentioned in Section 1 according to Table 1 when LULUCF/LUCF is excluded. I also calculated the percentages for CO_2 in total GHGs when LULUCF/LUCF is included, and the percentages of CO_2 is from 73.04% to 81.66% for the three main CO_2 emitting countries/regions in 1990 and 2005, 77.71% and 79.17% for Annex I Parties in 1990 and 2005 respectively. In order to make the global emission levels from the Synthesis Report comparable to our results derived from the RICE-2010 model, I simply use the number 0.78 as the conversion factor to convert the GHGs into CO_2. The INDCs may indicate lower global carbon emissions if I use a smaller conversion factor, but it will not affect the conclusion that the carbon emission levels from the INDCs are higher than Pareto improving scenarios, because the percentage of CO_2 has to be around 60% of the total GHGs when the emission levels from the INDCs are lower than Pareto improving scenarios, which is far out of any data support.

Figure 9: The global carbon emissions under different scenarios comparing with the INDCs

Unit: Billion metric tons carbon per period

Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.
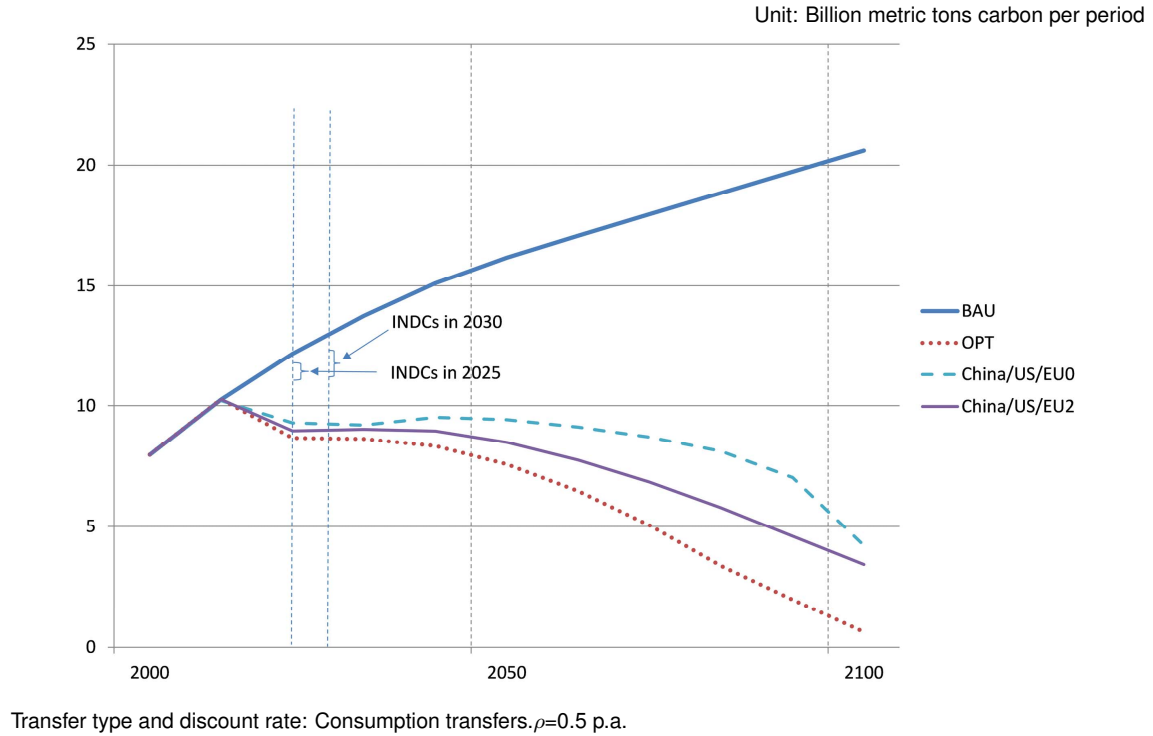
Figure 9 shows that the estimated carbon emission levels from the INDCs are between the BAU scenario and the Pareto improving scenarios. Comparing the different scenarios derived from the RICE-2010 model, we can rank the carbon emission levels as below:

$$BAU > INDCs > Pareto\,0 > Pareto\,2 > OPT \tag{23}$$

where *"Pareto 0"* and *"Pareto 2"* stand for the same scenarios as described in Subsection 4.1, but we compare global carbon emissions trends instead of global mean temperature trends. The result is consistent with the conclusion drawn in Subsection 4.1.

The three main CO$_2$ emitting countries/regions' carbon emissions comparison

Figures 10-12 show the annual industrial carbon emissions compared to the estimated carbon emission levels from the INDCs for the three main CO$_2$ emitting countries/regions respectively.

According to China's INDC, by 2020, China will lower carbon dioxide emissions per unit of GDP by 40% to 45% from the 2005 level; and lower carbon dioxide emissions per unit of GDP by 60% to 65% from the 2005 level by 2030. Sha et al. (2015) presents

the energy related CO_2 emissions level from 2005 to 2050 based on China's INDC in Table 4. China's energy related CO_2 emissions will increase to 182%, 201% and 84% by 2020, 2030 and 2050 respectively compared to the emission level in 2005, indicating that China's energy related CO_2 emissions will peak in 2030.

Table 4: Major factors in implementation of China's INDC (2005=100)

	2005	2010	2015	2020	2030	2040	2050
Population	100	103	105	108	112	112	111
GDP per capita	100	166	235	321	517	783	1103
Energy intensity per unit of GDP	100	81	68	59	43	29	18
Carbon intensity per unit of energy consumption	100	98	94	89	80	63	39
Energy related CO_2 emissions	100	135	158	182	201	158	84

Data Source: Sha et al. (2015)[19]

The total carbon emissions of China are 1.60 Gt in 2005, so we can obtain the estimated target carbon emission levels, which are equal to 2.91 Gt in 2020 and 3.22 Gt in 2030. Figure 10 is similar to Figure 5 but marked with the estimated carbon emission levels from China's INDC. It shows that the estimated carbon emission levels from China's INDC are higher than the emissions in both the Pareto improving scenarios and the OPT scenario, but lower than the BAU scenario.

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[19]This paper can also be found on the website of China National Center for Climate Change Strategy and International Cooperation (NCSC), retrieved from `http://www.ncsc.org.cn/article/yxcg/ir/201507/20150700001490.shtml`

Figure 10: China's carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period

Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.
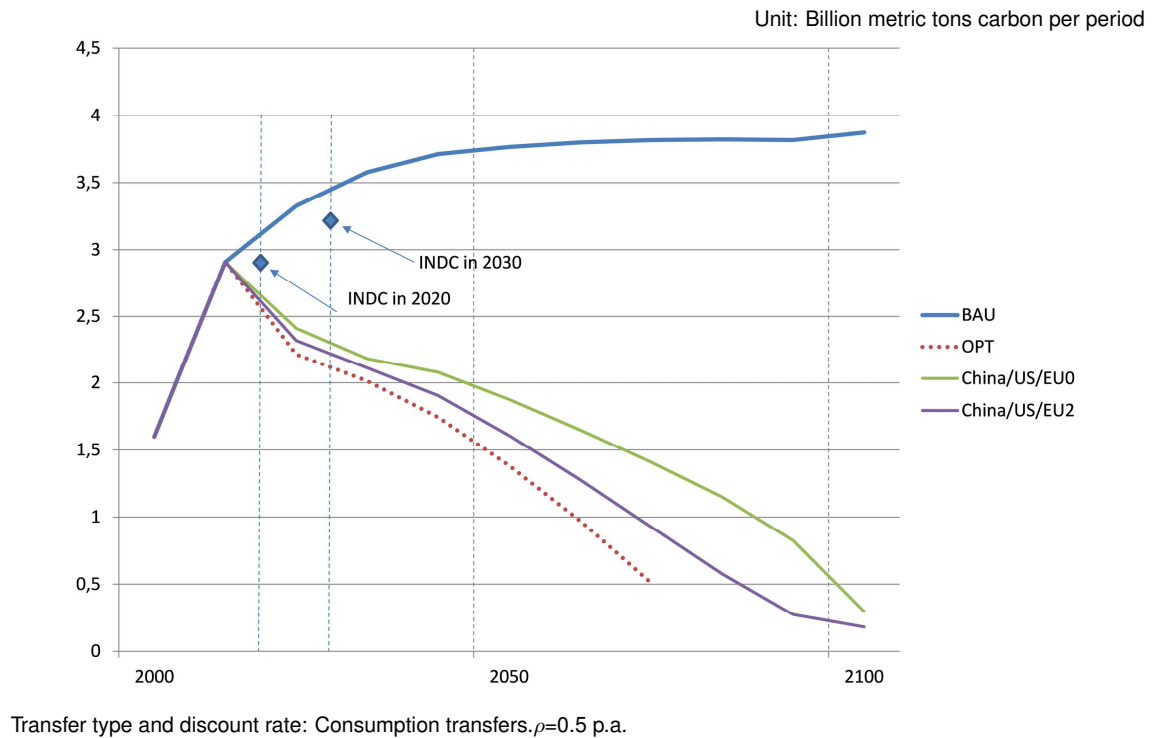
The US' INDC will reduce its greenhouse gas emissions by 26-28% below its 2005 level in 2025 and make best efforts to reduce its emission by 28%. According to the RICE-2010 model, US' emission level is 1.66 Gt carbon in 2005. The range for its carbon emissions target after cutting by 26-28% is from 1.20 to 1.23 Gt in 2025.

Figure 11 is similar to Figure 6 but marked with the estimated carbon emission levels from US' INDC, which shows that it is lower than the emissions in both the Pareto improving scenarios and the OPT scenario. In this section, the Pareto improving scenarios always assume that consumption transfers are allowed. When there are consumption transfers, the countries/regions do not need to abate as much as in the case with no transfers to achieve the same utility level. Or to say, the emission levels with consumption transfers are higher than the emission levels with no transfers under Pareto improvements. In reality, countries/regions cannot transfer as much as they want (A further discussion on this will be given in Subsections 4.3 and 5.1). This indicates that the proper emission levels have to be lower than when there are full transfers and higher than when there are no transfers. As a result, it is reasonable for the INDCs to have lower estimated carbon emission levels than the carbon emission levels with consumption transfers.

Figure 11: US' carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period
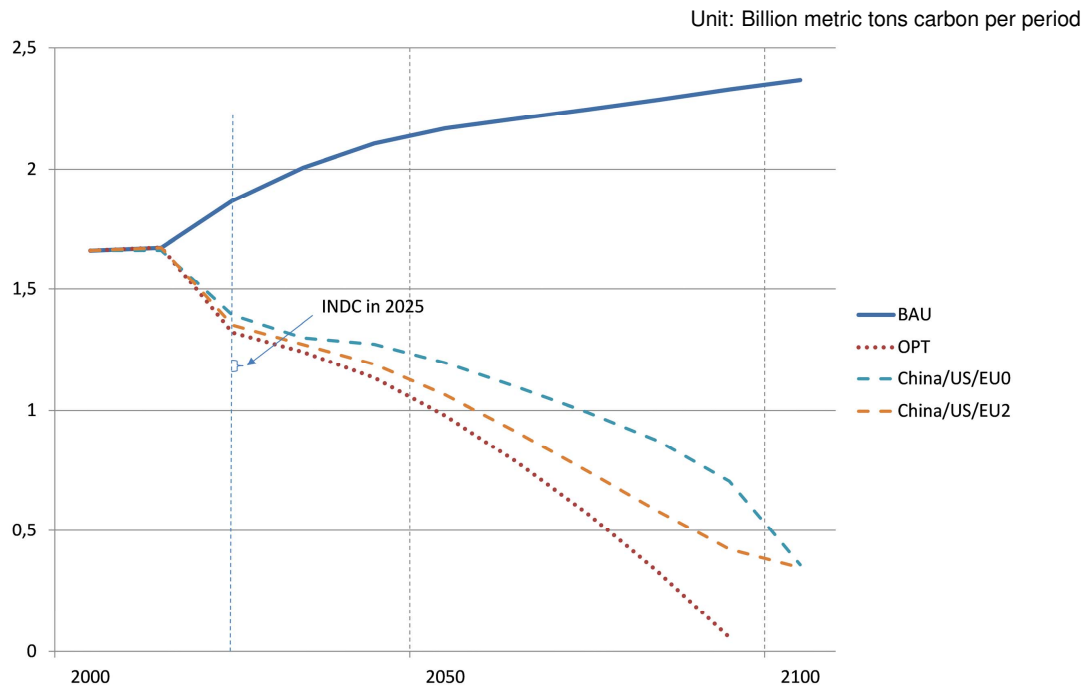
Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

EU's INDC has a binding target of at least 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990. In 1990, EU's total CO_2 emissions excluding LULUCF/LUCF were 4,437.03 Tg, which is 1.21 Gt carbon. Thus, its emission target after cutting by 40% is below 0.72 Gt carbon. Figure 12 is similar to Figure 7 but marked with the estimated carbon emissions level from EU's INDC. The INDC emissions are also lower than the emissions in both Pareto improving scenarios and the OPT scenario. Similarly, it is reasonable for EU's INDC to have lower estimated carbon emission levels than the carbon emission levels with consumption transfers, which has been explained in the paragraph above.
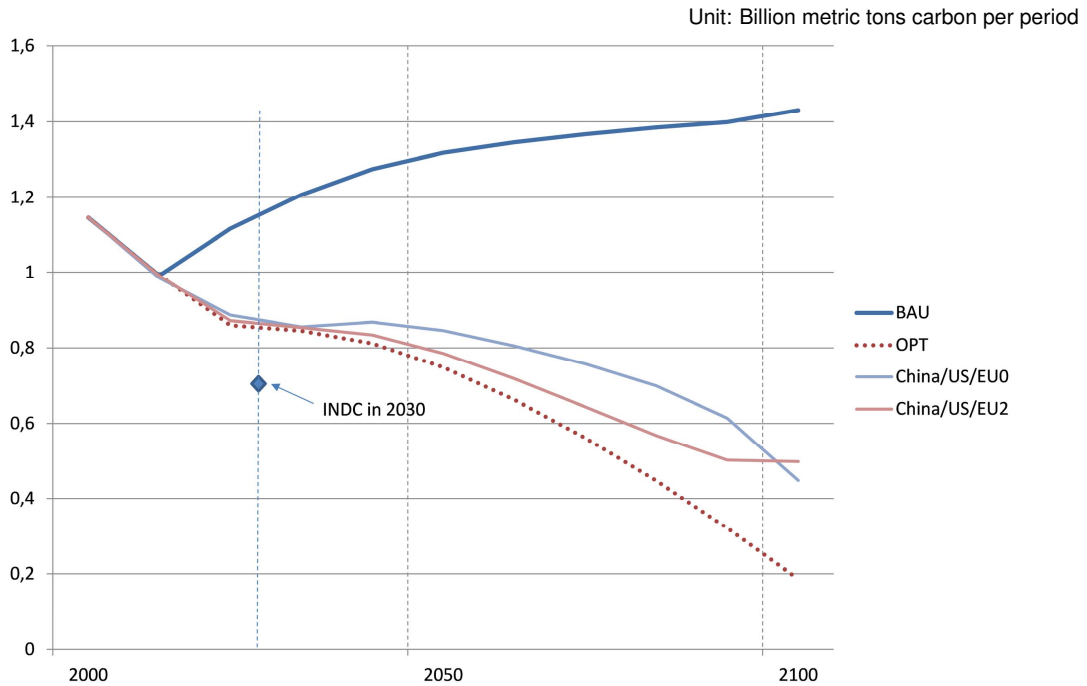
Figure 12: EU's carbon emissions under different scenarios comparing its INDC

Unit: Billion metric tons carbon per period

Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

As discussed, the Pareto improvements can be achieved with temperature above 2°C over the periods according to the simulation results from the RICE-2010 model. Then question may be asked, is the "2°C target" too ambitious according to our results? Here we should notice that the results in this section can only be achieved by consumption transfers, and not all the consumption transfers may be politically feasible. A further discussion on this will be given in Subsection 4.3.

4.3 Consumption transfers

In the previous simulations, the consumption transfers are always assumed to be allowed among countries, since transfers are part of climate finance. However, the transfers obtained from the simulations may not be politically feasible, so it is necessary to look further into these transfer levels.

Eyckmans et al. (1993) revealed that climate policy can redistribute the welfare with transfers, so countries/regions do not need to abate more to satisfy the distributional re-

quirements, when there are consumption transfers. But if the required transfer amounts cannot be fully implemented, countries/regions may have to abate more to meet the Pareto constraints. As the Pareto improving temperature trends in the case of unlimited consumption transfers are beyond 2°C, the target "below 2°C of warming" in the Paris Agreement may increase the countries/regions' welfare, and help to meet the Pareto constraints with limited transfers. Therefore, discussing transfer amounts are also very essential from this aspect before drawing the conclusion.

The Millennium Development Goals (MDGs) are *"the world's time-bound and quantified targets for addressing extreme poverty in its many dimensions"*[20], which focus on income poverty, hunger, disease, education and environmental sustainability etc. The internationally agreed framework contains eight goals, with technical indicators to measure progress towards the MDGs. One of eight goals, *"Develop a Global Partnership for Development"*, has an indicator named the Official Development Assistance (ODA). It has been specified in the MDGs that *"the UN Millennium Project's analysis indicates that 0.7% of rich world GNI can provide enough resources to meet Millennium Development Goals."*[21] Here I use the number 0.7% as the benchmark to discuss whether the consumption transfer amounts are reasonable.

Table 5 presents the consumption transfer rates to China in each period under Pareto improvements, i.e., the ratio of consumption transfers to net output[22]. We notice that the transfer rates to China in periods t2 and t3 when the future generation's welfare of China is maximized are extremely large, 19.34% and 10.52% respectively. This indicates that an amount equivalent to more than 10% of China's net output has to be transferred to China under Pareto improvements in order to satisfy the Pareto improving requirements. Some of the rest consumption transfer rates seem more reasonable, as they are lower than or around the benchmark 0.7%. On the whole, the consumption transfer rates to China when US or EU's welfare is maximized are closer to the benchmark than the consumption transfer rates when China's welfare is maximized, which indicates it is probably more politically feasible to base a policy on maximizing US or EU's welfare than maximizing China's welfare by using transfers. Besides, the consumption transfer rates to the present generations of China are closer to the benchmark than the consumption transfer rates to the future generations of China, which indicates that it may be more realistic to maximize the welfare of the present generations than the welfare of the future generations when

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[20] Details about MDG can be checked by the link `http://www.unmillenniumproject.org/goals/index.htm`

[21] *"The 0.7% target: An in-depth look"*. Retrieved from `http://www.unmillenniumproject.org/press/07.htm`

[22] In the RICE-2010 model, "net output" equals to the GDP deducting damages and abatement (equation (8) in Section 2). Here I used it as an approximate measurement of the GNI.

considering transfers.

Table 5: Period consumption transfer rates to China

Periods	China0	China2	US0	US2	EU0	EU2
t0	6,27 %	-0,43 %	-1,62 %	-0,42 %	-1,62 %	-0,42 %
t1	1,21 %	1,31 %	1,03 %	1,06 %	1,03 %	1,06 %
t2	0,25 %	19,34 %	0,25 %	-2,78 %	0,25 %	-2,78 %
t3	4,51 %	10,52 %	4,47 %	5,35 %	4,51 %	4,95 %

Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

Table 6 presents the period consumption transfer rates to US. We notice that the transfer rates to the future generations of US in periods t2 and t3 are extremely large, 24.97% and 7.84% respectively. Some of the other consumption transfer rates are also larger than the benchmark 0.7%, but the deviations are not as large as those of China.

Table 6: Period consumption transfer rates to US

Periods	China0	China2	US0	US2	EU0	EU2
t0	-1,07 %	-0,16 %	4,43 %	-0,16 %	-1,08 %	-0,16 %
t1	0,58 %	0,25 %	0,71 %	0,50 %	0,59 %	0,25 %
t2	0,84 %	-2,42 %	0,84 %	24,97 %	0,84 %	-2,42 %
t3	1,32 %	0,40 %	1,32 %	7,84 %	1,32 %	0,40 %

Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

The period consumption transfer rates to EU under different scenarios are presented in Table 7. The deviations from the benchmark are not large for most of the consumption transfer rates to EU, except that the transfer rates to the future generations of EU in periods t2 and t3 are far beyond the benchmark and not realistic, which are 26.88% and 7.76% respectively. This means that the welfare of EU's future generations is more politically difficult to maximize.

Table 7: Period consumption transfer rates to EU

Periods	China0	China2	US0	US2	EU0	EU2
t0	-1,12 %	-0,24 %	-1,13 %	-0,24 %	4,26 %	-0,25 %
t1	0,75 %	0,26 %	0,76 %	0,26 %	0,89 %	0,53 %
t2	0,07 %	-3,16 %	0,07 %	-3,16 %	0,07 %	26,88 %
t3	0,35 %	-0,56 %	0,35 %	-0,56 %	0,35 %	7,76 %

Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

By discussing the consumption transfer amounts, not all the transfer rates are below 0.7% and some of them are even far beyond the benchmark. Large consumption transfers are difficult to implement as large transfers are probably not politically feasible. Another reason for this is that large transfers may create problems in an economy with weak institutions, e.g., corruption, resource curse, "Dutch disease", or rent seeking. This indicates that countries/regions have to abate more to compensate the decrease in welfare caused by less consumption transfers. That is to say, the "2°C target" may be a more realistic target when the transfer amounts cannot be fully implemented. This will be shown in Subsection 5.1.

5   Sensitivity analysis

5.1   No transfers

In previous sections, I studied the cases where consumption transfers were available. In this subsection, I will analyze the case when no transfers are allowed. Here, consumption transfers cannot be used as a distribution instrument any more. Distribution of consumption is achieved by changing each country/region's emission level, which leads to different marginal productivity of emissions[23]; that is to say, carbon prices are different across countries/regions. The comparisons are also between the simulation results and the estimated effects from the INDCs when it comes to temperature and carbon emissions.

5.1.1   Temperature comparison

Figure 13 shows global mean temperature under the different scenarios and the estimated temperature from the INDCs. The highest temperature is still in the BAU scenario. In the OPT scenario, the change in the global mean temperature peaks at 2.3°C approximately, and goes below 2°C around the year 2175. It is surpassed by the Pareto improving trends when China's welfare is maximized (China0 and China2), which is again surpassed by the Pareto improving trends when US' welfare is maximized (US0 and US2) after 2150. The Pareto improving trends for EU (EU0 and EU2) are the lowest and below the trend in the OPT scenario.

Actually, the temperatures in the BAU scenario and the OPT scenario are the same as in the case when there are consumption transfers (Figure 3 and Figure 8). The reason is that both scenarios assume that no consumption direct transfers are possible within each generation, so they will not be affected by whether consumption transfers are allowed or not in the Pareto improving scenarios.

As illustrated in Figure 13, the trends when the welfare of the present generation and future generation of each country/region is maximized are quite close to each other (China0 is close to China2, etc.), indicating that the two generations share similar preferences under Pareto improvements. When transfers are not allowed, the future generation can benefits from the capital accumulated from the present generation, and thus it does

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[23]More about the specification for the no transfer case, please see Hoel et al. (2015), Section 2 and 4

not make a big difference which generation's welfare is maximized.

Figure 13: The global temperature under different scenarios comparing with the INDCs

Unit: °C
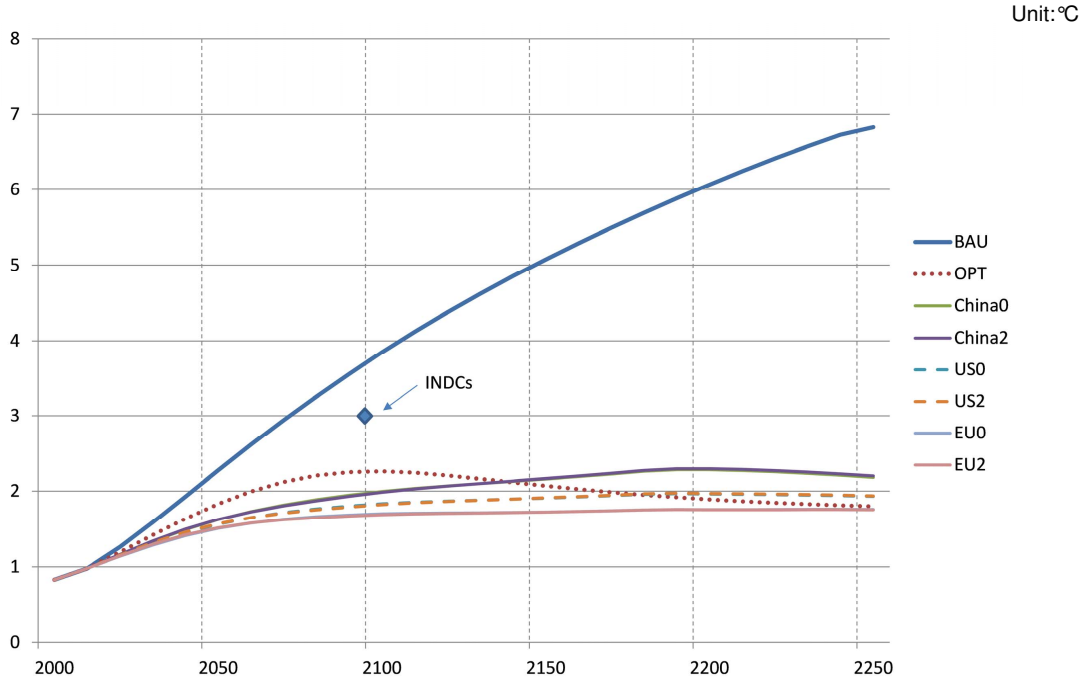
Transfer type and discount rate: No transfers. ρ=0.5 p.a.

In Section 3, I mentioned that when there are consumption transfers, the Pareto improving temperature will be beyond the "2°C target" from the Paris Agreement, and the Pareto improving emissions are unable to attain the "carbon budget" identified by IPCC. As climate policy redistributes the welfare, countries/regions have to abate more to satisfy the Pareto improving requirements when there are no transfers. Comparing with the case of consumption transfers in Figure 3 and Figure 8, there is less warming without transfers. The temperature trends when the welfare of US and EU is maximized (US0/US2 and EU0/EU2) under Pareto improving scenarios are well below 2°C over the periods, while the trends when China's welfare (China0/China2) is maximized are approximately 2.3°C at its peak. Thus, the trends under Pareto improvements when the welfare of US and EU are maximized (US0/US2 and EU0/EU2) are on the path to achieve the "2°C target" from the Paris Agreement in the case of no transfers. These give positive evidence to the speculation in the end of Section 4.3, stating that the "2°C target" may be a more realistic target when transfers cannot be fully implemented.

Moreover, in the Pareto improving scenarios, the temperature trends China0/China2

39

are the highest, EU0/EU2 are the lowest, and US0/US2 are in the middle. This indicates that the world abates the most when EU's welfare is maximized with the Pareto improving constraints, and the least when China's welfare is maximized with the Pareto improving constraints. The US is in the middle. This reflects that different countries/regions have different preferences towards temperature; China prefers a higher temperature, and EU prefers a lower temperature. The reason is that as a developing country, the marginal utility of one unit emissions for China is higher than US and EU, or one unit emissions can increase China's welfare more than for US and EU. On the other hand, US and EU, as developed countries/regions, the environment is more valuable for them relative to consumption, than for China, and hence they have more incentive to abate. As a result, we can rank the temperature from Figure 13 as below by 2100:

$$BAU > INDCs > OPT > Pareto\_China > Pareto\_US > Pareto\_EU \quad (24)$$

where *"Pareto_China"* stands for the global mean temperature when maximizing the welfare of China under Pareto improvements, *"Pareto_US"* stands for the global mean temperature when maximizing the welfare of US under Pareto improvements, and *"Pareto_EU"* stands for the global mean temperature when maximizing the welfare of EU under Pareto improvements.

5.1.2 Carbon emissions comparison

The global carbon emissions comparison

Figure 14 illustrates the different scenarios and the estimated carbon emission levels from the INDCs, when transfers are not available. The orange arrow still shows the emissions under the "carbon budget" constraint.

We can see that the carbon emissions under Pareto improvements are the lowest most of the time across the century, since the world has to abate much more without transfers than in the case with transfers in Figure 4 and Figure 9, otherwise the Pareto improving requirements cannot be satisfied. As explained in Subsection 5.1.1, the present generation and future generation of each country/region share similar preferences under Pareto improvements when there are no transfers. Hence, the emissions trends for the two generations are quite close to each other.

40

Figure 14: The global carbon emissions under different scenarios
comparing with the INDCs and the "Carbon budget"
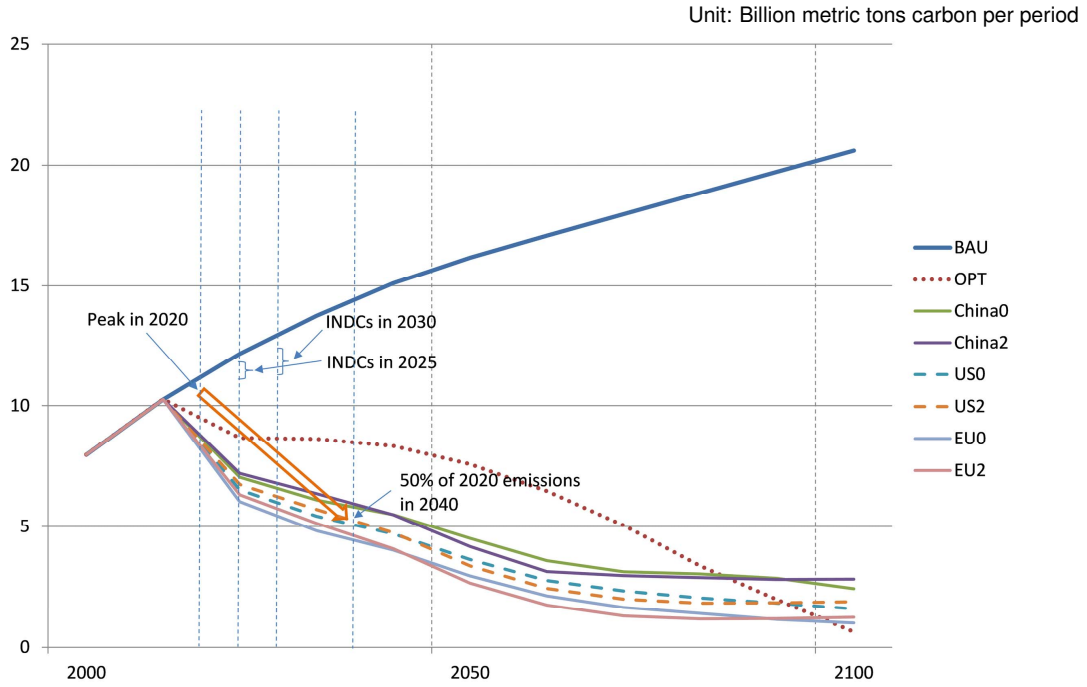
Transfer type and discount rate: No transfers.ρ=0.5 p.a.

Furthermore, as explained in 5.1.1, the marginal utility of one unit emissions for developed countries is usually lower than the developing countries, so the global carbon emission levels will be lower when the welfare of the developed countries/regions is maximized. This is consistent with the result we obtained from Subsection 5.1.1, since the temperature is tightly linked with emissions. Therefore, under Pareto improvements, global carbon emissions are the highest when China's welfare is maximized, and lowest when EU's welfare is maximized. The emissions from maximization of the US' welfare are in the middle. Now, comparing the estimated carbon emission levels from the INDCs with the different scenarios derived from the RICE-2010 model, we can rank the carbon emissions by 2030 when transfers are not allowed as below:

$$BAU > INDCs > OPT > Pareto\_China > Pareto\_US > Pareto\_EU \quad (25)$$

where *"Pareto_China"*, *"Pareto_US"* and *"Pareto_EU"* stand for the same scenarios as described in Subsection 5.1.1, but we compare global carbon emissions trends instead of global mean temperature trends.

As mentioned in Subsection 3.4, IPCC has identified the world's "carbon budget" as shown by the orange arrow in Figure 14. It seems that Pareto improving trends have an

41

earlier peak compared to the "carbon budget", where there are no consumption transfers. The decreasing trends afterwards are more promising about attaining the "carbon budget" than both the Pareto improving emission levels with consumption transfers and the IN-DCs. In other words, the Pareto improving emissions in the no transfer case can meet the "carbon budget" requirement better than the INDCs, and are thus much closer to the path to achieve the "2°C target" in the Paris Agreement.

The three main CO_2 emitting countries/regions' carbon emissions comparison

Figures 15-17 show the annual industrial carbon emissions compared to the estimated carbon emission levels from the INDCs for the three main CO_2 emitting countries/regions respectively. In each figure, the carbon emissions in the BAU scenario and the OPT scenario are the same as in Section 3 and 4. But emissions under Pareto improvements are no longer the same, and vary according to which country/region's welfare is maximized.

In Figure 15, we notice that carbon emissions in China are much higher when China's welfare is maximized (China0 and China2) under Pareto improvements than when the US' welfare is maximized, or when the EU's welfare is maximized. It reflects that when China's welfare is maximized, the other two countries/regions will not be in their welfare maximizing state. That is to say, one country/region prefers to enjoy the abatement from other countries/regions, instead of abating itself. The differences among the trends indicate the preferences conflict on emissions, or abatement allocations, among countries/regions.

The estimated carbon emissions level from China's INDC is quite close to emissions when China's welfare is maximized (China0/China2) under Pareto improvements. However, the carbon emission levels from China's INDC are much higher than the carbon emissions when US or EU's welfare is maximized (US0/US2 or EU0/EU2). This means that the estimated carbon emission levels from China's INDC are more likely on the path to maximize its welfare instead of the welfare of US and EU, indicating that China's INDC is not an altruistic abatement plan.

42

Figure 15: China's carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period
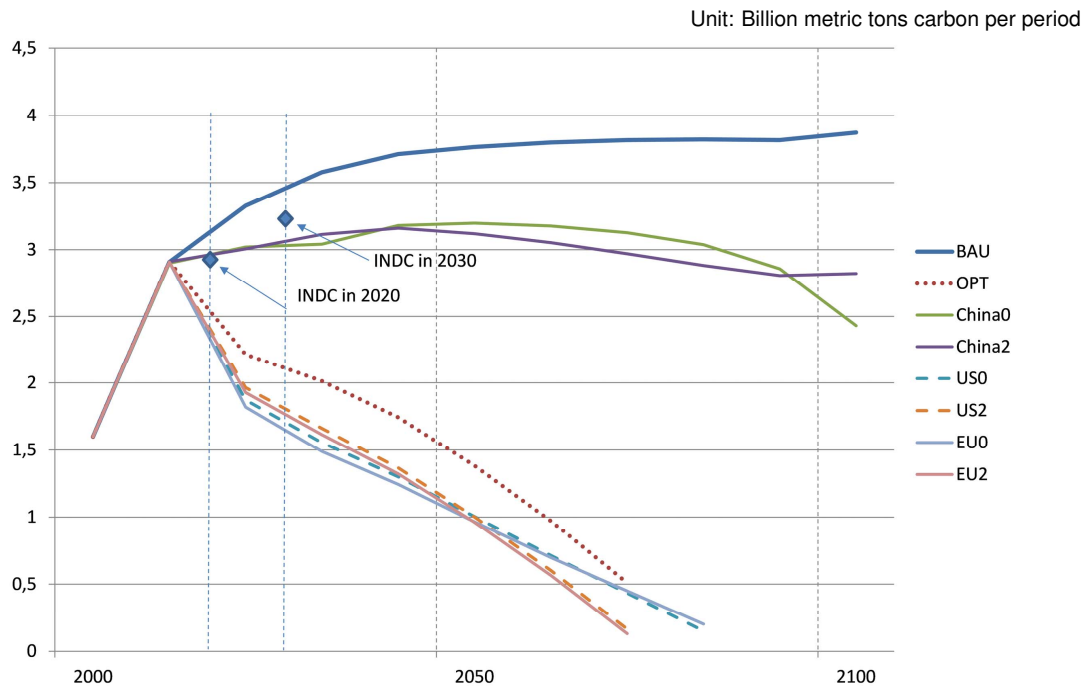
Transfer type and discount rate: No transfers. ρ=0.5 p.a.

Nevertheless, Figure 13 shows that when China's welfare is maximized, the global mean temperature will peak at 2.3°C in 2200. This means the estimated carbon emission levels from China's INDC are probably above the path to achieve the "2°C target" in the Paris Agreement. So it is more likely for China to achieve the target if its INDC is somewhere between the trends when China's welfare is maximized (China0/China2) and trends when US and EU's welfare is maximized (US0/US2 and EU0/EU2), i.e., if China has a lower emissions level than the present INDC.

From Figure 16 we see that when China and EU's welfare is maximized, US has much lower carbon emissions (China0/China2 and EU0/EU2) than the emissions when US' welfare is maximized (US0/US2). This confirms the discussion in China's case that one country/region prefers to leave the abatement task to other countries/regions, instead of abating itself. The preferences conflict on abatement among countries/regions can be illustrated by the following example. US maximizes its welfare at point X without hurting the welfare of other countries/regions, and at the area near point Y, US maximizes China's welfare or EU's welfare with a much lower emissions level. Points X and Y reflects two extremes of emission levels for one country/region under Pareto improvements, and the relative position of the selected emissions level (INDC) between the two "ends" reflects

the degree of altruism of the country/region, where the country/region is more altruistic when its emissions level is close to Y. Thus, the US seems to be more altruistic than China. An alternative interpretation is that the technological options are better in the US than described by the RICE-2010 model.

Figure 16: US' carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period

Transfer type and discount rate: No transfers. ρ=0.5 p.a.
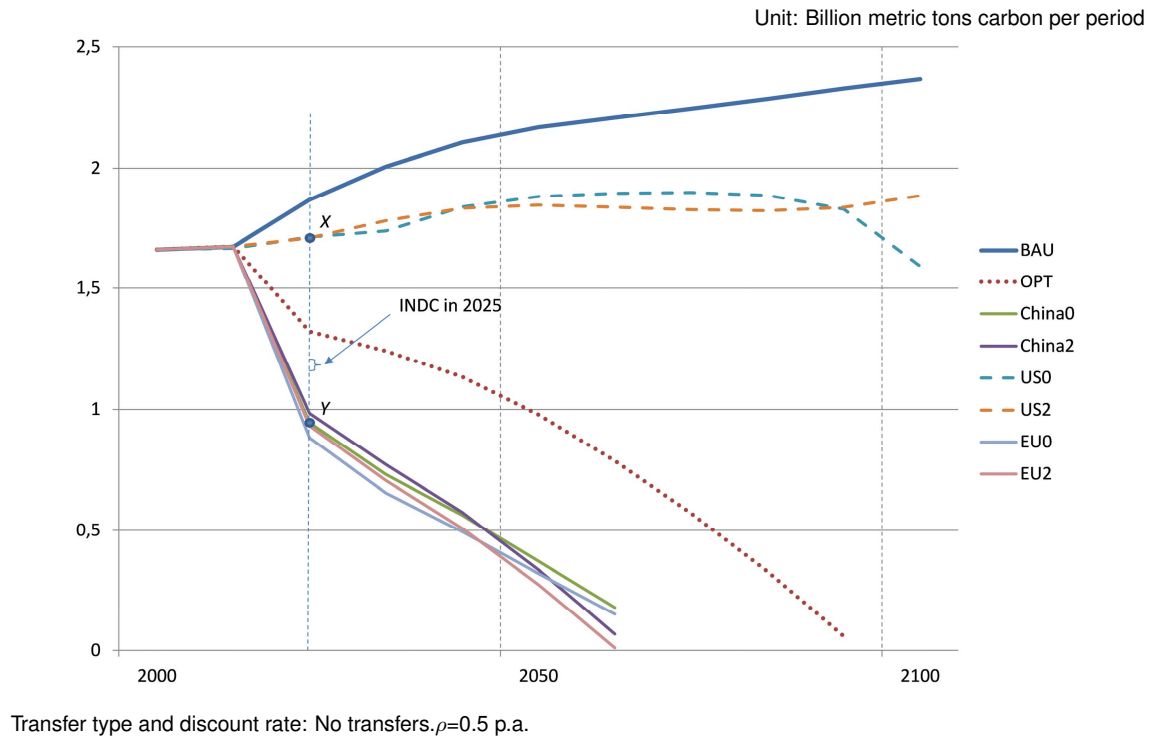
Figure 17 illustrates the different trends for EU. Similarly, when China and US' welfare is maximized, EU has much lower carbon emissions (China0/China2 and US0/US2) than the emissions when EU's welfare is maximized (EU0/EU2). The estimated carbon emission levels from EU's INDC in 2030 are between the trends where EU's welfare is maximized and the trends where China and US' welfare is maximized. Similarly, the relative position of the estimated carbon emissions level from EU's INDC between the Pareto improving trends for EU and other two countries reflects the degree of altruism of EU's INDC.

Figure 17: EU's carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period

INDC in 2030

BAU
OPT
China0
China2
US0
US2
EU0
EU2
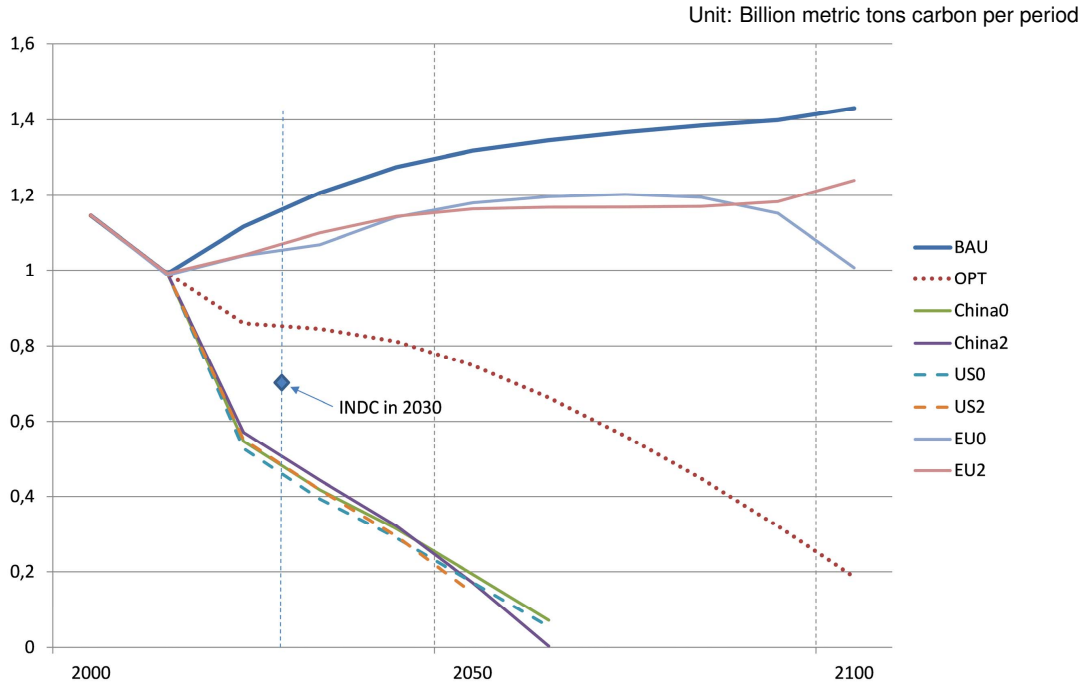
Transfer type and discount rate: No transfers.ρ=0.5 p.a.

From the discussion above, we can conclude that under Pareto improvements, the emission levels from US' and EU's INDCs are closer to the trends when the welfare of the other two countries/regions are maximized. While the emission levels from China's INDCs are just near the trends when its welfare is maximized. That is to say, US and EU may have more altruistic INDCs than China according to the simulation results. As mentioned, alternatively this may be due to better technological options in these countries/regions than described by the RICE-2010 model.

5.2   Different periods

In the previous sections, the analysis only focused on the cases when the welfare in t0 and t2 was maximized. In this part, I will analyze the case when the welfare in t1 and t3 is maximized with consumption transfers. Here I define t1 as the *"new present period"* and t3 as the *"new future period"*. I also compare the simulated temperature and carbon emissions with the INDCs.

5.2.1 Temperature comparison

Figure 18 shows global mean temperatures under the BAU, the OPT and the Pareto improving scenarios in addition to the estimated temperature from the INDCs.

Figure 18: The global temperature under different scenarios comparing with the INDCs
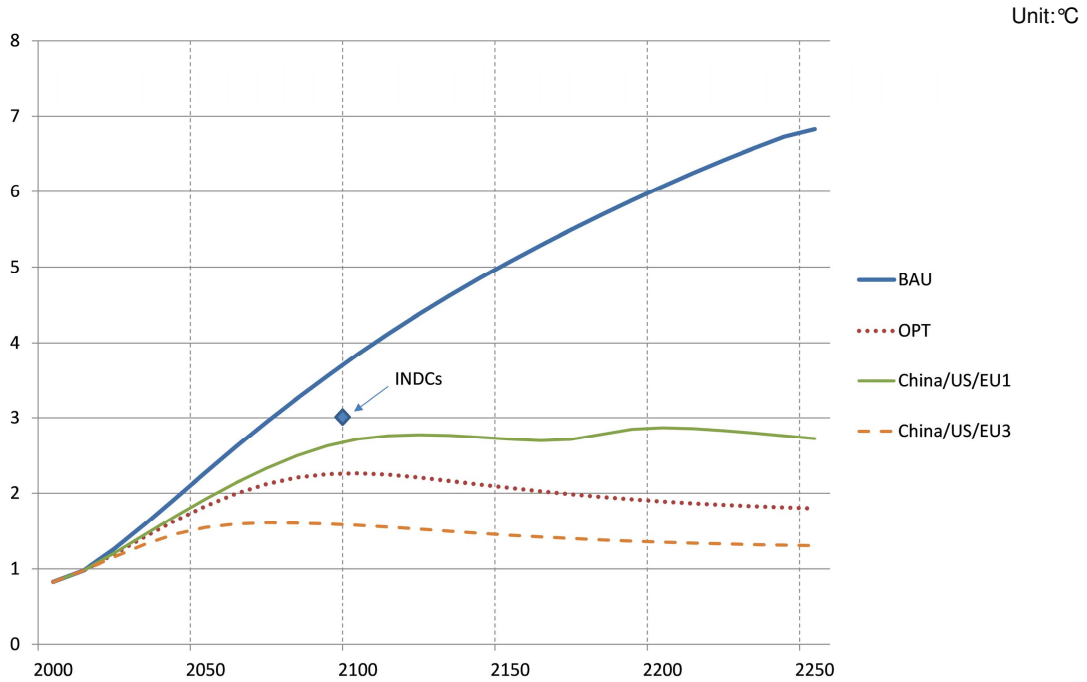
Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

The temperature in the BAU scenario and the OPT scenario are the same as in Figure 3 and Figure 8. The highest temperature is still in the BAU scenario. The temperature in the Pareto improving scenario of the new present period (China/US/EU1) is higher than for the OPT scenario and above 2°C over the periods, while the temperature in the Pareto improving scenario of the new future period (China/US/EU3) is lower than the OPT scenario and well below the 2°C over the periods. Comparing to Figure 3 and Figure 8, there is less warming when the welfare of the new future period is maximized. The reason is that the future generation always cares more about the environment than the present generation. The more "future" the maximized period is, the lower the simulated temperature will be. The global temperature when the welfare in the new present period is maximized (China/US/EU3) is quite close to the temperature when the welfare in t0 and t2 is maximized in Figure 3 and Figure 8 (China/US/EU0 and China/US/EU2), since the new period t1 is between t0 and t2, and they have similar preferences.

46

The temperature in the OPT scenario is in the middle of the Pareto improving scenario of the new present period and of the new future period. The reason is that the new present generation cares about the present, and the new future generation cares about the future. The OPT scenario takes into account the total welfare in all the periods, and is in the middle. We also find that the temperature when the welfare in the new present period is maximized has a later peak than for the OPT scenario, while the temperature when the welfare in the new future period is maximized has an earlier peak.

According to the simulation results, the temperature when the new future period is maximized satisfies the "2°C target" in the Paris Agreement under Pareto improvements if consumption transfers are allowed. In our model, an increase in temperature can be controlled around 2.7°C when the welfare of the new present period is maximized, and below 1.6°C when the welfare of the new future period is maximized by 2100 under Pareto improvements. In the OPT scenario, the temperature peaks at 2.3°C approximately, and goes below 2°C after the year 2175. As a result, we can rank the temperatures from Figure 18 as below:

$$BAU > INDCs > Pareto\,1 > OPT > Pareto\,3 \tag{26}$$

where *"Pareto 1"* stands for the global mean temperature when maximizing the welfare of the new present period under Pareto improvements, and *"Pareto 3"* stands for the global mean temperature when maximizing the welfare of the new future period under Pareto improvements. The emissions under the different scenarios and the INDCs are expected to follow the same ranking, which will be confirmed in 5.2.2.

5.2.2 Carbon emissions comparison

The global carbon emissions comparison

Figure 19 shows the carbon emissions under the different scenarios and the estimated carbon emission levels from the INDCs. The relationship between the Pareto improving trends and the "carbon budget" is shown by the orange arrow in Figure 19 as well.

Figure 19: The global carbon emissions under different scenarios comparing with the INDCs and the "Carbon budget"

Unit: Billion metric tons carbon per period
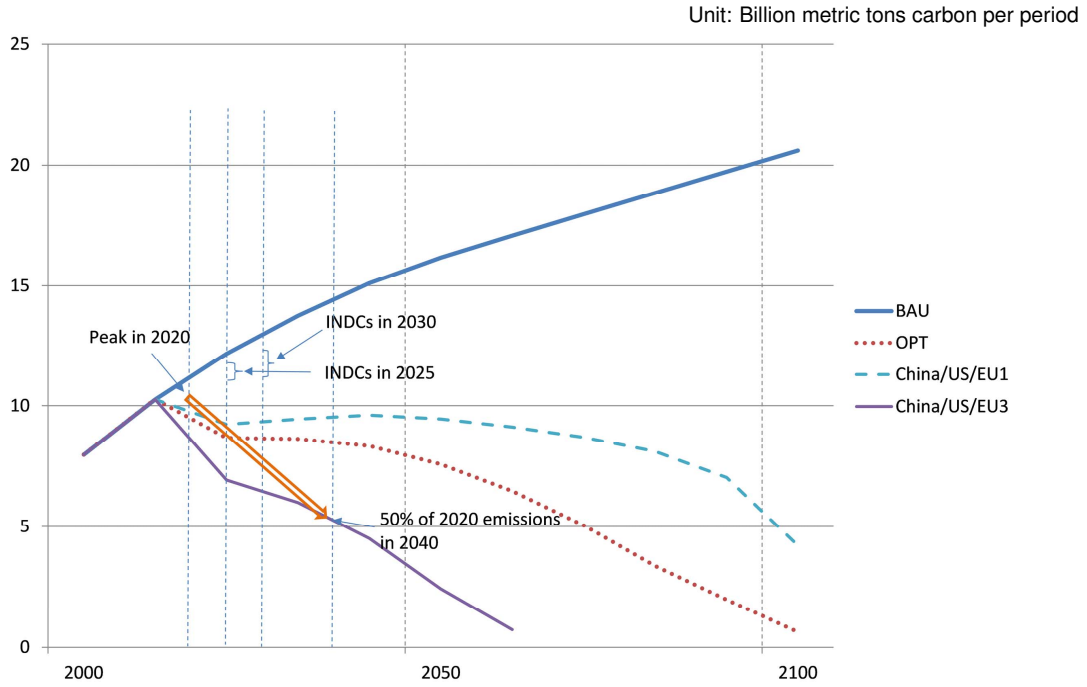
Transfer type and discount rate: Consumption transfers.ρ=0.5 p.a.

The emissions when maximizing the welfare of the new present period is quite similar to the Pareto improving emissions in Figure 4 and Figure 9. While the new future generation prefers much lower emissions, and the decreasing trend after 2015 are more promising about meeting the "carbon budget" identified by IPCC than in the cases when t0, t1 and t2 are maximized. We can rank the carbon emission levels as follows:

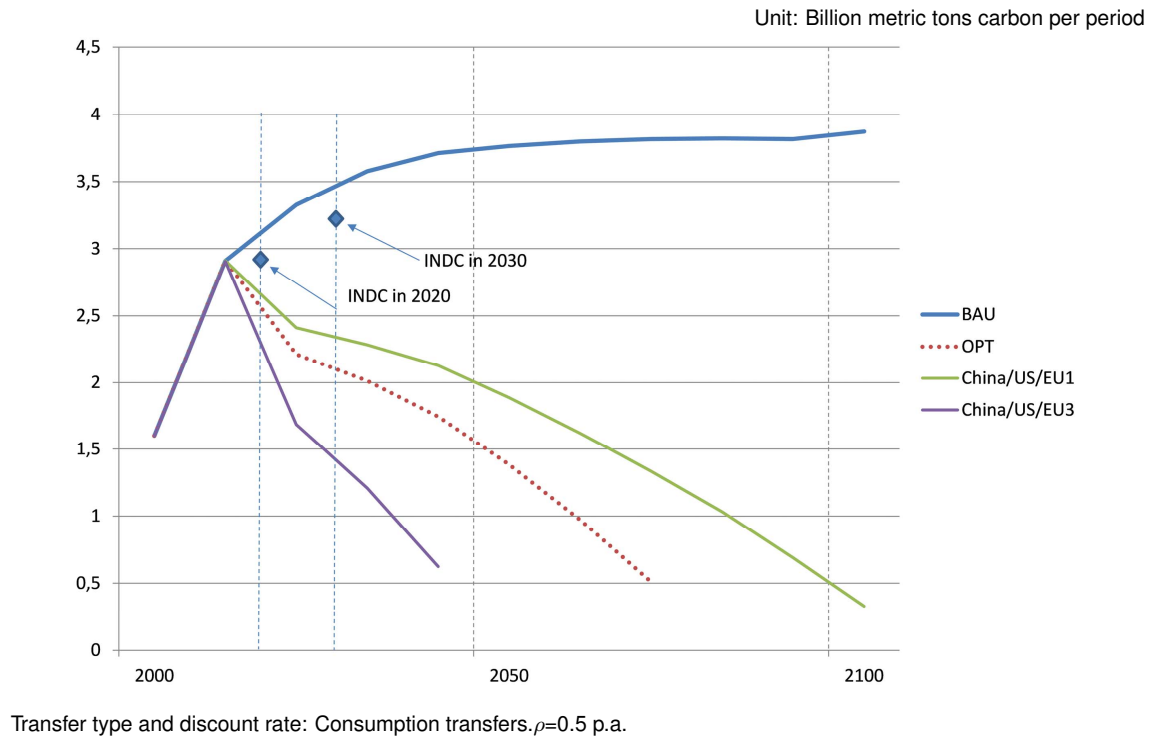$$BAU > INDCs > Pareto\,1 > OPT > Pareto\,3 \qquad (27)$$

where *"Pareto 1"* and *"Pareto 3"* stand for the same scenarios as described in Subsection 5.2.1. The result is consistent with the conclusion drawn in 5.2.1.

The three main CO$_2$ emitting countries/regions' carbon emissions comparison

Figures 20-22 show the annual industrial carbon emissions compared to the INDCs for the three main CO$_2$ emitting countries/regions respectively. In each figure, the carbon emissions in the BAU scenario and the OPT scenario are the same as in Section 3 and 4, since the two scenarios will not be affected by which period's welfare is maximized in the Pareto improving scenarios.

Figure 20 shows that when t3's welfare is maximized, China has much lower carbon emissions than in the OPT scenario, and the carbon emissions when t1's welfare is maximized is higher than in the OPT scenario. This is consistent with the conclusion that the future generations always prefer a lower temperature.

Figure 20: China's carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period

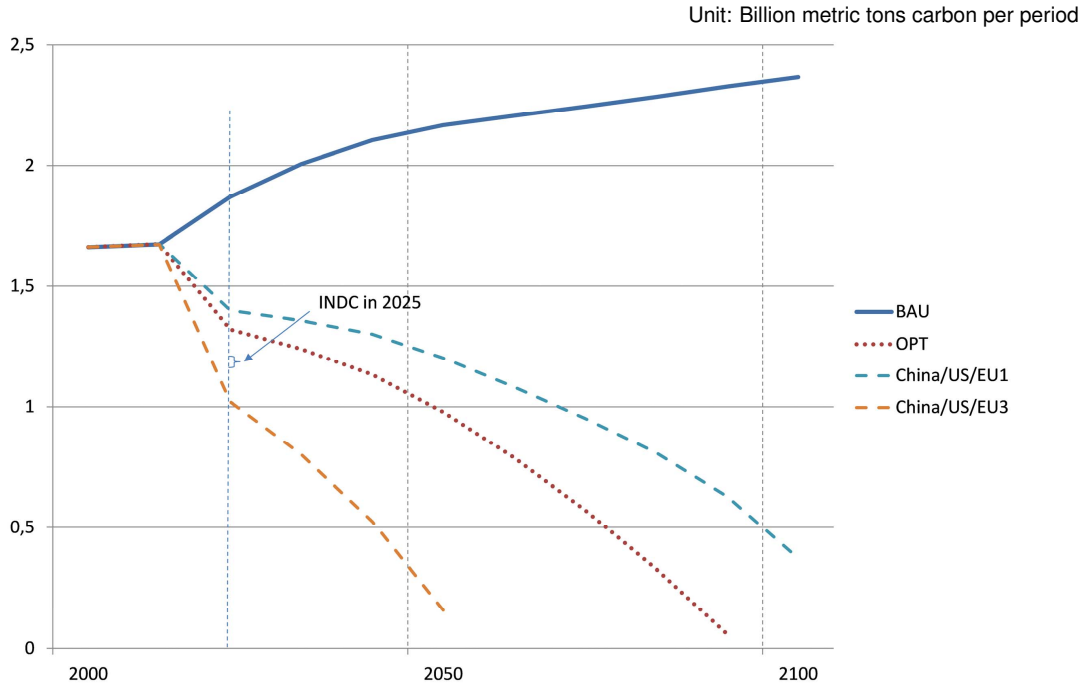Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

It seems that the estimated carbon emission levels from China's INDC have a similar relative position as in Figure 10, i.e. between the BAU scenario and the Pareto improving scenarios, where the welfare of t1 and t3 are maximized with consumption transfers, indicating that China is not on the path to maximize the welfare of these periods.

Figure 21 shows that the US has a much lower carbon emissions than in the OPT scenario when t3's welfare is maximized, and has higher carbon emissions than in the OPT scenario when t1's welfare is maximized.

Different from China, the estimated carbon emission levels from US' INDC is between the trends when t1 and t3's welfare is maximized. This indicates that US' INDC is similarly between the two "ends" in Figure 16, which maximized the welfare of the new present period or the new future period. Thus, the relative position reflects the degree of

altruism between the new present generations and the new future generations.

Figure 21: US' carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period

Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

Similarly, the emissions from maximizing the welfare of the new future generations are more likely on the path to achieve the "2°C target". However, we notice that the Pareto improving scenarios with consumption transfer always have higher carbon emissions than the actual Pareto improving emission levels, if the consumption transfers cannot be fully implemented as discussed in Subsection 5.1.

From Figure 22 we see that the emissions for EU when t1's and t3's welfare are maximized have the same feature as in Figure 20 and Figure 21. Nevertheless, compared with US, the estimated carbon emissions from EU's INDC is much closer to the "end" when the welfare of the new future generations is maximized, which is more likely on the path to achieve the "2°C target" in the Paris Agreement.

Figure 22: EU's carbon emissions under different scenarios comparing with its INDC

Unit: Billion metric tons carbon per period
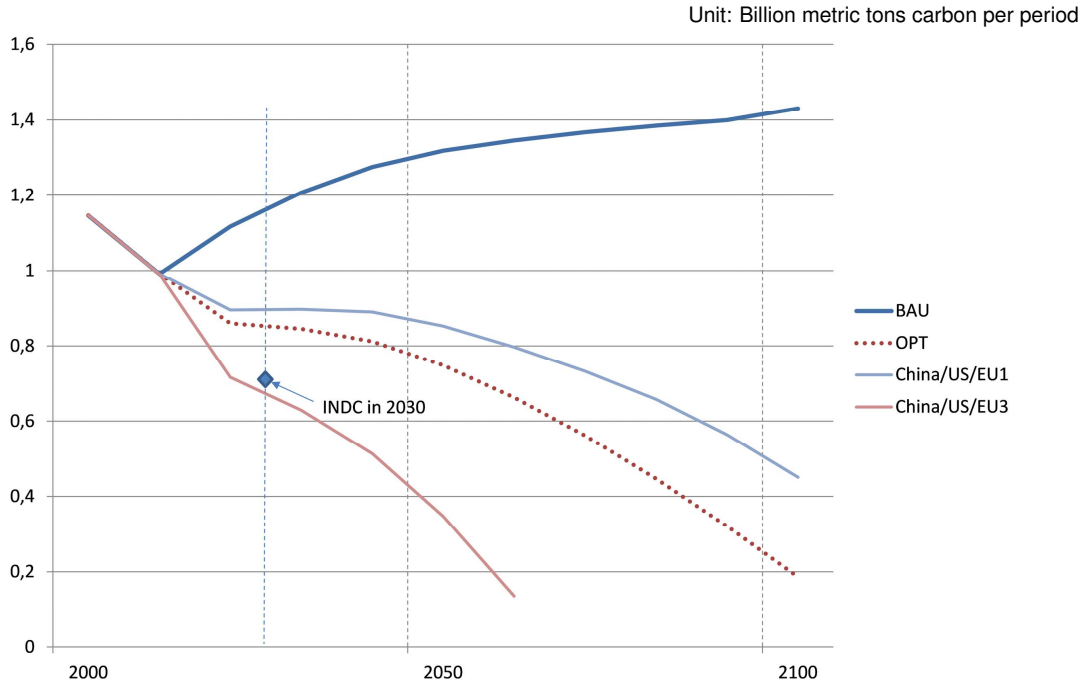
Transfer type and discount rate: Consumption transfers. ρ=0.5 p.a.

The simulations in the sensitive analysis for maximizing welfare in different periods show that there are always lower trends for global mean temperature when maximizing with respect to the future periods than with respect to the present periods. As mentioned in Section 3, the future generations have higher incentives to abate than the present generations, so that the temperature is lower when their welfare is maximized.

5.3 The utility discount rate

In all the previous parts, the discussions are based on the simulations with the utility discount rate ρ=0.5 p.a. In this subsection, the higher discount rate, ρ=1.5 p.a., will also be used, which is the same as in the original RICE-2010 model. Here, the maximized periods are now back to t0 and t2.

A higher utility discount rate means that future welfare is given less weight, or people care less about future warming. The simulation results are illustrated in Figure 22. The temperature in the BAU scenario and the OPT scenario are now different from those in

Figure 3, Figure 8 and Figure 13. The temperature in the BAU scenario is lower. The reason is that the high discount rate will decrease people's incentives to invest. Consequently, production declines, and emissions and temperature will be lower than in the case with a lower discount rate. For the OPT scenario, the temperature is higher than with a lower discount rate due to people's carelessness for future warming and future welfare. By increasing the utility discount rate from 0.5% to 1.5%, the temperature increases from 2.3°C to 2.7°C by 2100.

For the Pareto improving scenarios, a higher discount rate can affect global temperature in two ways. On one hand, Pareto improving scenarios are linked to BAU, as BAU sets an upper limit to these scenarios. A lower BAU may therefore lower the Pareto improving temperature; On the other hand, a higher discount rate will also decrease the incentives for abatement, which can increase people's welfare in the future, and in this situation, the temperature will be higher than in the case of a lower discount rate. Under the specific settings of this model, the second effect dominates the first, so the global temperature with a higher discount rate are higher than with a lower discount rate in the Pareto improving scenarios.

Figure 23: The global temperature under different scenarios
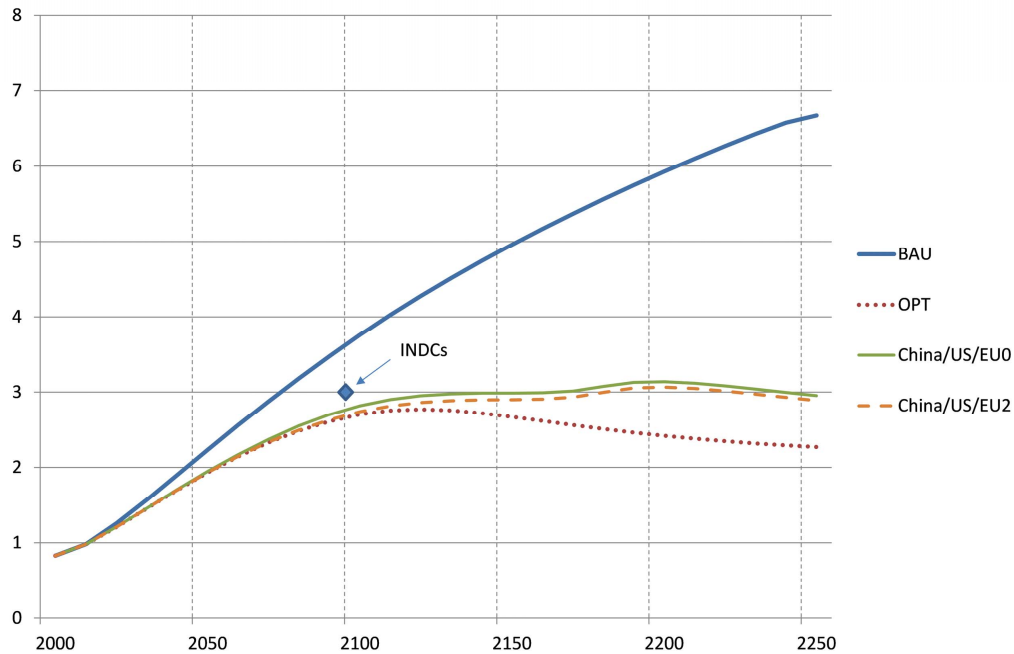
Transfer type and discount rate: Consumption transfers. ρ=1.5 p.a.

6 Conclusions

The Paris Agreement is the most important achievement of climate change negotiations in the past 20 years. However, no compulsory and specific abatement level or abatement allocations have been provided in this agreement. Whether the INDCs can ensure the "2°C target" is doubtful without revisions of the targets.

In my thesis, I constructed four regions (China, US, EU and ROW) and four periods (t0-t3) model. This has been done to find the Pareto improving climate policies for particular country/region and generations. A numerical model, RICE-2010, is used to simulate global mean temperature as well as global carbon emissions. Besides the Pareto scenarios, the business-as-usual and the social optimal scenarios are also derived as benchmarks. Specially, the simulations focus on the three main CO_2 emitting countries/regions, i.e., China, US and EU. Then, the estimated effects of the aggregated INDCs and of each country/region's INDC have been compared to the simulations.

The study finds that the social optimum is not necessarily on the Pareto improving frontier. This means that some countries/regions' welfare will be worse off under the social optimal scenario. Compared with the INDCs, the Pareto improving temperature with unlimited consumption transfers are above the "2°C target" in the Paris Agreement, and the carbon emissions trends are also beyond the "Carbon budget" identified by IPCC.

However, not all consumption transfers can be fully implemented in reality. In the sensitivity analysis section for the no transfer case, the global mean temperature trends are well below 2°C when the US and EU's welfare is maximized. And the global carbon emissions trends are more promising about attaining the "Carbon budget" as well, since countries/regions have to abate more when there are no transfers to satisfy the Pareto improving requirements.

For the three main CO_2 emitting countries/regions, the study also finds that in the no transfer case, the estimated carbon emission levels from China's INDC are quite close to the emissions trends when its welfare is maximized, while the estimated carbon emission levels from US' INDC is closer to the carbon emissions trends when the welfare of the other two countries/regions are maximized. This is also the case for the EU's INDC. This may indicate that the EU and US are more altruistic than China when choosing their INDCs. However, it may also be the case that these countries have better technological

options and therefore lower abatement costs than described by the RICE-2010 model.

The most important "take home" message from the thesis is that it is crucial to take the welfare of each country/region and generation into consideration when social planners are making climate policies. Social optimum may hurt the welfare of some countries/regions or some generations. By allocating the abatement in a Pareto improving way, we may reduce conflicts in international climate change negotiations.

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