Computable General Equilibrium Analyses of Global Climate Agreements: A Multi-sector and Multi-region Dynamic Model

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Abstract

This article examines global climate agreements for abating GHGs with interactions and heterogeneity among various countries. It uses the dynamic version of Evaluation Model for Environmental Damage and Adaption (EMEDA) developed for simulating global economic impacts resulting from climate change. Simulated results show that: 1) simulated economic damage derived from CO2 emissions reduction rates attained by official announcements varies among regions and sectors, 2) the real GDP losses of Japan, the U.S. and EU are improved by CO2 emissions reduction, but real GDP losses of other regions are deteriorated; and 3) there exist several sectors of which the real value-added losses decrease in each region.

JEL-Classification: C68, Q54
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1. Introduction

The anthropogenic greenhouse gas (GHG) driven climate crisis has received global attention over the last several decades, with 'global warming' and 'climate change' becoming important keywords and catalysts for controversial debates across academia, various institutions and broad areas of society. Since the early nineties many scholars have developed integrated assessment models (IAMs) to analyze global warming. The United Nations International Panel on Climate Change (IPCC) for example has employed IAMs to determine future socio-economic scenarios and to evaluate policy measures (Mori et al., 2008). Nordhaus (1991) first attempted to estimate the cost of climate change for the U.S. and the rest of world. Since then, many other studies have emerged addressing the global economic costs of climate change (Frankhauser, 1995; Nordhaus and Boyer, 2000; Nordhaus and Yang, 1996; Tol, 1995, 1999, 2002).

With many studies providing assessments of the global and regional economic costs of climate change, some focus on economic consequences from multiple sectors in multiple regions. Washida (2010) and Washida et al. (2013) developed the Evaluation Model for Environmental Damage and Adaption (EMEDA) as a static CGE model to simulate economic damages resulting from global warming and adaptation costs. Compared with the other global economic models such as the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) by Tol (1995), there are several advantages to EMEDA. Firstly, it captures not only domestic economic impacts but also indirect economic impacts on world trade among nations affected by global warming. Secondly, it utilizes the Global Trade, Assistance, and Production version 7 (GTAP7) Data Base which has rich global economic data including that from developing countries. Lastly, damage functions may be inserted more easily into this model than other CGE models.

This study constructs a dynamic version of EMEDA to simulate the world economy as eight regions including Japan, China and the U.S., with each region broken down into eight sectors for the period 2004-2100. To calculate recursive competitive equilibrium year by year, we have utilized the GTAP7 Data Base and GAMS. Additionally, we have added global warming and damage functions modified from DICE2010 and RICE2010 (Nordhaus, 2012).

Simulated results by the dynamic EMEDA indicate that: 1) simulated economic damage derived from CO2 emissions reduction rates attained by official announcements varies among regions and sectors, 2) the real GDP losses of Japan, the U.S. and EU are improved by CO2 emissions reduction, but real GDP losses of other regions are deteriorated; and 3) there exist several sectors of which the real value-added losses decrease in each region.

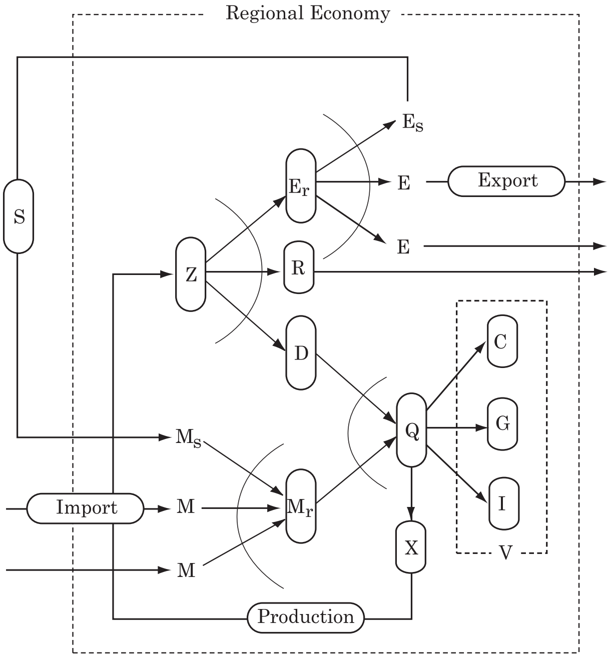

Figure 1: Flow of Goods in A Regional Economy from Washida (2010)

2. Methodology

In this section we extend EMEDA as a static CGE model to a dynamic model.

2.1. An overview of EMEDA

Figure 1, from Washida (2010, pp.6, Figure 4), depicts the flow of goods in a regional economy. S is savings, Z is domestic production, E is total export, E_s is export to each region, R is international transport service, D is domestic demand, M_r is total import, Q is Armington good, C is consumption, G is government expenditure, I is investment, V is value-added, and X is intermediate input. A regional economy is depicted by the outer dashed line.

Domestic production mainly consists of domestic demand and total exports. On top of this, international transport services also have a share of domestic productions. These demands are obtained by non-linear Constant Elasticity of Transformation (CET) functions, which are depicted by the left-side-open curves in Figure 1. Total exports are also divided into exports to other regions by non-linear CET functions (Washida 2010).

Armington goods are obtained from domestic demand and total imports by Constant

Elasticity of Substitution (CES) functions, which are depicted as right-side-open curves in Figure 1. Total imports also contain imports from each region using CES functions (Washida 2010). Finally, consumption, government expenditure, investment and intermediate input are used to measure Armington goods (Washida 2010).

Following Washida (2010), a value-added production function of EMEDA is as:

$$V_{jr} = \pi^V_{jr} \left\{ \alpha^V_{jr} K_{jr}^{\frac{\beta^V_{jr}-1}{\beta^V_{jr}}} + \left(1 - \alpha^V_{jr}\right) L_{jr}^{\frac{\beta^V_{jr}-1}{\beta^V_{jr}}} \right\}^{\frac{\beta^V_{jr}}{\beta^V_{jr}-1}}. \tag{1}$$

Capital demand function is as:

$$K_{jr} = \left\{ \frac{\pi_{jr}^{\frac{\beta^V_{jr}-1}{\beta^V_{jr}}} \alpha^V_{jr} p^V_{jr}}{\left(1 + \tau^F_{jr}\right)\left(1 + \tau^K_{jr}\right) r_r} \right\}^{\beta^V_{jr}} V_{jr}. \tag{2}$$

Labor demand function is as:

$$L_{jr} = \left\{ \frac{\pi_{jr}^{\frac{\beta^V_{jr}-1}{\beta^V_{jr}}} \alpha^V_{jr} p^V_{jr}}{\left(1 + \tau^F_{jr}\right)\left(1 + \tau^L_{jr}\right) w_r} \right\}^{\beta^V_{jr}} V_{jr}, \tag{3}$$

where V_{jr} is value-added, K_{jr} is capital, L_{jr} is labor, p^V_{jr} is value-added price, τ^K_{jr} is capital tax, τ^F_{jr} is production tax, τ^L_{jr} is labor tax, r_r is capital service price, and w_r is nominal wage rate. A sector: $j = 1, \ldots, 8$ and a region: $r = 1, \ldots, 8$ (See Table 1, 2 and 3)[1,2]. A π^V_{jr} is a scale parameter, α^V_{jr} is a partition parameter, and β^V_{jr} is an elasticity of substitution. EMEDA also contains final demand functions, income and savings functions, trade functions, and market equilibriums for export and import goods[3].

2.2. Extension to dynamic EMEDA

In the literature, impacts of global warming are considered as time dimensional objects since accumulation of GHGs emissions leads to a rise in atmospheric temperature. Accordingly, we extend a EMEDA from Washida (2010) to a dynamic CGE model in which

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[1] In our model, the sixteen sectors and sixteen regions used in the Washida (2010) study are aggregated into eight sectors and eight regions for computational convenience.

[2] Sector codes in Table 3 are available on GTAP webpage. https://www.gtap.agecon.purdue.edu/databases/v7/v7_sectors.asp.

[3] See Appendix in this paper, Washida (2010) and Washida et al. (2013) for details.

	Regions		Sectors
1	Japan	1	Agriculture
2	China	2	Forestry
3	USA	3	Fishing
4	EU25_WEurope	4	Extraction
5	FSU_EEurope	5	LightMnfc
6	OAsiaOceania	6	HeavyMnfc
7	OAmerica	7	TransComm
8	Africa	8	OthServices

Table 1: Regions and Sectors for Dynamic EMEDA

Abb.	Name	Country codes (GTAP7)
1	Japan	JPN
2	China	CHN, HKG
3	USA	USA
4	EU25_ WEurope	AUT, BEL, CYP, CZE, DNK, EST, FIN, FRA, DEU, GRC, HUN, IRL, ITA, LVA, LTU, LUX, MLT, NLD, POL, PRT, SVK, SVN, ESP, SWE, GBR, XEF, NOR, CHE
5	FSU_ EEurope	RUS, ALB, BGR, BLR, HRV, ROU, UKR, XEE, XER, KAZ, KGZ, XSU, ARM, AZE, GEO
6	OAsiaOceania	IND, KOR, AUS, NZL, XOC, TWN, XEA, KHM, IDN, LAO, MMR, MYS, PHL, SGP, THA, VNM, XSE, BGD, PAK, LKA, XSA, IRN, TUR, XWS
7	OAmerica	CAN, MEX, XNA, ARG, BOL, BRA, CHL, COL, ECU, PRY, PER, URY, VEN, XSM, CRI, GTM, NIC, PAN, XCA, XCB
8	Africa	NGA, SEN, XWF, XCF, XAC, ETH, MDG, MWI, MUS, MOZ, TZA, UGA, ZMB, ZWE, XEC, BWA, ZAF, XSC, EGY, MAR, TUN, XNF

Table 2: Regions Considered in Dynamic EMEDA

Abb.	Name	Sector codes (GTAP7)
1	Agriculture	PDR, WHT, GRO, PCR, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, CMT, OMT
2	Forestry	FRS
3	Fishing	FSH
4	Extraction	COA, OIL, GAS, OMN
5	LightMnfc	VOL, MIL, SGR, OFD, B_T, TEX, WAP, LEA, LUM, PPP, FMP, MVH, OTN, OMF
6	HeavyMnfc	P_C, CRP, NMM, I_S, NFM, ELE, OME, ELY, GDT, WTR, CNS
7	TransComm	TRD, OTP, WTP, ATP, CMN
8	OthServices	OFI, ISR, OBS, ROS, OSG, DWE

Table 3: Sectors Considered in Dynamic EMEDA

competitive equilibrium is recursively calculated year by year from 2004[4] to 2100 without any loss of the advantages of an EMEDA. Therefore we have improved an EMEDA on five levels. First, we adopt capital accumulation by sector in each region. In each period a present capital stock is the sum of the previous capital stock minus depreciation of the previous capital stock plus a previous gross investment. We set the depreciation rate of each sector to four percent per annum following the GTAP7 database. Second, we introduce population growth into labor supply. Population growth rates are calculated by world projections from United Nations (UN) data. Third, we introduce the Hicks neutral technological progress into the value-added production function. The growth rates of technological progress are calculated by fitting the estimated values of real GDP in a dynamic EMEDA to those of real GDP in the scenario of Shared Socio-economic Pathways (SSP) in which both potential damage of global warming and marginal cost of mitigation are determined by the low (SSP1), which is in turn estimated by the OECD ENV-linkage model (SSP Database, 2012). Figure 2 illustrates changes in real GDP growth rates by region in SSP1.

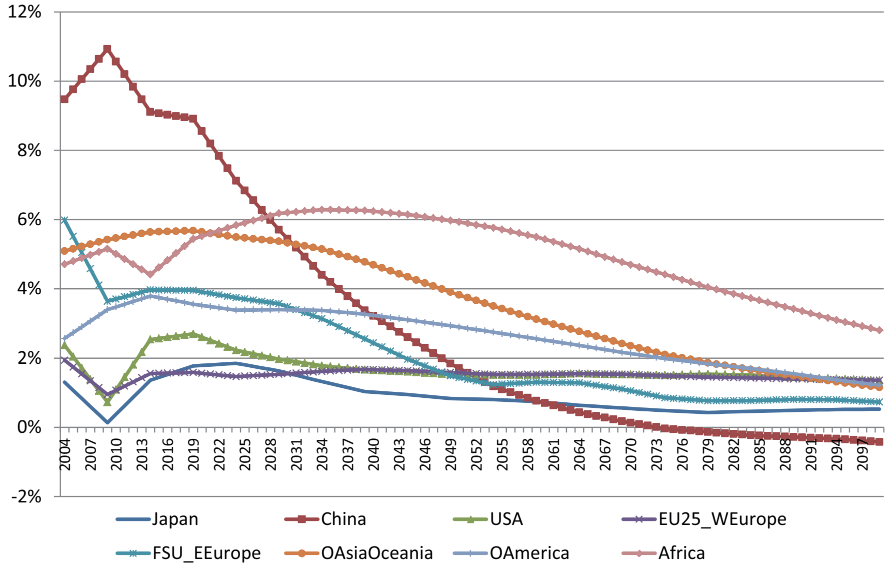

Figure 2: Changes in Real GDP Growth Rates by Region in SSP1

Fourth, we consider CO2 emissions and damages from global warming[5]. CO2 emissions in 2004 are calculated by input energy data in GTAP7 Data Base (Lee, 2008). This

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[4] Data in GTAP7 is available for 2004. Therefore, Washida (2010) set the year 2004 as the base year.

[5] Effects of non-CO2 GHGs are given exogenously according to DICE2010.

	Japan	China	USA	EU25_ WEurope	FSU_ EEurope	Oasia Oceania	OAmerica	Africa
Agriculture	0.070342	0.162142	0.124978	0.088221	0.139385	0.053058	0.092138	0.024317
Forestry	0.065633	0.109027	0.050185	0.053807	0.317288	0.031962	0.080667	0.033935
Fishing	0.423212	0.283442	0.264394	0.209174	0.144837	0.272827	0.102655	0.108659
Extraction	0.139023	0.488464	0.068438	0.077564	0.170186	0.062192	0.264992	0.102994
LightMnfc	0.019292	0.168772	0.058036	0.03145	0.172826	0.104082	0.041993	0.100977
HeavyMnfc	0.174954	1.869972	0.44905	0.233544	2.263606	0.926848	0.386714	1.560264
TransComm	0.058703	0.230866	0.171369	0.097818	0.460827	0.259246	0.307276	0.274136
OthServices	0.010252	0.048448	0.007816	0.005901	0.126179	0.018156	0.012494	0.027607
Households	0.0103362	0.0526218	0.0283849	0.0208521	0.130155	0.0463183	0.036024	0.0520026

Table 4: CO2 Emission Coefficients of Dynamic EMEDA in 2004

Region	On non-SLR		On SLR	
	α_1	α_2	β_1	β_2
Japan	0	0.161723	0.00053	0.000053
China	0.077445	0.126287	0.011646	0.000001
USA	0	0.141413	0	0.000255
EU25_WEurope	0.000568	0.158733	0.004453	0
FSU_EEurope	0	0.121042	0.000043	0.000026
OAsiaOceania	0.220391	0.1624	0.002181	0.000351
OAmerica	0.043514	0.14078	0.001759	0.000051
Africa	0.340974	0.19832	0.003509	0

Table 5: Parameters of SLR and Non-SLR Damage Functions in 2004

data includes CO2 emissions of 8 regions and 9 sectors, which consist of our 8 sectors and households. With this data, the CO2 emission coefficient for each industry, $\sigma_{jr,t}$, is defined as the ratio of CO2 emissions to the value-added of sector j in 2004. Similarly, the CO2 emission coefficient of households, $\sigma^H_{r,t}$, is defined as the ratio of CO2 emissions to total value-added in 2004. Table 4 shows CO2 emission coefficients in 2004. Due to technological progress in abatement, the CO2 emission coefficient has decreased each year. We assume a CO2 emission coefficient has decreased by about 2% annually according to RICE2010. Additionally, the absolute value of the rate of change in CO2 emission coefficient has also decreased per year according to RICE2010. Using these assumptions, CO2 emissions after 2004 are calculated by the CO2 emission coefficients and estimated in terms of real value-added.

Finally, we build a global warming model modified from DICE2010 and RICE2010 (Nordhaus, 2010, 2012). This is essentially a box model consisting of three components: the atmosphere, the ocean surface and the deep ocean. In this model we consider two types of damages from global warming. The first is damage arising from sea level rise (abbreviated as SLR) with the other being that caused by other events (non-SLR events) driven by warming global temperatures. SLR and non-SLR damages are given by

$$\frac{D_{r,t}(T_t, SLR_t)}{1 + D_{r,t}(T_t, SLR_t)} F_{jr,t}(K_{jr,t}, L_{jr,t}) \tag{4}$$

where $F_{jr,t}$ is a value-added production function without damages and $D_{r,t}$ is a SLR and non-SLR damage function modified from RICE2010. According to RICE2010, $D_{r,t}$ is given by

$$D_{r,t}(T_t, SLR_t) = \alpha_{1,r} T_t + \alpha_{2,r} T_t^2 + 2(\beta_{1,r} SLR_t + \beta_{2,r} SLR_t^2)(\frac{\sum_{j=1}^{n} V_{jr,t-1}}{\sum_{j=1}^{n} V_{jr,2004}})^{0.25} \tag{5}$$

where T_t is the rise in atmospheric temperature (°C compared to the year 1900) and SLR_t is the level of SLR caused by higher temperatures (in meters compared to the year 2000). By definition, these damage functions are different for each region. Table 5 shows the parameters of the damage functions. Moreover, in our model each region can reduce CO2 emissions at the expense of value-added production. This relationship is represented by abatement cost functions which are also modified from RICE2010. An abatement cost is expressed by

$$\frac{ACOST_{jr,t}(\mu_{jr,t})}{1 + D_{r,t}(T_t, SLR_t)} F_{jr,t}(K_{jr,t}, L_{jr,t}) \tag{6}$$

where $ACOST$ is an abatement cost function. This is given by

$$ACOST_{jr,t}(\mu_{jr,t}) = c_{jr,t}(\sigma_{jr,t} + \sigma_{r,t}^{H})\mu_{jr,t}^{2.8} \tag{7}$$

where $\mu_{jr,t}$ is the rate at which CO2 emissions decline, and $c_{jr,t}$ is the parameter of abatement cost functions. Table 6 exhibits parameters by sector for each region's abatement cost function in 2004. We assume that these parameters decrease as time passes[6]. Additionally, other parameters in our global warming model are calculated according to DICE2010.

Following Washida (2010), we use the GTAP7 Data Base for simulating the extended EMEDA, naming this extended version with global warming *a dynamic EMEDA*.

2.3. CO2 emission reduction scenario

In this subsection, we define a series of scenarios regarding various reduction rates for world CO2 emissions. In the base scenario, each region gradually increases the rate of

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[6] This reflects technical progress in backstop technology since $c_{jr,t}$ represents backstop price.

	Japan	China	USA	EU25_WEurope	FSU_EEurope	OAsiaOceania	OAmerica	Africa
Agriculture	0.0511	0.0685	0.0624	0.0685	0.0731	0.0488	0.0720	0.0379
Forestry	0.0481	0.0515	0.0320	0.0469	0.1214	0.0385	0.0656	0.0427
Fishing	0.2744	0.1071	0.1191	0.1444	0.0746	0.1569	0.0779	0.0799
Extraction	0.0945	0.1725	0.0394	0.0618	0.0815	0.0533	0.1691	0.0771
LightMnfc	0.0188	0.0706	0.0352	0.0328	0.0822	0.0739	0.0438	0.0761
HeavyMnfc	0.1173	0.6128	0.1942	0.1597	0.6492	0.4783	0.2375	0.8017
TransComm	0.0437	0.0904	0.0813	0.0745	0.1603	0.1502	0.1929	0.1622
OthServices	0.0130	0.0322	0.0147	0.0168	0.0695	0.0317	0.0273	0.0396

Table 6: Parameters of Abatement Cost Functions in 2004

Region	2020	2050	2051-2100
Japan	-25% below '90	-80% below '90	-2% p.a.
China	-40% below '05[a]	-50% below '90	-2% p.a.
USA	-4% below '90	-50% below '90	-2% p.a.
EU25_WEurope	-20% below '90	-50% below '90	-2% p.a.
FSU_EEurope	-20% below '90	-50% below '90	-2% p.a.
Oasia Oceania	-40% below '05	-50% below '90	-2% p.a.
OAmerica	-40% below '05	-50% below '90	-2% p.a.
Africa	-40% below '05	-50% below '90	-2% p.a.

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[a] Comparison by CO2 emissions intensity.

Table 7: CO2 Emissions Reduction in the Base Scenario

CO2 emissions reductions according to Table 7. In Table 7, the 2020 CO2 emission reduction targets for the five major regions of Japan, China, the U.S., the European Union (EU) and Former Soviet Union (FSU) are derived from those officially announced at COP15 (den Elzen et al., 2010). For the other three regions of other Asia and Oceania (OAsiaOceania), other American countries (OAmerica) and Africa, we have adopted 40% below 2005 levels for simplification purposes. For long-term CO2 emissions reduction targets for 2050, we have followed targets set out by the International Energy Agency (IEA) and the Group of Eight (G8), which predict reduction rates for CO2 emissions in 2050 as 50% below 1990 levels (IEA, 2009; G8 Summit, 2007).

That said however, we have adopted an 80% target for Japan since this country officially pledged such reductions by the year 2050 (METI, 2010). Finally, we assume that each region reduces its CO2 emissions after 2050 by 2% per annum.

Figure 3 represents changes in atmospheric temperature in both the base scenario and that where no region reduces its CO2 emissions. In the dynamic EMEDA, the temperature

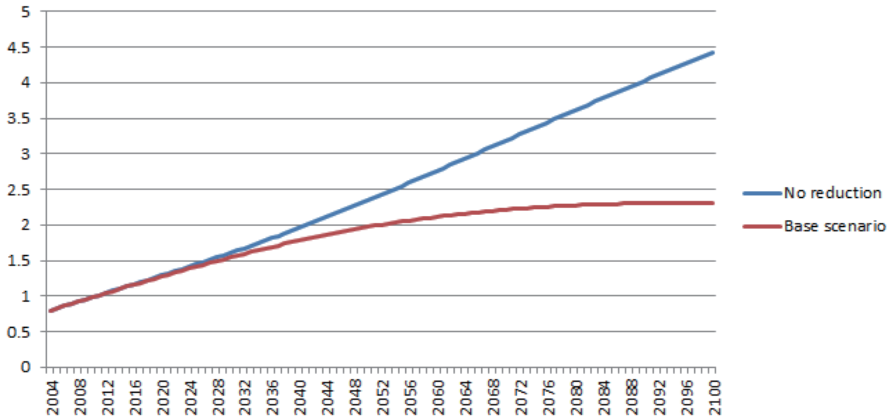

Figure 3: Changes in Temperature (°C above 1900) in the Base Scenario

increase in 2100 is about 2.31°C above 1900 in the base scenario and about 4.43°C above 1900 in the case of no reduction. Therefore, attaining the base scenario is sufficiently effective for limiting global warming as per the current goal of 2 degrees relative to pre-industrial temperatures.

3. Results

Simulated EMEDA results are affected not only by direct impacts, but also by indirect effects. This is because CGE models incorporate interrelationships among regions. Therefore, we can consider these indirect effects when EMEDA focuses on damage impacts from global warming. This research simulates a dynamic EMEDA to emphasize effect of CO2 emissions reduction for eight regions. From hereon, we will therefore discuss simulated dynamic EMEDA results by region for both real GDP and real value-added by sector. For this EMEDA simulation we use the General Algebraic Modeling System (GAMS) version 23.2[7].

In this subsection, firstly, we focus on each region's real GDP for the two periods of 2050 and 2100. Secondly, we calculate rate of change in real value-added by sector for these periods. Finally, we measure effects of CO2 reduction on the world economy from 2004 to 2100 when CO2 emissions of each regions are reduced according to the base scenario or not.

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[7] http://www.gams.com/

	2050			2100		
Region	None	Base scenario		None	Base scenario	
Japan	7,771	7,713	-0.7%	9,623	10,068	4.6%
China	30,613	28,855	-5.7%	32,569	32,440	-0.4%
USA	26,865	26,773	-0.3%	53,367	56,424	5.7%
EU25_WEurope	23,307	23,324	0.1%	43,368	46,118	6.3%
FSU_EEurope	3,776	3,674	-2.7%	5,914	5,781	-2.2%
OAsiaOceania	42,964	38,315	-10.8%	115,106	106,806	-7.2%
OAmerica	12,862	12,564	-2.3%	32,522	33,230	2.2%
Africa	9,765	8,931	-8.5%	82,172	77,227	-6.0%

Table 8: Real GDP (in Billions of US$ 2004 Equivalent) of All Regions in 2050 and 2100

	2050		2100	
Region	None	Base scenario	None	Base scenario
Japan	-222	-205	400	-185
China	1,037	467	-6,463	-6,067
USA	-2,863	-2,779	938	-2,457
EU25_WEurope	-1,511	-1,603	4,627	87
FSU_EEurope	45	53	-120	-110
OAsiaOceania	4,599	5,122	11,644	11,073
OAmerica	288	64	2,625	1,151
Africa	448	515	-1,645	5,118

Table 9: Real Trade Balance (in Billions of US$ 2004 Equivalent) of All Regions in 2050 and 2100

3.1. GDP

Table 8 displays change in real GDP (in billions of US$ 2004 equivalent) for all regions in the base scenario in the years 2050 and 2100[8]. The best scenarios for each player are those where there is the base scenario for Japan, the U.S. and EU, and no reduction (None) in CO2 emissions for other regions. Focusing on real GDP in 2050, seven of eight regions prefer no reduction in CO2 emissions relative to the base scenario since high reduction rates require higher abatement costs than in a no reductions scenario. Especially in regard to the rate of change in real GDP, China bears more abatement costs (i.e., higher CO2 emissions reduction rates) than the U.S. because of differences in economic growth rates, as can be seen in Figure 2.

Focusing on real GDP in 2100, here it can be seen that the base scenario constitutes the best outcome for Japan, the U.S., EU and other America whereas for other regions it is no reduction in CO2 emissions. This is due to differences in the effects of CO2 emission reductions. Comparing the cases of no reduction and the base scenario, real GDP for Japan and the U.S. increases as CO2 emissions are reduced, while China's real GDP decreases. This is for the reason that abatement costs required to meet the base scenario are higher in China than in developed countries[9] such as Japan and the U.S. This discrepancy in abatement costs between developed countries and other countries such as China can be explained by the result of dynamic EMEDA which shows that the rate of economic growth in developed countries is lower than in other countries, as shown in Figure 2.

Table 9 shows the real trade balance (in billions of US$ 2004 equivalent) for the years 2050 and 2100. As CO2 emissions are reduced in relation to the base scenario, the real trade balance of Japan and the U.S. in 2100 increases despite a decrease in real GDP for both countries. The reason for this is that industry in Japan and the U.S. bears relatively lower abatement costs than China. As a result, this change in real trade balance may negatively affect China's economy. In addition to this, real trade balance in some developed countries decreases as CO2 emission decline, even though real GDP increases. The reason for this is that the increase in domestic demand in developed countries resulting from global warming mitigation exceeds the decrease in real trade balance, which is derived from decrements of real exports and increments of real imports in developed countries.

These results suggest that a reduction in CO2 emissions is more beneficial to developed countries than for other countries. This implies that international cooperation for climate

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[8] Real GDP is defined by sum of real value-added.

[9] For details, real GDP of the U.S., Japan, EU and OAmerica increases as CO2 emissions are reduced.

change mitigation requires higher abatement costs in developed countries in order to ensure fairness between developed and other countries.

3.2. Value-added by sector

We determine in detail how each region may improve real value-added when reducing CO2 emissions. To obtain rates of change for real value-added by sector in the dynamic EMEDA the no reductions scenario is compared with others.

Table 10 shows the rate of changes in real value-added for the base scenario in the year 2050. Firstly, for the majority of sectors with the exception of heavy manufacturing (HeavyMnfc) of the U.S. and EU, in each region the real-value added for the no reductions scenario is higher than that for the base scenario. This shows that excessive CO2 emissions abatement leads to a deterioration of the overall economy. Secondly, in light manufacturing (LightMnfc) real value-added always decreases as a result of a reduction in CO2 emissions. It could therefore be argued that additional policies such as emissions trading may be required in order to improve the economies of all sectors.

Next, we compare the rate of change in the value-added for several sectors and regions in 2100. Table 11 displays the rate of change in the value-added for all scenarios in 2100. First of all, for agriculture, real value-added for both the U.S. and EU rapidly decreases in the base scenario, while both Japan and China see an increase since the diminution of their imports of agricultural goods exceeds that of their exports. Second, for the industry of heavy manufacturing, real value-added for both China and the U.S. increases while Japan sees a decrease in the base scenario since Japanese domestic goods in the heavy manufacturing sector are substituted by an increase in imports from other countries, such as China. Third, for the services category such as transport and communication (TransComm) and other services (OthServices) real value-added for developed countries such as Japan, U.S. and EU experience an increase as the domestic demand for services expands. Finally, value-added for the extraction industry diminishes in most regions except Africa. This most probably reflects the large share represented by the extraction sector in the overall African economy, which will be, accelerated by rapid economic growth on SSP1, as shown in Figure 2. These results suggest that global warming mitigation may dramatically alter the global economic structure.

By comparison of Table 10 and 11, we find that a) for most of all sectors the rate of change in 2100 is higher than that in 2050 since damage from global warming is more severe in 2100 than in 2050 by temperature rise, as shown in Figure 3, b) the losses of the U.S. and EU's value-added of heavy manufacturing are improved in the base scenario in the years 2050 and 2100; and c) there exists a region whose losses of value-added are

	Agri.	Forestry	Fishing	Extraction	LightMnfc	HeavyMnfc	TransComm	OthServices
Japan	-2.5%	-3.4%	-6.6%	-0.9%	-2.6%	-0.2%	-0.9%	-0.9%
China	-3.2%	-4.9%	-4.9%	-17.6%	-5.3%	-6.5%	-5.7%	-4.6%
USA	-6.0%	-2.8%	-1.4%	17.7%	-1.2%	0.3%	-0.6%	-0.6%
EU25_WEurope	-2.2%	-2.1%	-0.7%	14.1%	-1.3%	1.1%	-0.3%	-0.1%
FSU_EEurope	-2.9%	-16.0%	-2.4%	-0.2%	-3.3%	-3.3%	-3.1%	-2.7%
OAsiaOceania	-11.1%	-9.8%	-16.0%	-3.6%	-10.9%	-11.6%	-12.2%	-12.0%
OAmerica	-6.5%	-3.0%	-2.6%	-13.5%	-2.4%	-2.7%	-1.8%	-0.6%
Africa	-6.2%	-7.6%	-9.7%	-7.3%	-8.3%	-12.2%	-9.4%	-8.8%

Table 10: Rate of Change of Real Value-Added by Sector in the Base Scenario in 2050

	Agri.	Forestry	Fishing	Extraction	LightMnfc	HeavyMnfc	TransComm	OthServices
Japan	7.0%	-2.7%	-6.4%	-47.3%	-5.8%	-1.3%	6.3%	7.8%
China	3.2%	-1.3%	-0.2%	-39.7%	-2.0%	0.9%	-1.3%	-2.2%
USA	-32.6%	-15.8%	-1.6%	-25.5%	0.1%	3.3%	5.7%	8.4%
EU25_WEurope	-11.4%	-8.8%	2.9%	-54.8%	-1.5%	0.3%	4.9%	12.0%
FSU_EEurope	1.8%	-9.2%	0.1%	-6.2%	0.1%	-2.1%	-2.4%	-2.1%
OAsiaOceania	-0.7%	0.5%	-5.1%	-12.7%	-6.2%	-7.5%	-8.0%	-7.4%
OAmerica	-9.6%	1.9%	3.1%	-27.0%	2.3%	2.9%	4.4%	6.3%
Africa	1.4%	-3.0%	-8.0%	5.2%	-7.4%	-9.6%	-10.4%	-12.7%

Table 11: Rate of Change of Real Value-Added by Sector in the Base Scenario in 2100

deteriorated in every sector.

3.3. GDP and value-added losses

Finally, we measure effects of CO2 reduction on the world economy from 2004 to 2100 in the base scenario.

Figure 4 shows the ratio of NPV of real GDP loss of each region with respect to the benchmark when a discount rate of real GDP loss is 3 percent per annum. For China, Former Soviet Union, other Asia and Oceania, other American countries and Africa, CO2 reduction of these regions leads to an increase in their real GDP loss ratio. Especially, real GDP loss ratio of other Asia and Oceania and Africa deteriorates rapidly. On the other hand, each of Japan, the U.S. and EU may improve its real GDP loss ratio by CO2 reduction. Moreover, we can find that all players improve real GDP loss ratio by participation in the CO2 abatement games.

Figure 5 presents NPV of real value-added loss of each region by sector. This shows that there exist several sectors of which the real value-added losses decrease in each region. For details, we can find that the real value-added losses of extraction and heavy manufacturing of all players are improved by participation in the CO2 abatement games. For services, the real value-added of other services of Japan and the U.S. are also improved.

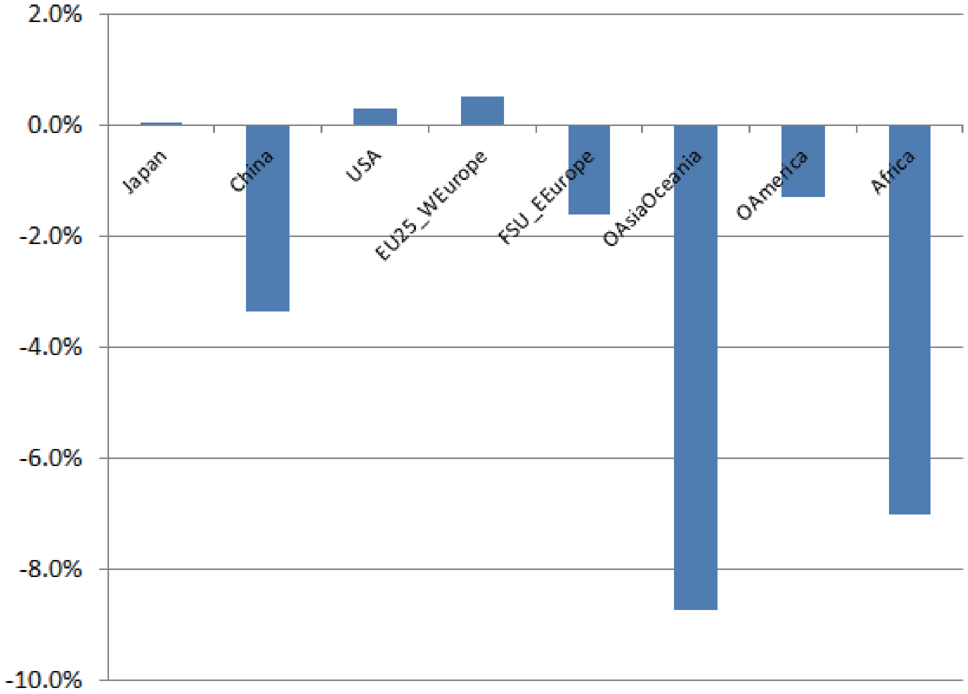

Figure 4: The Ratio of NPV of Real Value-added Loss of Each Region by Sector

Moreover, the real value-added losses of several sectors of Japan, China, the U.S., EU and other American countries are improved by CO2 reduction though those of all sectors of the other three regions are deteriorated.

4. Concluding Remarks

Simulated results from a dynamic EMEDA indicate that: 1) simulated economic damage derived from CO2 emissions reduction rates attained by official announcements varies among regions and sectors, 2) the real GDP losses of Japan, the U.S. and EU are improved by CO2 emissions reduction, but real GDP losses of other regions are deteriorated; and 3) there exist several sectors of which the real value-added losses decrease in each region.

These results suggest that it will be difficult to attain adequate CO2 abatement without suitable environmental policies. It should therefore be noted that when considering abatement costs, a reduction in CO2 emissions is not necessarily beneficial to all countries involved. Especially in the case of developing countries, real GDP tends to decrease as CO2 emissions decline. This is principally because abatement costs are higher in these

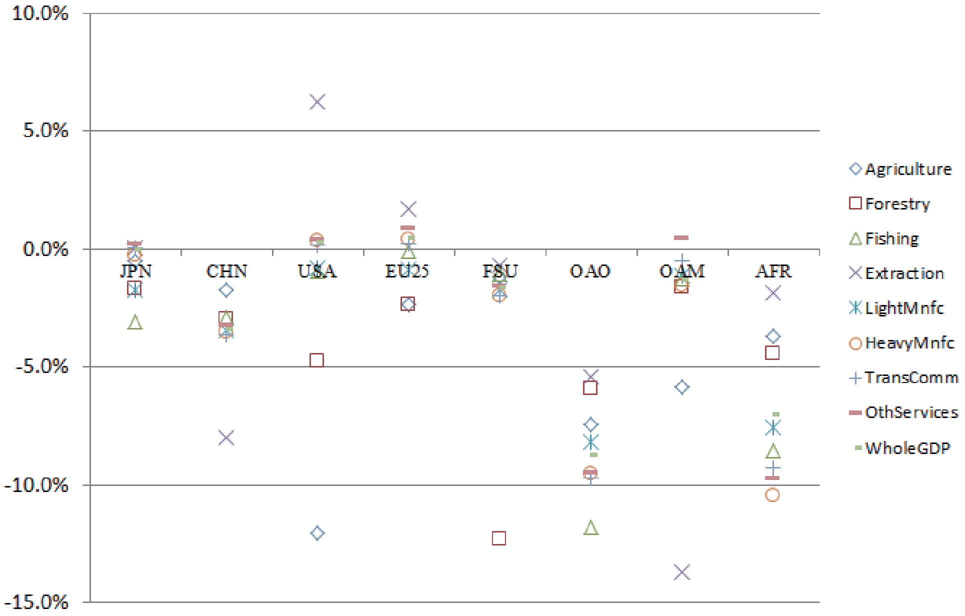

Figure 5: The Ratio of NPV of Real Value-added Loss of Each Region by Sector

countries in the base scenario and because the economies in developing countries are set to grow rapidly as shown in Figure 2. It is therefore essential that this unfairness be corrected in order to secure the participation and cooperation of developing countries in the goal of reducing global CO2 emissions.

Appendix A. Equations in dynamic EMEDA

Washida (2010) investigated EMEDA simulation. Washida (2010), however, is a mimeo and written in Japanese. Therefore, we introduce all EMEDA equations in the Appendix. For details and calibration in EMEDA, see Washida (2010). All equations in EMEDA, where a good i, a sector j, and regions r and s, $r \neq s$. EN is a set of energy commodities, J is a set of sectors, R is a set of regions and $\mu_{jr,t}$ is a CO2 reduction rate.

A1. Equations on global warming

Value-added production function without damages (in millions of US$ 2004 equivalent) is;

$$F_{jr,t}(K_{jr,t}, L_{jr,t}) = \pi^V_{jr,t} \left\{ \alpha^V_{jr} K_{jr,t}^{\frac{\beta^V_{jr}-1}{\beta^V_{jr}}} + (1-\alpha^V_{jr}) L_{jr,t}^{\frac{\beta^V_{jr}-1}{\beta^V_{jr}}} \right\}^{\frac{\beta^V_{jr}}{\beta^V_{jr}-1}}. \tag{A-1}$$

Value-added production function with damages and abatement costs is;

$$V_{jr,t} = \frac{1 - ACOST(\mu_{jr,t})}{1 + D_{r,t}(T_t, SLR_t)} F_{jr,t}(K_{jr,t}, L_{jr,t}). \tag{A-2}$$

Damage function is as;

$$D_{r,t}(T_t, SLR_t) = \alpha_{1,r} T_t + \alpha_{2,r} T_t^2 + 2(\beta_{1,r} SLR_t + \beta_{2,r} SLR_t^2)\left(\frac{\sum_{j=1}^n V_{jr,t-1}}{\sum_{j=1}^n V_{jr,2004}}\right)^{0.25}. \tag{A-3}$$

Abatement cost function is as;

$$ACOST_{jr,t}(\mu_{jr,t}) = c_{jr,t}(\sigma_{jr,t} + \sigma^H_{r,t})\mu^{2.8}_{jr,t}. \tag{A-4}$$

An equation for change in parameters for abatement cost functions is;

$$c_{jr,t+1} = 0.1c_{jr,2004} + (c_{jr,t} - 0.1c_{jr,2004})(1 - 0.005). \tag{A-5}$$

CO2 emissions (KtC) equation is;

$$\tilde{q}_{jr,t} = (1 - \mu_{jr,t})(\sigma_{jr,t} + \sigma^H_{r,t}) F_{jr,t}(K_{jr,t}, L_{jr,t}), \quad \mu_{jr,2004} = 0. \tag{A-6}$$

CO2 emission coefficient of each industry in 2004 is;

$$\sigma_{jr,2004} = \frac{\sum_{i \in EN} CO2_{ijr,2004}}{V_{jr,2004}} \frac{12}{44}. \tag{A-7}$$

CO2 emission coefficient of households in 2004 is;

$$\sigma^H_{r,2004} = \frac{\sum_{i \in EN} CO2_{iHr,2004}}{\sum_{j=1}^n V_{jr,2004}} \frac{12}{44}, \quad H = households. \tag{A-8}$$

An equation for reduction of CO2 emissions coefficient for each industry taking into account technological progress is as;

$$\sigma_{jr,t+1} = (1 - \delta^G_{r,t})\sigma_{jr,t}. \tag{A-9}$$

An equation for reduction of CO2 emissions coefficient for households taking into account technological progress is as;

$$\sigma^H_{r,t+1} = (1 - \delta^G_{r,t})\sigma^H_{r,t}. \tag{A-10}$$

An equation for change in reduction rate of CO2 emission coefficient is;

$$\delta^G_{r,t+1} = -0.0025 + (\delta^G_{r,t} + 0.0025)(1 - 0.1)^{0.1}. \tag{A-11}$$

An equation for atmosphetic concentration of CO2 (GtC) is;

$$M_t = (1 - (100 - 88)/10)M_{t-1} + 4.704M^U_{t-1} + \tilde{q}_{t-1}/1000000. \tag{A-12}$$

An equation for concentration of CO2 in shallow oceans (GtC) is;

$$M^U_t = (100 - 88)/10M_{t-1} + 0.94796M^U_{t-1} + 0.00075M^L_{t-1}. \tag{A-13}$$

An equation for concentration of CO2 in deep oceans (GtC) is;

$$M^L_t = 0.005M^U_{t-1} + 0.99925M^L_{t-1}. \tag{A-14}$$

Exogenous forcing (W/m^2) equation is;

$$O_t = \max\{0.3, O_{t-1} + 0.01(0.3 - 0.83)\}. \tag{A-15}$$

Radiative forcing (W/m^2) equation is;

$$F_t = 3.8\{\log(M_t/596.4)/\log 2\} + O_t. \tag{A-16}$$

An equation for temperature of atmoshere (°C above 1900) is;

$$T_t = T_{t-1} + 0.0208\{F_t - (3.8/3.2)T_{t-1} - 0.031(T_{t-1} - T^L_{t-1})\}. \tag{A-17}$$

An equation for temperature of deep oceans (°C above 1900) is;

$$T^L_t = T^L_{t-1} + 0.005(T_{t-1} - T^L_{t-1}). \tag{A-18}$$

Thermal expansion (m above 2000) equation is;

$$TE_t = TE_{t-1} + 0.00779322611181183T_t. \tag{A-19}$$

Glaciers and Small Ice Caps (m above 2000) equation is;

$$GSIC_t = GSIC_{t-1} + 0.0017607798289604(0.26 - GSIC_{t-1})T_t. \tag{A-20}$$

Greenland Ice Sheet (m above 2000) equation is;

$$GIS_t = GIS_{t-1} + 0.0017607798289604(7.3 - GIS_{t-1})T_t. \tag{A-21}$$

Antarctic Ice Sheet (m above 2000) equation is;

$$AIS_t = 0.0000993664138598933(56.6 - AIS_{t-1})T_t \; if \; T_t > 3, \; (AIS_t = 0 \; otherwise). \tag{A-22}$$

Sea Level Rise (m above 2000) is;

$$SLR_t = TE_t + GSIC_t + GIS_t + AIS_t. \tag{A-23}$$

A2. Equations on production

Components of production are capital and labor that capital includes land and natural resources for GTAP data. Capital, labor and value-added production are shown as constant elasticity substitution (CES) functions on equation (A-2). Government imposes tax with a firm investing capital and inputting labor. Therefore, intermediate inputs, $X_{ijr,t}$, and value-added, $V_{jr,t}$, are determined by fixed coefficient Leontief production function as;

$$Z_{jr,t} = \min\left(\frac{V_{jr,t}}{a_{0jr}}, \frac{X_{1jr,t}}{a_{1jr}}, \cdots, \frac{X_{njr,t}}{a_{njr}}\right) \qquad j = 1, 2, \cdots, n \tag{A-24}$$

where $Z_{jr,t}$ is domestic production. Following the economic theory, it will not settle production when a firm maximizes her profits because of a linear homogeneous function. Thus, we suppose an input demand is decided by cost minimization for production, $Z_{jr,t}$. We also assume that there is no excess profit in production. Therefore, intermediate inputs and value-added are determined by equations (A-32) and (A-33). Input-output coefficients, $(L_{jr,t}/V_{jr,t}, K_{jr,t}/V_{jr,t})$, are determined by minimizing cost of value-added production. Therefore, cost of value-added production is as;

$$p^V_{jr,t} V_{jr,t} = (1 + \tau^F_{jr}) \left\{ (1 + \tau^L_{jr}) w_{r,t} L_{jr,t} + (1 + \tau^K_{jr}) r_{r,t} K_{jr,t} \right\} \tag{A-25}$$

where $p^V_{jr,t}$ is price of value-added, τ^F_{jr} is production tax, τ^L_{jr} is labor tax, $w_{r,t}$ is nominal wage rate, τ^K_{jr} is capital tax, and $r_{r,t}$ is capital service price. Solving cost minimization problem on equation (A-25), we obtain two equations for calculating demand functions of capital (A-29) and labor (A-30) as;

$$\frac{K_{jr,t}}{V_{jr,t}} = \frac{(\alpha^V_{jr})^{\beta^V_{jr}} \{(1 + \tau^K_{jr}) r_{r,t}\}^{-\beta^V_{jr}}}{\pi^V_{jr} H_{jr,t}^{\frac{\beta^V_{jr}}{\beta^V_{jr}-1}}}, \tag{A-26}$$

$$\frac{L_{jr,t}}{V_{jr,t}} = \frac{(1-\alpha_{jr}^{V})^{\beta_{jr}^{V}}\{(1+\tau_{jr}^{L})w_{r,t}\}^{-\beta_{jr}^{V}}}{\pi_{jr}^{V} H_{jr,t}^{\frac{\beta_{jr}^{V}}{\beta_{jr}^{V}-1}}} \tag{A-27}$$

where $H_{jr,t} = (1-\alpha_{jr}^{V})^{\beta_{jr}^{V}}\{(1+\tau_{jr}^{L})w_{r,t}\}^{1-\beta_{jr}^{V}} + (\alpha_{jr}^{V})^{\beta_{jr}^{V}}\{(1+\tau_{jr}^{K})r_{r,t}\}^{1-\beta_{jr}^{V}}$. Substituting equations (A-26) and (A-27) into equation (A-25), we obtain;

$$\frac{1}{H_{jr,t}^{\frac{\beta_{jr}^{V}}{\beta_{jr}^{V}-1}}} = \left(\frac{\pi_{jr}^{V} p_{jr,t}^{V}}{1+\tau_{jr}^{F}}\right)^{\beta_{jr}^{V}}. \tag{A-28}$$

Substituting equation (A-28) into equations (A-26) and (A-27), we obtain capital and labor demand functions, respectively. Capital demand function is;

$$K_{jr,t} = \left\{\frac{(\pi_{jr,t}^{V})^{\frac{\beta_{jr}^{V}-1}{\beta_{jr}^{V}}} \alpha_{jr}^{V} p_{jr,t}^{V}}{(1+\tau_{jr}^{F})(1+\tau_{jr}^{K})r_{r,t}}\right\}^{\beta_{jr}^{V}} V_{jr,t}. \tag{A-29}$$

Labor demand function is;

$$L_{jr,t} = \left\{\frac{(\pi_{jr,t}^{V})^{\frac{\beta_{jr}^{V}-1}{\beta_{jr}^{V}}} (1-\alpha_{jr}^{V}) p_{jr,t}^{V}}{(1+\tau_{jr}^{F})(1+\tau_{jr}^{L})w_{r,t}}\right\}^{\beta_{jr}^{V}} V_{jr,t} \tag{A-30}$$

where $g_{tfp,t}$ is a TFP growth rate and

$$\pi_{jr,t+1}^{V} = (1+g_{tfp,t})\pi_{jr,t}^{V}.$$

Unit price function is;

$$p_{jr,t}^{Z} = p_{jr,t}^{V} a_{0jr} + \sum_{i} p_{ir,t}^{Q} a_{ijr}. \tag{A-31}$$

Input coefficients are;

$$X_{ijr,t} = a_{ijr} Z_{jr,t}, \tag{A-32}$$

$$V_{jr,t} = a_{0jr} Z_{jr,t}. \tag{A-33}$$

A3. Equations on final demand

Utility function of composite goods, u_r, which EMEDA equations do not include but demand functions directly hold, is as;

$$u_{r,t} = \left\{ \phi_r^C C_{r,t}^{\frac{\zeta_r - 1}{\zeta_r}} + \phi_r^S S_{r,t}^{\frac{\zeta_r - 1}{\zeta_r}} + \phi_r^G G_{r,t}^{\frac{\zeta_r - 1}{\zeta_r}} \right\}^{\frac{\zeta_r}{\zeta_r - 1}}, \tag{A-34}$$

$$\phi_r^C + \phi_r^S + \phi_r^G = 1, \tag{A-35}$$

$$Y_{r,t} = p_{r,t}^C C_{r,t} + p_{r,t}^S S_{r,t} + p_{r,t}^G G_{r,t}. \tag{A-36}$$

Expenditure functions for consumption, savings (equivalent to investment) and government expenditure are;

$$C_{r,t} = \frac{(\phi_r^C)^{\zeta_r} Y_{r,t}}{(p_{r,t}^C)^{\zeta_r} \sum_{h=C,S,G} (\phi_r^h)^{\zeta_r} (p_{r,t}^h)^{1-\zeta_r}}, \tag{A-37}$$

$$S_{r,t} = \frac{(\phi_r^S)^{\zeta_r} Y_{r,t}}{(p_{r,t}^S)^{\zeta_r} \sum_{h=C,S,G} (\phi_r^h)^{\zeta_r} (p_{r,t}^h)^{1-\zeta_r}}, \tag{A-38}$$

$$G_{r,t} = \frac{(\phi_r^G)^{\zeta_r} Y_{r,t}}{(p_{r,t}^G)^{\zeta_r} \sum_{h=C,S,G} (\phi_r^h)^{\zeta_r} (p_{r,t}^h)^{1-\zeta_r}}. \tag{A-39}$$

Utility function for individual consumption is;

$$C_{r,t} = \left(\sum_{i=1}^{n} \psi_{ir}^C C_{ir,t}^{\frac{\zeta_r^C - 1}{\zeta_r^C}} \right)^{\frac{\zeta_r^C}{\zeta_r^C - 1}}. \tag{A-40}$$

Budget constraint on individual consumption is;

$$p_{r,t}^C C_{r,t} = \sum_{i=1}^{n} p_{ir,t}^Q C_{ir,t}. \tag{A-41}$$

Individual consumption demand is;

$$C_{jr,t} = \frac{(\psi_{jr}^C)^{\zeta_r^C} p_{r,t}^C C_{r,t}}{(p_{jr,t}^Q)^{\zeta_r^C} \sum_{i=1}^{n} (\psi_{ir}^C)^{\zeta_r^C} (p_{ir,t}^Q)^{1-\zeta_{r,t}^C}}. \tag{A-42}$$

Consumption price function for composite goods is;

$$p_{r,t}^C = \left\{ \sum_{i=1}^{n} (\psi_{ir}^C)^{\zeta_r^C} (p_{ir,t}^Q)^{1-\zeta_r^C} \right\}^{\frac{1}{1-\zeta_r^C}}. \tag{A-43}$$

Price function for government expenditure is;

$$p_{r,t}^{G} = \sum_{i=1}^{n} p_{ir,t}^{Q} g_{ir} \quad where \sum_{i=1}^{n} g_{ir} = 1. \tag{A-44}$$

Price function for savings (s_i: component ratio of savings = component ratio of investment. Define savings as the numeraire. Then, we set $p_{r,t}^{S} = 1$ for holding Walras' law.) is;

$$p_{r,t}^{S} = \sum_{i=1}^{n} p_{ir,t}^{Q} s_{ir} \quad where \sum_{i=1}^{n} s_{ir,t} = 1. \tag{A-45}$$

A4. Equations on income and savings

Private revenue is;

$$Y_{r,t}^{P} = w_{r,t}\overline{L}_{r,t} + r_{r,t}\overline{K}_{r,t}. \tag{A-46}$$

Private savings is;

$$S_{r,t}^{P} = Y_{r,t}^{P} - p_{r,t}^{C} C_{r,t}. \tag{A-47}$$

Government revenue (we treat as export tax revenue, or do not include this in EMEDA) is;

$$\begin{aligned} Y_{r,t}^{G} &= \sum_{j=1}^{n} [\tau_{jr}^{F} \left\{ (1+\tau_{jr}^{L}) w_{r,t} L_{jr,t} + (1+\tau_{jr}^{K}) r_{r,t} K_{jr,t} \right\} \\ &\quad + \tau_{jr}^{L} w_{r,t} L_{jr} + \tau_{jr}^{K} r_{r,t} K_{jr,t}] + \sum_{i} T_{ir,t}^{M}. \end{aligned} \tag{A-48}$$

Government expenditure is;

$$G_{ir,t} = g_{ir} G_{r,t}, \qquad g_{ir} = \frac{G_{ir,2004}}{\sum_{i=1}^{n} G_{ir,2004}}. \tag{A-49}$$

Government savings is;

$$S_{r,t}^{G} = Y_{r,t}^{G} - p_{r,t}^{G} G_{r,t}. \tag{A-50}$$

Gross revenue is;

$$Y_{r,t} = Y_{r,t}^{P} + Y_{r,t}^{G} + S_{r,t}^{F}. \tag{A-51}$$

Savings and investment (S: gross savings, I: gross investment, S^F : trade balance, I_i: investment of good i) are;

$$I_{ir,t} = s_{ir} S_{r,t}, \qquad s_{ir} = \frac{I_{ir,2004}}{\sum_{i=1}^{n} I_{ir,2004}}. \tag{A-52}$$

Following equations, we hold (but not in EMEDA);

$$p^S_{r,t} S_{r,t} = S^P_{r,t} + S^G_{r,t} + S^F_{r,t}. \tag{A-53}$$

A5. Equations on international trade

Trade balance in region r and period t, $S^F_{r,t}$ is;

$$\sum_i p^{HE}_{ir,t} E_{ir,t} + \sum_i p^R_{ir,t} R_{ir,t} + S^F_{r,t} = \sum_i \sum_s p^{IW}_{isr,t} M_{isr,t}. \tag{A-54}$$

where $E_{ir,t}$ is export, and $M_{ir,t}$ is import. $M_{ir,t}$ excludes tariff since government revenue, $Y^G_{r,t}$, includes tariff. Equations on aggregated export ($D_{i,t}$: domestic demand of domestically produced goods, $p^D_{i,t}$: domestic demand price of domestically produced goods, R: international transportation service which consists of a sector of transportation service, T) are;

$$Z_{ir,t} = \theta_{ir} \left(\eta^E_{ir} E_{ir,t}^{\frac{\lambda_{ir}+1}{\lambda_{ir}}} + \eta^D_{ir} D_{ir,t}^{\frac{\lambda_{ir}+1}{\lambda_{ir}}} + \eta^R_{ir} R_{ir,t}^{\frac{\lambda_{ir}+1}{\lambda_{ir}}} \right)^{\frac{\lambda_{ir}}{\lambda_{ir}+1}}, \tag{A-55}$$

$$\eta^E_{ir} + \eta^D_{ir} + \eta^R_{ir} = 1 \qquad (\eta^R_{ir} = 0, i \neq T),$$

$$E_{ir,t} = \left(\frac{\eta^E_{ir} \theta_{ir}^{\frac{1+\lambda_{ir}}{\lambda_{ir}}} p^Z_{ir,t}}{p^{HE}_{ir,t}} \right)^{-\lambda_{ir}} Z_{ir,t}, \tag{A-56}$$

$$D_{ir,t} = \left(\frac{\eta^D_{ir} \theta_{ir}^{\frac{1+\lambda_{ir}}{\lambda_{ir}}} p^Z_{ir,t}}{p^D_{ir,t}} \right)^{-\lambda_{ir}} Z_{ir,t}, \tag{A-57}$$

$$R_{ir,t} = \left(\frac{\eta^R_{ir} \theta_{ir}^{\frac{1+\lambda_{ir}}{\lambda_{ir}}} p^Z_{ir,t}}{p^R_{ir,t}} \right)^{-\lambda_{ir}} Z_{ir,t} \qquad\qquad i = T. \tag{A-58}$$

Implicit budget constraint is;

$$p^Z_{ir,t} Z_{ir,t} = p^{HE}_{ir} E_{ir,t} + p^D_{ir,t} D_{ir,t} + p^R_{ir,t} R_{ir,t}, \qquad p^R_{ir,t} = 0, i \neq T.$$

Export to each foreign region (Eirs is an export of a good i from a region r to a region s) are;

$$p_{ir,t}^{HE}E_{ir,t} = \sum_s p_{irs,t}^{IE}E_{irs,t},$$

$$E_{ir,t} = \theta_{ir}^{E}\left(\sum_{s=1}^{R}\eta_{irs}^{IE}E_{irs,t}^{\frac{\lambda_{ir}^{E}+1}{\lambda_{ir}^{E}}}\right)^{\frac{\lambda_{ir}^{E}}{\lambda_{ir}^{E}+1}} \qquad i = 1, 2, \cdots, n, \tag{A-59}$$

$$E_{irs,t} = \left\{\frac{\eta_{irs}^{IE}(\theta_{ir}^{E})^{\frac{\lambda_{ir}^{E}+1}{\lambda_{ir}^{E}}}p_{ir,t}^{HE}}{p_{irs,t}^{IW}}\right\}^{-\lambda_{ir}^{E}} E_{ir,t} \qquad s = 1, 2, \cdots, R. \tag{A-60}$$

Equations on import ($Q_{ir,t}$: the Armington goods) are;

$$p_{ir,t}^{Q}Q_{ir,t} = p_{ir,t}^{HM}M_{ir,t} + p_{ir,t}^{D}D_{ir,t},$$

$$Q_{ir,t} = \sigma_{ir}\left\{\delta_{ir}M_{ir,t}^{\frac{\xi_{ir}-1}{\xi_{ir}}} + (1-\delta_{ir})D_{i,t}^{\frac{\xi_{ir}-1}{\xi_{ir}}}\right\}^{\frac{\xi_{ir}}{\xi_{ir}-1}}, \tag{A-61}$$

$$M_{ir,t} = \left(\frac{\delta_{ir}\sigma_{ir}^{\frac{\xi_{ir}-1}{\xi_{ir}}}p_{ir,t}^{Q}}{p_{ir,t}^{HM}}\right)^{\xi_{ir}} Q_{ir,t}, \tag{A-62}$$

$$D_{ir,t} = \left\{\frac{(1-\delta_{ir})\sigma_{ir}^{\frac{\xi_{ir}-1}{\xi_{ir}}}p_{ir,t}^{Q}}{p_{ir,t}^{D}}\right\}^{\xi_{ir}} Q_{ir,t}. \tag{A-63}$$

Import from each foreign region ($M_{isr,t}$ is an import of a good i in a region r from a region s) are;

$$p_{ir}^{HM}M_{ir,t} = \sum_s (1+\tau_r^{IM})p_{isr,t}^{IW}M_{isr,t},$$

$$M_{ir,t} = \sigma_{ir}^{M}\left(\sum_{s=1}^{R}\delta_{isr}^{M}M_{isr,t}^{\frac{\xi_{ir}^{M}-1}{\xi_{ir}^{M}}}\right)^{\frac{\xi_{ir}^{M}}{\xi_{ir}^{M}-1}}, \tag{A-64}$$

$$M_{isr,t} = \left\{\frac{\delta_{isr}^{M}(\sigma_{ir}^{M})^{\frac{\xi_{ir}^{M}-1}{\xi_{ir}^{M}}}p_{ir,t}^{HM}}{(1+\tau_{isr}^{IM})p_{isr,t}^{IW}}\right\}^{\xi_{ir}^{M}} M_{ir,t} \qquad s = 1, 2, \cdots, R. \tag{A-65}$$

Equation on import tax is;

$$T^{M}_{ir,t} = \sum_{s} \tau^{IM}_{isr} p^{IW}_{isr,t} M_{isr,t}. \tag{A-66}$$

Equation on export tax (for simplifying our model, EMEDA does not consider tax reveue on domestic balance) is;

$$T^{E}_{ir,t} = \sum_{s} \tau^{IE}_{irs} p^{IW}_{irs,t} E_{irs,t}. \tag{A-67}$$

A6. Equations on market equilibrium for international and domestic markets

Supply-demand balance for export and import goods, which determines the individual international price of tradable goods, $p^{IW}_{irs,t}$, is;

$$(1 + \mu_{irs})(1 + \tau^{E}_{irs})E_{irs,t} = M_{irs,t} \tag{A-68}$$

where μ_{irs} is a percentage of cost paying for international transportation service sector. Supply-demand balance for international transportation services, which determines the price of international transportation service, $p^{R}_{T,t}$, is;

$$\sum_{i}\sum_{r} R_{ir,t} = \sum_{i}\sum_{s}\sum_{r} \mu_{irs}(1 + \tau^{E}_{irs})E_{irs,t}. \tag{A-69}$$

Supply-demand balance for domestic Armington goods, which determines the price of Armington goods, p^{Q}_{ir}, is;

$$Q_{ir,t} = C_{ir,t} + G_{ir,t} + I_{ir,t} + \sum_{j} X_{ijr,t}. \tag{A-70}$$

Supply-demand balance for capital service, which determines the price of capital service, $r_{r,t}$, is;

$$\overline{K}_{r,t} = \sum_{j} K_{jr,t} \tag{A-71}$$

where $\delta_{K,t}$ is a depreciation rate and

$$\overline{K}_{r,t+1} = (1 - \delta_{K,t})\overline{K}_{r,t} + \hat{q}_r \sum_{i=1}^{n} I_{ir,t}, \qquad \hat{q}_r = \frac{\overline{K}_{r,2004}}{VKB_{r,2004}},$$

$$K_{jr,t+1} \geq (1-\delta_{K,t})K_{jr,t}.$$

Supply-demand balance for labor, which determines wage rate, $w_{r,t}$, is;

$$\overline{L}_{r,t} = \sum_j L_{jr,t} \tag{A-72}$$

where $g_{L,t}$ is a population growth rate and

$$\overline{L}_{r,t+1} = (1+g_{L,t})\overline{L}_{r,t}.$$

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