Comparison between Nash Equilibrium and Bargaining Solution based on the Integrated Simulation Model for Climate Change

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Abstract

The purpose of this paper is to estimate the strength of tendency for each international region to reduce emission of green house gasses with a integrated simulation model that includes the regional economic system and global geophysical model. We divided the world into ten regions, Japan, China, USA, EU, India, Middle East, High Income, Middle Income, and Low Income regions. First we estimated Nash Equilibrium, and then we estimated a bargaining solution. We compared those two situations and specified a degree of the inclination to bargaining. Our result showed that EU has high inclination to bargaining, and though India and Low Income region do not try to reduce emission of green house gasses largely, the bargaining can reach high reduction compared with the failure of bargaining.

1 Introduction

People increasingly concern the global warming problem and now it is one of major issues on the world politics. Since IPCC fourth assessment reports were published in 2007, information and data for this problem are well arranged and the accessibility to them is highly facilitated. The first commitment period of Kyoto Protocol has started in 2008. People look at the activities of Japan for attaining its commitment, one of major countries of global warming gases emission. Discussions for the post Kyoto Protocol have also started, and the Bali Roadmap of UNFCC was published in 2007.

The global environment is a kind of public goods. Its status affects welfare of people who live in anywhere in the world. On the one hand, the improvement of the environment or avoiding disasters increases their welfare; on the other hand it takes costs for mitigation and adaptations in individual country. Interests for each country or region conflict with each other. This situation requires bargaining. On this bargaining, they may be able to reach an agreement with all participating regions or countries. Each region can, however, escape from the bargaining and decide to be free rider. Bargaining processes are complex and cannot be anticipated its result plainly.

The global warming problem affects the welfare not only for current generations but also for future generations. Therefore when we decide how much we have to reduce global warming gasses what schedule for reduction we have to employ, we have to consider the degree of effects on future generations. In this point, there are many theoretical analysis and simulation. IPCC fourth assessment reports refer to many papers for those theoretical and simulation analysis.

Those many simulation analysis, however, do not necessarily consider the ongoing bargaining processes. They also do not explicitly incorporate the fact that the considerations of private return of each country in the future affect their attitude toward the bargaining. Their concerns are mainly concentrated in policy assessment based on many scenarios, which make clarify optimal schedules for emission reduction.

We would like to know how much the bargaining processes are affected by the difference of the future social and economic damages, the difference of the benefit by emitting green house gasses, and the difference of technology. In order to know them, first, we are required to have a simulation model that includes both the mechanism of global warming and economic systems, that the world are divided into regions or countries

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to a certain extent that analysis are possible. Second, some analytical frameworks, on which we can compare the situations of what the world cannot reach an agreement and the situation that cannot be reach to such agreement, are required.

Eyckmanns have written a series of papers (Eyckmans [1, 2, 3]) that used this type of model based upon the Nordhause's RICE model and the coalition type of game theoretic framework. It should be highly evaluated that they originally calculated Nash equilibrium using an integrated assessment model. Although the coalition process has a cetain level of rationality to express some international negotiation, in real negotiation process, coalition with transferable gains are not influential strategy.

In this paper, we define the state of a breakdown of negotiation as Nash equilibrium, and the state of agreement as the Nash bargaining solution derived by a multi regional integrated assessment model. The differences of welfare levels give by those two states have to affect the attitudes of negotiation. The regions or countries that the welfare losses are large have high dependency on the negotiation and try to avoid breakdown of negotiation. On the other hand, the countries or regions with small differences between those two states may have negative attitudes for negotiations. Or they may rest on some bold strategy as they have small risk for taking those attitudes.

The first purposes of this paper are to measure the rate of losses caused by the result of breakdown of the negotiation. We use the index of inclination of negotiation that are defined by the difference between breakdown and agreement. The second purpose is to analyze the influence of the consequences of the negotiations upon processes of reduction of green house gasses.

The simulation models that we use to attain those purposes incorporate ten regions or countries, the global geophysical system that causes the global warming and economic systems for each regions . We compare the results of Nash equilibriums and bargaining solutions and derive the indexes of inclination toward global bargaining for emmision reduction. The model based upon the Nordhaus's DICE2007model (Nordhaus [11]). We disaggregate the model into ten region, Japan, China, USA, EU, India, Middle East, High Income, Middle Income, and Low Income, using the newest data in 2005 that is available at the present time. The some of parameters, however, use that of RICE1999 (Nordhaus [10]).

2 Simplified Theoretical Framework

We have to define two series of emission of global warming gasses. The first one is realized in the situation of the breakdown of negotiation, and the second one is realized in agreement of the negotiation. Even if every region behaves selfishly in the situation of the breakdown, each region is affected by the behavior of the other regions, because of the fact that the global environment is a kind of public goods. This situation is generally expressed by Nash equilibriums. Those equilibriums are the states that every subject that has interrelated interests has no motivation to change his strategy, it means that his strategy is optimized, provided that the strategies of the other subjects are given.

On the other hand, the second series based upon the global agreement should be the one of Pareto optimal situations. Nash bargaining solution attains this requirement and some other rational axioms. We use this solution as the situation that the world reaches an agreement.

Now let us define the vectors of time series emission as $E^i = (E^i_0, E^i_1, \cdots, E^i_n), i = 1, 2, \cdots, m$. Then we can express the welfare level of each region U^i as follows.

$$U^i = U^i(E^1, E^2, \cdots, E^m).$$

Nash equilibrium $\overline{E}^1, \overline{E}^2, \cdots, \overline{E}^m$ is the solution of the following problem.

$$\begin{aligned} \underset{E^i}{max} \quad & U^i(\overline{E}^1, \cdots, \overline{E}^{i-1}, E^i, \overline{E}^{i+1}, \cdots, \overline{E}^m) \qquad\qquad i = 1, 2, \cdots, m \\ & s.t. \\ & \sum_{t=0}^{n} E^i_t \leq E^i_{max} \end{aligned}$$

We define the welfare levels of attained by this solution as $\overline{U}^i$.

Next let us show the bargaining solution.

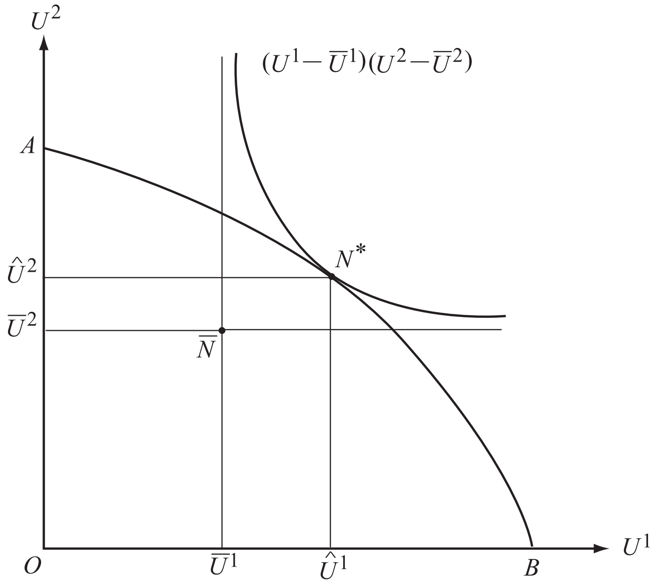

Figure 1: Nash equilibrium and bargaining solution

The feasible domain for welfare level D as follows.

$$D = \left\{ (U^1, U^2, \cdots, U^m) \middle| \sum_{t=0}^{n} E_t^i \leq E_{max}^i \quad i = 1, 2, \cdots, m \right\}$$

Then the bargaining solution is given by the solution of the next problem.

$$\max_{U^1, U^2, \cdots, U^m} \quad \prod_{i=1}^{m} (U^i - \overline{U}^i)$$

$$s.t.$$

$$(U^1, U^2, \cdots, U^m) \in D$$

Let the welfare level realised by the bargaining solution make to be $\hat{U}^i, i = 1, 2, \cdots, m$. As mentioned above, the solution is included in the Pareto optimum solutions.

Then the index Γ_i is defined as follows.

$$\Gamma_i = \frac{\hat{U}^i - \overline{U}^i}{\overline{U}^i}$$

That is, it is defined as the ratio of welfare losses by falling into a Nash equilibrium as consequence of the breakdown of the bargaining.

Let us show the states of Nash equilibrium and bargaining solution on Figure 1.

3 Model and Data

3.1 Disaggregating of DICE2007 model

Nordhaus's DICE-2007 model incorporates both the global economic system and the global geophysical system that can treat the global warming mechanism. In the model, however, the world is integrated as one economic system. This clearly prevent from constituting the interactive situation among regions on which Nash equilibrium and Bargaining solution depend. RICE 1999 model, preceding DICE 2007, incorporated the the disaggregated world. Nordhaus announced that the disaggregated version of DICE 2007 is now constructing. The model, however, is not published at the time of point that this paper have written.

Therefore we construct the model that maintain the basic structure of DICE2007 and simultaneously the world is disaggregated into Japan, China, USA, EU, India, Middle East, High Income, Middle Income, and Low Income. Countries that constitute each region is listed in Appendix 2.

The primal revision compared with DICE2007 is to remove the participation rate of the policy of global gases emission. The cost function backstop technology and the structure are mostly maintained in our model except for the disaggregating. The geophysical system is maintained for both structures and parameters.

Mathematical equations of our model are described in Appendix 1.

The important restriction of our model is not incorporate international trade. Thus, it does not include emission trading too. In the model, regions are interrelated by the global environment. This restriction will have to be removed in the future version of this research works.

3.2 Constructing the Data

The summary of procedure to make disaggregated data for this simulation is as follows. The data for carbon dioxide emission are quoted by "Energy Information Administration, International Energy Annual 2005 H.1co2, World Carbon Dioxide Emissions from the Consumption and Flaring of Fossil Fuels, 1980-2005" [1].

GDP and ppp data are based upon "World Economic Outlook Database, October 2007, [2], Gross domestic product based on purchasing-power-parity (PPP) valuation of country GDP".

World population is based upon "UN. World Population Prospects: The 2006 Revision, Medium Variant, [3]".

We estimate the capital stock data as follows.

(1) For countries listed in Fixed Capital Stock by OECD, OECD Stat's data we used its data in 2000-2005 data. (i.e. Austria, Belgium, Finland, France, Germany, Italy, Netherlands, Portugal, Australia, Japan, Denmark, South Korea, Sweden, USA, Hungary). if some data are lacked then we estimate them based on the assumption that the capital coefficients are identical. In this procedure, we used the nominal GDP data by OECD.

(2) For Russia, we use the capital stock data shown in "Rossiiskii statisticheskii ezhegodnik, Moscow: Goskomstat Rossii, 2006, p.323".

(3) For the other countries, first, we used data in 1990 estimated by Nehru [9] as the benchmark for our estimation. Then, the data for countries Mexico, Turkey, Brazil, Zimbabwe, Uruguay, Mozambique, Azerbaijan, Nicaragua, which monetary reformation were executed, are adjusted to make consistent data. Finally, by using the investment data before 2004 in IMF, International Financial Statistics, we estimate the capital stock data in 2005. The lacked parts of the investment data are estimated by GDP data based upon the assumption that the capital coefficients are identical. If there is no GDP data for the lacked years we use the capital stock data in the nearest year. All data are estimated as the national prices in 2005.

(4) We aggregate those data to the region, JAPAN, USA, CHINA, INDIA, EU, RUSSIA, MiddleEast, HighIncome, MiddleIncome, LowIncome EE, LowIncome Africa, LowIncome OtherAsia, LowIncome Other-America, LowIncome Oceania, LowIncome ROW.

(5) Using ppp rate, those values are transformed into wolrd prices (US Dollar). In case for Zimbabwe, we assume pp = 1 because of the data inconsistency affected by monetary transformation.

Among data that we made, some data series are shown in the following Table 1, where the elasticity of capital stock are assumed 0.3. CO2 are measured by Carbon.

4 Simulation Scenarios

We have performed two types of simulations. The first is the case that environmental restriction is rather loose and the permitted quantity for CO2 emission allocated to each region are 800Gt-C. The amount is fairly large. In DICE 2007 model, Nordhaus supposed the upper limit of the total emission is 6000Gt-C. This means that the average limit for ten regions is 600Gt-C. We call this simulation A. The other simulation, we call it simulation B, is restrictive. In this simulation, the total emission is 6000Gt-C same as the DICE 2007 model and allocate this amount to each region proportional to their population.

[1] http://www.eia.doe.gov/iea/
[2] http://www.imf.org/external/pubs/ft/weo/2007/02/weodata/download.aspx
[3] http://esa.un.org/unpp/

	CO2 10^6t-C	GDP 10^{12}US$	POP 10^6	CAPITAL 10^{12}US$	TFP	CAP /GDP	LAB /GDP
JAPAN	335.6	3.942	127.9	9.119	0.068070	2.313	32.44
USA	1624.6	12.208	299.8	35.687	0.077100	2.923	24.56
CHINA	1451.6	8.854	1313.0	20.212	0.023587	2.283	148.29
INDIA	317.9	3.740	1134.4	7.659	0.014765	2.048	303.34
EU	1166.1	13.288	490.4	36.504	0.059067	2.747	36.91
RUSSIA	462.5	1.580	144.0	3.112	0.034669	1.970	91.11
MiddleEast	439.8	1.853	264.7	4.177	0.024301	2.255	142.87
HighIncome	529.3	3.820	131.1	9.193	0.064674	2.407	34.32
MiddleIncome	706.1	6.746	687.4	13.627	0.031819	2.020	101.89
LowIncome	655.4	5.811	1922.1	20.498	0.011806	3.527	330.76
WORLD	7688.9	61.841	6514.8	159.790	0.028872	2.584	105.35

Table 1: Regional Data in 2005

The number of the time periods is 30, each one period means ten years. The first period consists of ten years after 2005. We do not necessarily require those 300 years results. This structure is needed to remove the effects caused by final period situation (transversality conditions).

In this types of simulations, damage parameters are plays very important roles. We tried to newly estimate the damage functions. The fourth assessment report of IPCC provides many data and information for estimating damage parameters. It takes, however, too much time to estimate those parameters. Therefore we resigned to estimate and used the parameters consist in the RICE 1999 model[4].

Nash equilibriums are calculated by the simulation software GNES and GENEC that are developed by the author [5]. GENES is the server executed on a network. GENEC is a client executed on the same network as GENES. Each GENEC plays a role of one region. GENES defines the global and common parameters for regions. It receives the optimal emission from each GENEC, which is based on the given total emission other than itself and global environment. GENES distributes the information on situations of other regions. The total emission influences on the global warming. This mechanism is common to all and calculation is performed in each GENEC.

Each region optimizes its emission schedule over period asynchronously. Those processed are not synchronized. From the view point of the software, since it takes different time to solve the optimization problem, synchronization is essentially difficult and inefficient. If the total emission of the other regions is not different from the level informed in the pervious access with the small errors, then the region does not invoke the optimization process. If every region stops the optimization, that situation is a Nash equilibrium. In the situation, geophysical variables, e.g. global mean temperature, are also common for every region.

This method is not applicable if the Nash equilibrium is unstable. We have not, however, encountered such instable Nash equilibrium. We could confirm that the Nash equilibriums are strong tendency of convergence.

Finally, let us show the procedure to have the bargaining solutions. We are required the point of welfare in the situation of the breakdown of bargaining. We employed the point as Nash equilibrium. The bargaining solutions are given the point that maximize the Nash products in the domain restricted by the breakdown point. It is fairly difficult to obtain this point on the simulation model. This is because the value of Nash products becomes very large. For our model, we have ten regions. It means that the errors are multiplied ten times. Therefore, we use two stage algorism. We first derived one of Pareto optimum points using linear additive objective function, then we optimize the Nash product as started from the derived point. This method leads us to the bargaining solutions.

5 Simulation Results

Let us show the results of two simulations.

[4]Refer to Labriet [6]、Tol [13, 14] for damage functions

[5]Software, GENES, GENEC, GEBEC used in this paper are published in the authors web site-http://genes.eco.genv.sophia.ac.jp/. All of them are freely downloadable.

	JAP.	USA	CHI.	IND.	EU	RUS.	M.E.	H.I.	M.I.	L.I.
Allocation	800	800	800	800	800	800	800	800	800	800
Nash	254.6	800.0	800.0	800.0	538.2	800.0	800.0	324.5	800.0	800.0
Bargain	202.8	785.8	800.0	237.0	356.5	456.6	800.0	273.1	714.1	542.7
CO2/GDP	0.085	0.133	0.164	0.085	0.088	0.293	0.223	0.139	0.105	0.102

Table 2: Emission Limits and Total Emission: Simulation A

	JAP.	USA	CHI.	IND.	EU	RUS.	M.E.	H.I.	M.I.	L.I.
Nash	2.3	4.4	3.3	4.2	8.8	0.1	2.4	1.9	3.7	5.2
Bargain	13.1	21.2	17.4	8.5	37.0	3.0	8.6	17.3	9.4	12.0

Table 3: Reduction Rate in 2015-2025 (%): A

5.1 Large Emission Limit: Simulation A

The total emission for each region is shown in Table 2.

Large limits make some regions, Japan, EU and High Income, not to use up the emission limits in the Nash equilibrium. It means that in those regions environmental restriction is not considered and the results simply show the optimal growth path for each region. This result partly depends upon the fact that the economic scale of those regions are comparatively small.

In the bargaining solution, though China and Middle East use up the emission limits, many regions leave their emission limits. A remarkable thing is that though India and Low Income region use up their limits in the Nash equilibrium they significantly reduce their emissions in the bargaining solution. This means that economic achievements of those regions are remarkably depend upon the result of international negotiation.

The time series of CO2 emission is shown in the Figure 2. Those graphs show the emission series starting in the first period (2005-2015). Each period consist of ten years and the unit is Gt-C. Moreover the series of the rate of CO2 emission reduction is given on Figure 3. This reduction rate does not means the rate of reduction compared with a specific year (e.g. 1990). The rate is give by comparing with the state that no reduction policy is implemented in that region. Therefore it may adequate to call the rate the control rate as used in the Nordhause's Papers.

To see the years until about 2100, the emissions by U.S.A., China and EU are noticeable. It also show that the large limit make many regions avoid large reduction[6].

We picked up the reduction level in 2015-2025 on Table 3. The rate of reduction is generally small.

The amount of emission reduction and the rate of reduction in the bargaining solution is given on Figure 4 and Figure 5. The amount of reduction remarkably decreases in the bargaining solution. Many region prefer the reduction in early periods. The amount of reduction becomes large compared with Nash equilibrium. It shows that many regions selected high reduction direction in the early periods.

As the result of the bargaining, the region who agrees with highest reduction level is EU, and followed by U.S.A., China, High Income, Japan. We have to notice that India, Low Income and Middle Income will attain high reduction in the later half of this century. The reduction level of Russia attained by the bargaining is low throughout. Moreover the U.S.A. situation in bargaining solution is fairly different from the situation in Nash equilibrium. This tendency is also confirmed for Japan, High Income.

Figure 6 shows how much the global mean temperature increases in the Nash equilibrium and the bargaining solution.

This graph show that we can not expect large decrease in the temperature even if the international negotiation is succeeded.

[6] Initial rate of reduction is fixed on 0.005.

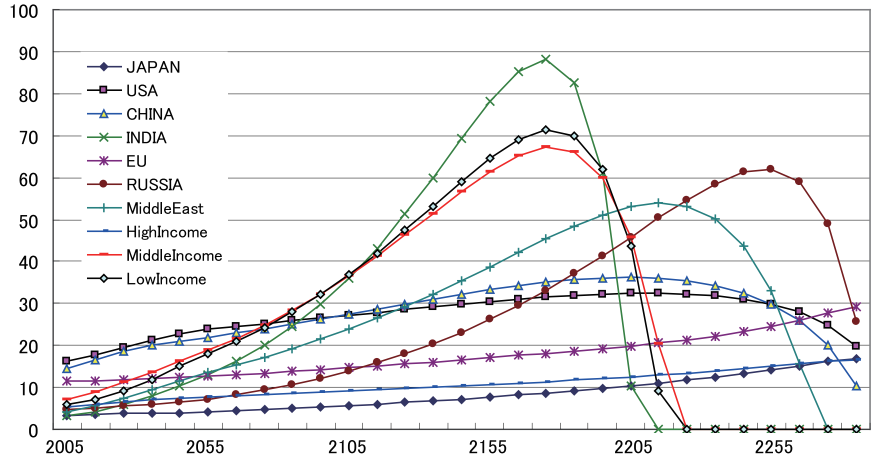

Figure 2: CO2 Emission in Nash Equilibrium: A

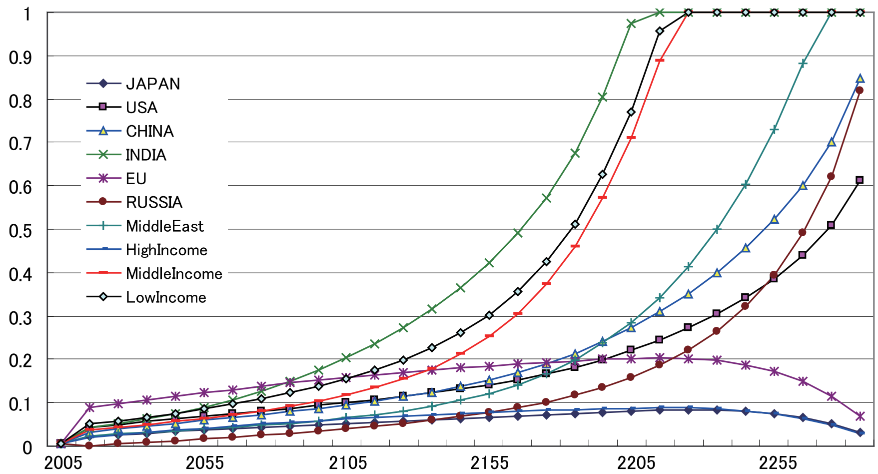

Figure 3: Rate of Reduction in Nash Equilibrium: A

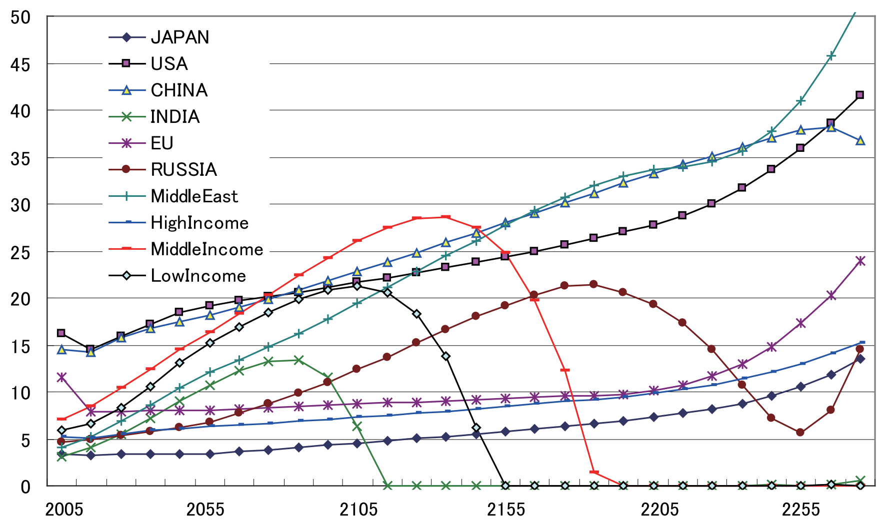

Figure 4: CO2 Emission in Bargainning Solution: A

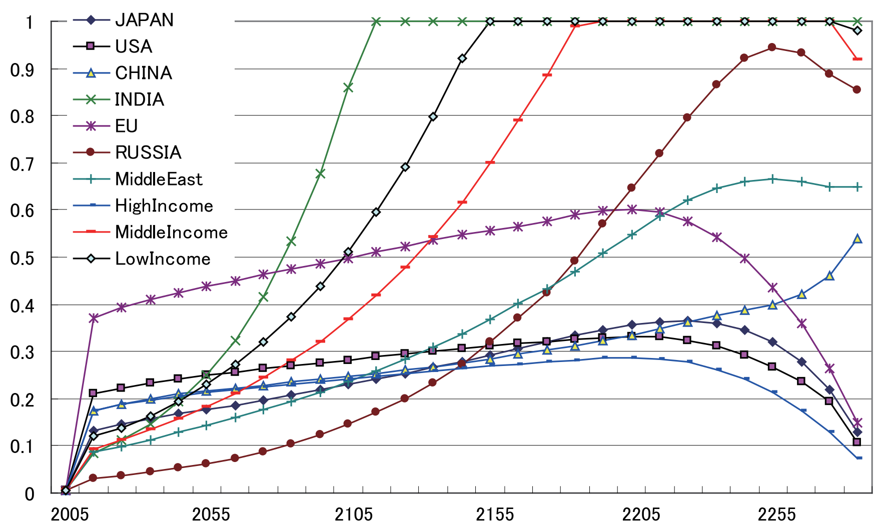

Figure 5: Rate of Reduction in Bargainning Solution: A

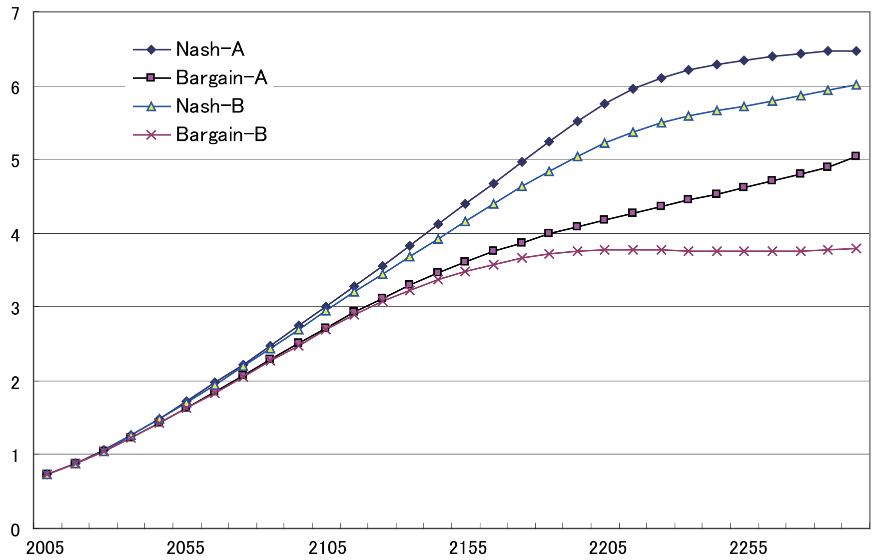

Figure 6: Global Mean Temparature in Nash equilibrium and bargaining solution. (Compared with 1900) : A and B

	JAP.	USA	CHI.	IND.	EU	RUS.	M.E.	H.I.	M.I.	L.I.
Allocation	66.9	262.7	919.7	1082.5	313.0	70.4	312.2	98.4	578.5	2295.7
Nash	66.9	262.7	919.7	1082.5	313.0	70.4	312.2	98.4	578.5	2295.7
Bargain	66.9	262.7	919.7	205.3	277.2	70.4	312.2	98.4	535.8	399.9

Table 4: Emission Limits and Total Emission: Simulation B

5.2 Restriction of Emission: Simulation B

Let us show the simulation results for the case that the limit of world total emission is to be 6000Gt-C which is allocated to each region proportional to its population size.

Emission limits and total emission in simulation B listed in Table 4. The difference compared with simulation A is in that all regions use up the emission limit allocated to each region in Nash equilibrium. On the other hand, in the bargaining solution, the regions India, EU, Middle Income and Low Income do not use up their emission limits. Specifically, India and Low Income remarkably reduce their emission and this fact equivalent to the result of simulation A.

The time series of CO2 emission is shown in Figure 7. Those regions with continuous emission growth in simulation A are finally reduce their emission in last periods. The paths of reduction rate are shown in Figure 8. The graph show the rapid increase of the reduction rate.

The reduction rate in regions are listed in Table 5. One noticeable feature that although the reduction rates in the Nash equilibrium is rather different from those in simulation A, those in the bargaining solution is not so different from simulation A.

	JAP.	USA	CHI.	IND.	EU	RUS.	M.E.	H.I.	M.I.	L.I.
Nash	4.7	10.0	3.1	4.2	9.1	3.6	2.9	7.1	3.8	5.2
Bargain	13.9	24.8	16.8	8.3	36.6	4.9	9.4	19.1	9.6	11.6

Table 5: Reduction Rate in 2015-2025 (%): B

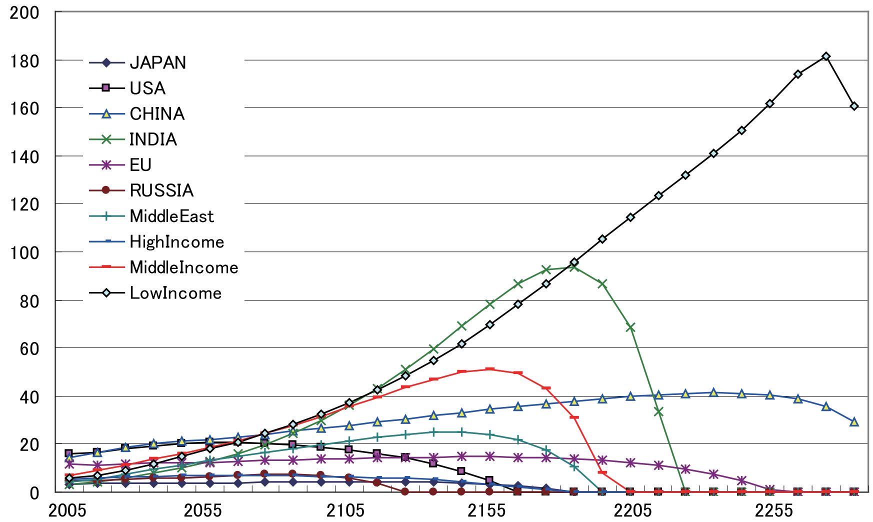

Figure 7: CO2 Emission in Nash Equilibrium: B

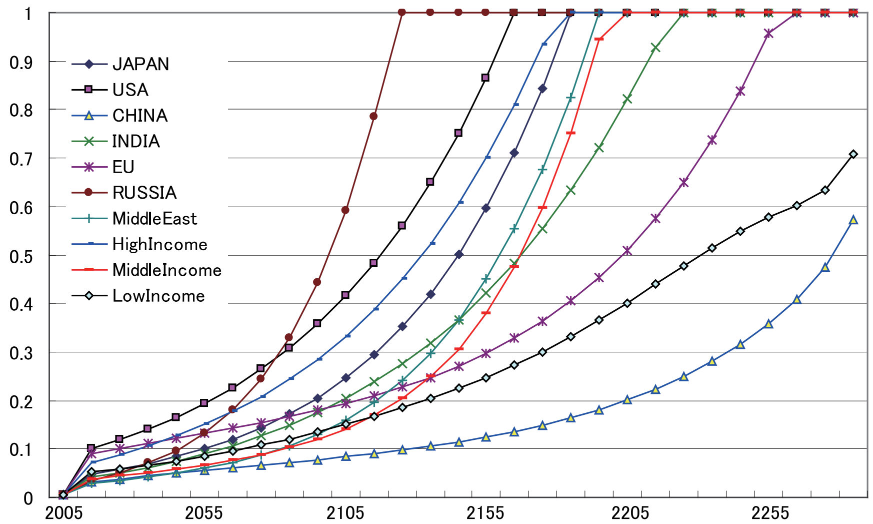

Figure 8: Rate of Reduction in Nash Equilibrium: B

	JAP.	USA	CHI.	IND.	EU	RUS.	M.E.
A Nash	-10000	-10000	-10000	-10000	-10000	-10000	-10000
A Bargain	-9986.2	-9991.6	-9991.7	-9994.1	-9976.2	-9997.5	-9990.0
A Index	13.8	8.4	8.3	5.9	23.8	2.5	10.0
B Nash	-10000	-10000	-10000	-10000	-10000	-10000	-10000
B Bargain	-9987.5	-9991.3	-9993.3	-9995.2	-9980.1	-9997.4	-9990.0
B Index	12.5	8.7	6.7	4.8	19.9	2.6	10.0

	H.I.	M.I.	L.I.
A Nash	-10000	-10000	-10000
A Bargain	-9980.7	-9996.1	-9993.3
A Index	19.3	3.9	6.7
B Nash	-10000	-10000	-10000
B Bargain	-9982.1	-9996.6	-9994.7
B Index	17.9	3.4	5.3

Table 6: Indexes of Inclination to Bargainning

The time series in the bargaining solution Figure 9 and Figure 10.

Compared with simulation A, although the changes in next centuries are large, the changes in this centuries are small. Here we can also confirm that the situation in the bargaining solution is not largely affected by the restriction.

5.3 Indexes of Inclination to Bargaining

Let us derive the indexes for bargaining using the results of those two simulations. Two remarks are given. The first is that the welfare level for each region is given by negative value. This is due to the specification of the utility function used in this model. The second is that in order to have the solution effectively we adjust the final welfare level to be 10000 in Nash equilibrium. This adjustment does not affect to the Nash solution show in the previous sections.

We can show two indexes based on the two simulation. Results are shown in Table 6. A indexes are derived by simulation A and B indexes are derived by simulation B. In this table, the indexes are simply expressed by the difference between two solution. This means that the unit of those value is $10^{-2}\%$. The maximum index is for EU in simulation A. The value means that EU can increase their welfare 0.24% by the agreement of bargaining. The amount, however, seems to be rather small.

The indexes in order is shown in Figure 11.

The values of indexes in the restrictive simulation B are slightly smaller than simulation A.

6 Concluding Remarks

The indexes derived by our simulation are reflect ongoing bargaining process. EU and Japan, who have strong inclination to success the international bargaining, are ranked at high position. Russia and India, who seem to be small concerned about international negotiation, are at low ranks. It suggests that our analytical process and our premises, that the difference between welfare in Nash equilibrium and that in bargaining solution makes different attitude toward the bargaining, are both effective.

As mentioned above, our models do not incorporate the process of international trade. If the international trade for emission rights is incorporated, a country in high marginal abatement costs buy a certain amount of emission right from a low country. This causes increase in welfare situation for both countries. It makes relax the decrease of welfare in restrictive simulation. It is not clear, however, how this new situation influences to the order of bargaining indexes.

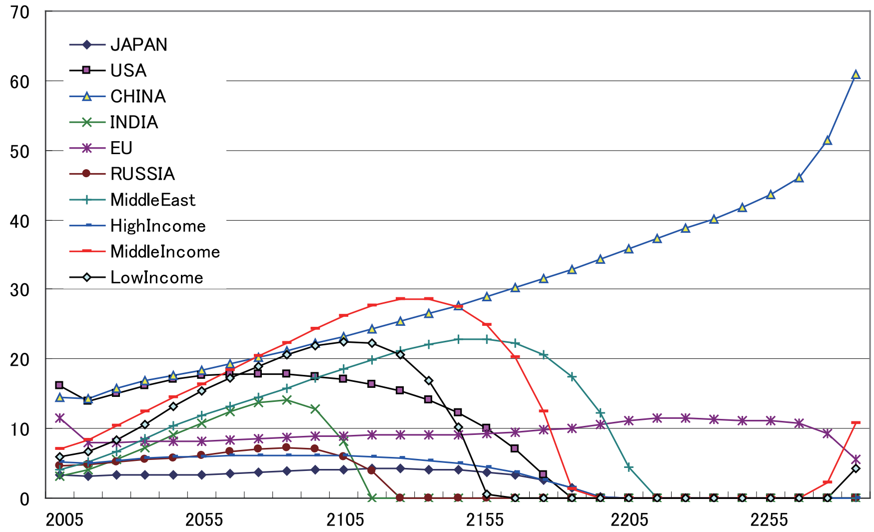

Figure 9: CO2 Emission in Bargainning Solution: B

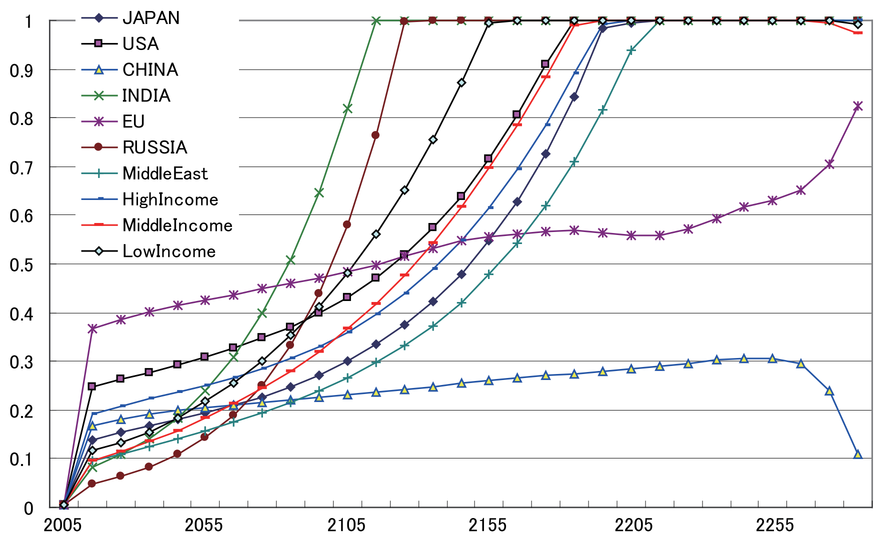

Figure 10: Rate of Reduction in Bargainning Solution: B

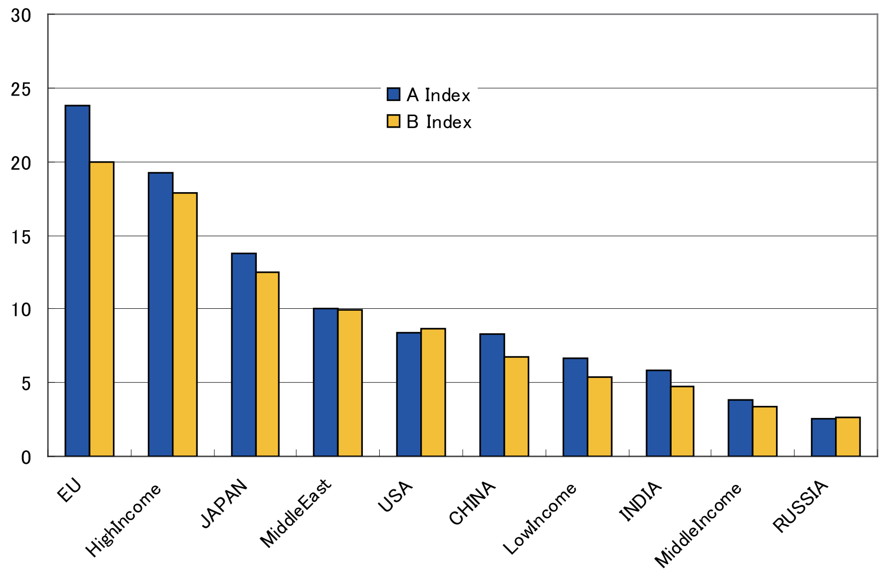

Figure 11: Bargainning Indexes in Order

The other weak point of this paper is that we cannot show the shadow prices for CO2 emission. This is caused by the limitation of the software to calculate the Nash equilibriums and the bargaining solutions.

In the next version of our simulation, we will try to remove those defects.

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Appendix1: Structure of the model

Mathematical Formulation

The primar structure of our models are based on the DICE2007 model (Nordhaus [11]).

t with suffic $t = 1, 2, \cdots, T^{max}$ express periods. T^{max} is the final period. One period means ten years and total simulation periods 30. Suffic i shows a resion.

Welfare of each region is expressed by the following two equations.

$$U^i = \sum_{t=1}^{T^{max}} \frac{L_t^i u_t^i}{(1+\rho)^{t-1}} \tag{1}$$

$$u_t^i = \frac{\left(\frac{C_t^i}{L_t^i}\right)^{1-\alpha} - 1}{1-\alpha} \tag{2}$$

L denotes population and it simultaneously means labor supply for the region. C is consumption level and u is utility function percapita. The elasticity of marginal utility for consumption is constant for this utility function. U is total utility for the region and it is calculated using discount factor ρ. The production function that shows the technology for the region is as follows.

$$Y_t^i = A_t^i (K_t^i)^{\eta} (L_t^i)^{1-\eta}, \tag{3}$$

where Y is gross GDP, K capital stock and A is total factor productivity. The capital accumulation is expressed as follows.

$$K_{t+1}^i = I_t^i + (1-\delta) K_t^i, \tag{4}$$

where I is investment, δ is the depreciation rate of the capital and common to all regions.

Supply and demand equations are expressed as follows.

$$\Omega_t^i Y_t^i = C_t^i + I_t^i \tag{5}$$

where Ω expresses the reduction GDP caused by abatement costs and damages that are expressed in (8). The emission of global warming gasses E is as follows.

$$E_t^i = (1 - \mu_t^i) \sigma_t^i Y_t^i \tag{6}$$

where μ is the reduction rate compared with BAU scinario. σ is emission factor.

Emission limits AE are given to every region. Therefore the following conditions should be satisfied.

$$\sum_{t=1}^{T} E_t^i \leq AE^i \tag{7}$$

Damage costs and abatement costs are given by the following integrated equations.

$$\Omega_t^i = \frac{1 - B_t^i (\mu_t^i)^{\theta}}{1 + \psi_1^i T_t^{atm} + \psi_2^i (T_t^{atm})^2} \tag{8}$$

The numerator expressed the abatement costs. B is the parameter that include the effects of cost reduction with backstop technology. The denominator is the damage costs caused by the increase in the global average temparature.

The following equations express the mechanism of global warming. The accumulation equations of CO2 in the atomosphere is as follows.

$$M_t^{atm} = \sum_i E_t^i + E_t^{tree} + b_{11} M_{t-1}^{atm} + b_{12} M_{t-1}^{upp}, \tag{9}$$

where M^{atm} is the amount of CO2 acculated in the atomosphere. E^{tree} expresses the emission from forests. b_{11} is the amount retained from the previous period. b_{12} is the ration of transfering to the the atmosphere from the surface of ocean. The next equations determin the concentration of CO2 in low levels of the oceans. b_{23} is the coefficient denoting the transfer to the lower parts of the ocean from the upper pert. b_{33} is the coefficient for retaining CO2 in the lower parts.

$$M_t^{low} = b_{23} M_{t-1}^{upp} + b_{33} M_{t-1}^{low} \tag{10}$$

The next equation shows the amount of CO2 accumulation in the upper oceans. b_{12} is the transfer coefficient to the upper ocean from the atomosphere. b_{22} is the retaining rate in the upper ocean. b_{32} is the transfer coefficient form the lower parts of oceans to the upper parts of oceans.

$$M_t^{upp} = b_{12} M_{t-1}^{atm} + b_{22} M_{t-1}^{upp} + b_{32} M_{t-1}^{low} \tag{11}$$

The next equation expresses the force of radiation.

$$F_t = \zeta \log_2 \left(\frac{M_t^{atm}}{596.4} \right) + F_t^{other} \tag{12}$$

where F_t^{other} is the force of radiation from the gasses other than CO2. The value 596.4 means the concentration of CO2 before the industrial revolution.

The next two equations show the global average temparature compared with that in 1900.

$$T_t^{atm} = T_{t-1}^{atm} + \xi_1 \{ F_{t-1} - \lambda T_{t-1}^{atm} - \xi_3 (T_{t-1}^{atm} - T_{t-1}^{low}) \} \tag{13}$$

$$T_t^{low} = T_{t-1}^{low} + \xi_4 (T_{t-1}^{atm} - T_{t-1}^{low}) \tag{14}$$

Basic Parameters

There are numerous parameters required for functioning the simulation models. Our model employed many parameters used in the DICE 2007 model. However the some of the parameters express the feature of each region are newly estimated. Some are employed directly from RICE 1999 model. The basic parameters are listed in the following table.

η	0.3	ξ_1	0.220
ρ	0.015	ξ_3	0.300
δ	0.1	ξ_4	0.050
α	2.0	ζ	3.8
b12	0.189288	θ	2.8
b23	0.05		

Table 7: Basic Parameters

Appendix 2: Definition of Regions

EU	Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovenia, Slovakia, Sweden, United Kingdom
MiddleEast	Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Palestinian, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
HighIncome	Australia, New Zealand, Canada, South Korea, Iceland, Norway, Switzerland, Hong Kong, Singapore, Brunei, Bahamas, Barbados, Trinidad and Tobago, Equatorial Guinea
MiddleIncome	Turkey, Mexico, Malaysia, Maldives, Kazakhstan, Turkmenistan, Thailand, Argentina, Antigua and Barbuda, Saint Kitts and Nevis, Chile, Costa Rica, Uruguay, Brazil, Panama, Grenada, Dominican Republic, Colombia, Croatia, Bosnia and Herzegovina, Azerbaijan, Belarus, Seychelles, Libya, Botswana, Mauritius, South Africa, Tunisia
LowIncome EE	Albania, Armenia, Georgia, Macedonia, Moldova, Montenegro, Serbia, Ukraine, Monaco, Liechtenstein
LowIncome Africa	Algeria, Republic of the Congo, Democratic Republic of the Congo, Central African Republic, Rwanda, Burundi, Sudan, Kenya, Tanzania, Uganda, Djibouti, Eritrea, Ethiopia, Somalia, Angola, Lesotho, Malawi, Mozambique, Namibia, Swaziland, Zambia, Zimbabwe, Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Cape Verde, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Sao Tome and Principe, Senegal, Sierra Leone, Togo, Comoros, Madagascar, Morocco, Reunion, Western Sahara, Zaire
LowIncome Asia	Kyrgyzstan, Tajikistan, Uzbekistan, Macau, Mongolia, North Korea, Taiwan, Cambodia, East Timor, Indonesia, Laos, Myanmar, Philippines, Vietnam, Afghanistan, Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka
LowIncome America	Aruba, Bermuda, Belize, British Virgin Islands, Bolivia, Cuba, Dominica, Ecuador, El Salvador, Falkland Islands, Guatemala, Honduras, Paraguay, Peru, Puerto Rico, Venezuela, Cayman Islands, Greenland, Guadeloupe, Guyana, Haiti, Jamaica, Martinique, Montserrat, United States Navassa, Netherlands Antilles, Nicaragua, Saint Barthe'lemy, Saint Lucia, Saint Martin, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Turks and Caicos Islands, United States Virgin Islands, French Guiana, Saint Helena, Suriname, Anguilla
LowIncome Oceania	Christmas Island, Cocos Islands, Norfolk Island, Fiji, New Caledonia, Papua New Guinea, Solomon Islands, Vanuatu, Federated States of Micronesia, Guam, Kiribati, Marshall Islands, Nauru, Northern Mariana Islands, Palau, Cook Islands, French Polynesia, Niue, Pitcairn Islands, Samoa, Tokelau, Tonga, Tuvalu, Wallis and Futuna Islands, Pitcairn, American Samoa
LowIncome ROW	Antarctica, Faroe Islands, Gibraltar, Hawaiian Trade Zone, Former Czechoslovakia, Former Serbia and Montenegro, Former U.S.S.R., Former Yugoslavia, East Germany, West Germany, U.S. Pacific Islands, Wake Island, Andorra, Channel Islands, Faeroe Islands, Holy See, Isle of Man, San Marino