

# Dynamic Efficiency of CO<sub>2</sub> Emission Permit Trading beyond Kyoto: Implications for Asian Countries

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*An integrated climate-economic dynamic optimization model is constructed to evaluate the potential gains for Asian countries to participate in the Kyoto protocol under alternative emission permit trading scenarios. The main findings are: (1) Impacts of interregional only and interregional plus interperiod permit trading scenarios on the economic growth of Asian countries are similar; (2) China, India, and South Asia could improve their economic growth significantly by selling permits; and (3) Japan could reduce negative economic impacts of emission mitigations effectively but not entirely through permit trading.*

*Keywords: Climate Change, Economic Growth, Tradeable CO<sub>2</sub> Emission Permits*

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## I. Introduction

The issue of global warming, caused by emissions of CO<sub>2</sub> and other greenhouse gases (hereafter GHGs), has become an important policy issue in many countries (Intergovernmental Panel on Climate Change (hereafter IPCC), 2001a; 2007a). The Kyoto Climate Change Conference (COP-3), held in December 1997, reached an agreement on targets and timetables for GHG emissions reductions. Based on the Kyoto Protocol, 38 industrialized countries and economies of transition, the so-called Annex B countries, committed to limit or reduce their GHG emissions by an average of 5.2% of 1990 levels in the period 2008-2012. In November 1998, a Climate Change Conference of 170 governments in Buenos Aires (COP-4) agreed on a two-year Plan of Action to accelerate the work of the Convention and the implementation of the Kyoto Protocol, and to create incentives for developing country involvement. Unfortunately, at COP-4 only two developing countries signed the Kyoto Protocol. After COP-4, greater emphasis has been placed on attracting non-Annex B countries' participation in the Kyoto Protocol, as well as on the potential financial assistance and technology transfer from Annex B countries to enable non-Annex B countries to mitigate climate change and adapt to its effects.

Since non-Annex B countries may contribute a large portion of global GHG emissions in the future, their participation is crucial to the success of the Kyoto Protocol. However, the long-term economic impact of their participation in the Kyoto Protocol is a major concern for non-Annex B countries. With a focus on Asian countries, which are currently projected to have relatively high growth rates of GHG emissions among non-Annex B countries, an integrated climate-economic model is developed in this paper to explore the impacts of the Kyoto Protocol on their long-term economic growth.

Since the late 1980s, much scientific research has focused on improving our understanding of the climate system and assessing the vulnerability of natural and human systems to climate change (IPCC, 1991, 1996a, 2001a, 2007a). So far, most scientists have concluded that the projected climate change during the 21<sup>st</sup> century has the potential to lead to future large-scale and possible irreversible damages in natural and human systems. On the other hand, social science research has aimed primarily at estimating the economic costs of reducing GHG emissions to some targets (Buonanno *et al.*, 2003; Manne and Richels, 1995; Nordhaus and Boyer, 1999; Nordhaus and Yang, 1996) and at quantifying the potential damages of global warming (Fankhauser, 1994; Hall, 2001; Plambeck and Hope, 1996; Tan and Shibasaki, 2003; Tol, 1995).<sup>1</sup>

By coupling a dynamic multi-region economic growth model with a global climate change model, some integrated assessment models have simulated several national or international optimal carbon emissions trajectories to advise policy makers (Nordhaus and Yang, 1996; Peck and Teisberg, 1994; Tol, 1997).<sup>2</sup> After the 1997 Kyoto Protocol, several studies have evaluated the consequences of the Kyoto emission reduction commitments on Annex B and non-Annex B countries under noncooperative and cooperative scenarios.<sup>3</sup> However, a greater focus has been placed on how the Kyoto Protocol would affect the long-term economic growth of Annex B countries; there has been relatively little effort to evaluate the economic impacts of the Kyoto Protocol on non-Annex B Asian countries (Boyd and Ibararán, 2002).

It is widely recognized that the consequences of global warming may differ from one country to another due to their specific social and natural characteristics, but global warming itself depends on worldwide aggregate GHG emissions. Also, countries may have different marginal abatement costs of controlling CO<sub>2</sub> emissions, depending on the degree of their dependence on production activities that emit CO<sub>2</sub> and their technologies (including energy use efficiency). With a global public good, like CO<sub>2</sub> emissions, the noncooperative Nash equilibrium resulting from individual abatement efforts will not be globally Pareto efficient. Therefore, in order to reach a globally

Pareto optimal CO<sub>2</sub> emission control, international cooperation between countries is required (Eyckmans *et al.*, 1993).

Command and control regulatory policy instruments have been the traditional approaches to control pollution emissions. However, they may be very inefficient in achieving the emission reduction goal. To reduce the impacts of GHG emission reductions, the use of tradeable emission permits have often been proposed as a cost-effective economic instrument (Barrett *et al.*, 1992; Rose and Stevens, 1993; Springer, 2003). Under a static emission permits trading regime, it is optimal for a country to sell (buy) permits as long as the market price of a permit is higher (lower) than its own marginal abatement cost. In equilibrium, marginal abatement costs are equalized across all countries in each period. Furthermore, if countries are allowed to allocate the use of permits freely through time (by banking or borrowing), it is optimal for them to distribute abatement across periods such that their present values of marginal abatement costs are equalized (Rubin, 1996; Stevens and Rose, 2002). Therefore, it is obvious that a system of tradeable permits is an effective instrument to increase the efficiency of GHG emissions control (Hagen and Westskog, 1998). The Kyoto Protocol for reducing CO<sub>2</sub> emissions in Annex B countries is a good example of how a system of tradeable permits can be used to achieve a given national emission limits at minimum costs.<sup>4</sup>

To evaluate the economic costs and environmental benefits of alternative CO<sub>2</sub> emission mitigation policies in a more precise way, integrated climate-economic models have been broadly used to assess the economic and environmental impacts of the Kyoto Protocol under alternative CO<sub>2</sub> permit trading scenarios in recent years. Although there are quantitative differences among models due to differences in assumptions and differences in the detail of model structure, it is widely agreed upon in recent modelling analyses that emission permits trading could substantially reduce the costs of accomplishing any given level of carbon emission reductions. However, the purpose of this study is not to re-examine the economic costs or environmental benefits

of the Kyoto Protocol in general, but to examine and evaluate the potential gains for Asian countries to participate in the Kyoto Protocol under alternative permit trading scenarios.

An integrated assessment model has been constructed to explore the dynamic efficiency of tradeable permits in order to analyze the interactions between economic activities and the climate change simultaneously.<sup>5</sup> Structurally, the model constructed in this study is based on the Rose-Stevens model (Rose and Stevens, 1993, 1998; Stevens and Rose, 2002). However, it extends the Rose-Stevens model by combining a simple global climate change model with a globally integrated economic climate-damage and abatement-cost model to form a climate-economic dynamic optimization model. In addition, the “Asian Tigers” are disaggregated into Hong Kong, Singapore, South Korea, and Taiwan to analyze implications specifically for emerging Asian economic powers.

This paper is organized as follows: The fundamental structure of the integrated climate-economic model and the equations of the model are described in the next section. A brief summary of basic socioeconomic and CO<sub>2</sub> emissions data for each country/region and the calibration of key parameters in the marginal abatement cost functions and climate change damage functions are presented in the third section. Global simulation results for different mitigation policies and alternative permit trading scenarios are discussed in the fourth section. The impacts of different mitigation policies and alternative permit trading scenarios on economic growth of Asian countries are discussed in the fifth section. The last section provides some conclusions.

## II. Structure of the Integrated Climate-Economic Model

Figure 1 shows the fundamental elements and interactions within a simplified integrated climate-economic model. Basically, there are three distinct submodels: economic, climate, and time trend. The evolution and linkage of these three submodels

can be used to describe the state of global society as well as regional society over time. The economic model used here is a Ramsey-type economic growth model. At any point in time, given population and production technology calculated in the trend model, new output, consumption, and capital stock are calculated to describe the state of the economy. Meanwhile, CO<sub>2</sub> emissions associated with production activities can be calculated by multiplying output by the emission/output ratio, which is decreasing over time and depends in part on the level of the Autonomous Energy Efficiency Improvement (hereafter AEEI). In the climate model, CO<sub>2</sub> is considered as the major anthropogenic radiative-forcing agent, and the level of CO<sub>2</sub> emissions is used to calculate the atmospheric carbon concentrations and the global mean temperature change.

In combining the economic growth model with the climate model, the major tradeoff faced by society is between the current and future output levels. By taking steps to reduce CO<sub>2</sub> emissions to slow down the pace of the climate change, society may have to divert resources from other productive uses. Under the framework of economic growth theory, not only current levels of consumption and investment levels will be affected by this CO<sub>2</sub> emission control, but also the future amount of output, consumption, and investment. Compared to the case of no mitigation action, the major benefit of CO<sub>2</sub> emission control is higher levels of output in the future from lower climate change damages. Therefore, the objective of cooperative global society is to find a global optimal CO<sub>2</sub> emission control path to maximize global social welfare (e.g., maximize the sum of regional discounted utility of consumption). In the case where specific emission control levels have been agreed upon among countries (e.g., the Kyoto Protocol), cooperative global society can minimize the sum of global warming damages and net abatement costs by introducing cost-effective policy instruments like tradeable emission permits in the emission control regime.<sup>6</sup> The detailed equations of the integrated climate-economic model are discussed in the following five subsections.



## 2.1 Objective Function

From the perspective of each region, the objective is to maximize the regional social welfare function subject to a number of economic constraints. The decision variables that are available to each region include intertemporal consumption, investment, and CO<sub>2</sub> emission control. Here I assume the social welfare function is increasing with respect to the level of consumption per capita, with diminishing marginal utility of consumption. The utility flow is assumed to be discounted over time at the pure rate of time preference.<sup>7</sup> Based on the above assumptions, the objective function for each region can be represented by

$$W_i = \sum_t d_i(t) U_i[c_i(t), L_i(t)] \quad (1)$$

where  $W_i$  is the social welfare of region  $i$ ,  $U_i[c_i(t), L_i(t)]$  is the utility of consumption for region  $i$ ,  $c_i(t)$  is the consumption per capita at period  $t$ ,  $L_i(t)$  is the population at period  $t$ , and  $d_i(t)$  is the discount factor which is calculated from

$$d_i(t) = (1 + \rho_i(t))^{-t} \quad (2)$$

where  $\rho_i(t)$  is the pure rate of time preference at period  $t$ , which I assume is 4% and constant over time.

From the perspective of global society, the global objective function (equation (1)) is to maximize

$$W = \sum_i W_i \quad (1a)$$

where  $W$  is the global social welfare. Here I simply assume the global social welfare is the algebraic sum of regional welfare without taking into account the equity considerations.

## 2.2 Economic Growth Model

Utility is measured as the population times the logarithmic utility function of consumption per capita:

$$U_i[c_i(t), L_i(t)] = L_i(t) \ln c_i(t) \quad (3)$$

Based on historical population data and long-term population growth rates projected by United Nations (United Nations, 2004), I assume the population is exogenously given by

$$L_i(t) = \bar{L}_i(1 + g_i)^t \quad (4)$$

where  $L_i$  is the reported population for region  $i$  at the base period, and  $g_i$  is the projected constant long-term population growth rate for region  $i$ .

In this paper, production is represented by a modification of standard neoclassical production function, that is, each country/region only produces a single commodity, which can be used for either consumption or investment. The economic growth process is represented by a Ramsay-type growth model that explains the fundamentals of consumption and capital accumulation in a dynamic equilibrium setting. Within this optimal growth framework, economic impacts of CO<sub>2</sub> mitigation and global warming damages on the long-run economic growth for each country/region can be readily simulated through the incorporation of mitigation cost functions and global warming damage functions.

Production is represented by a Cobb-Douglas function with Hicks-neutral technological change. The inputs to this function are capital and labor, and each region is endowed with an initial capital stock, labor, and technology. While population growth and technology change are exogenously determined, the capital stock is determined by the optimal consumption and investment decisions over time. The production function can be represented as

$$Q_i(t) = A_i(t)K_i^{\alpha_i}(t)L_i^{1-\alpha_i}(t) \quad (5)$$

where  $Q_i(t)$  is the output of region  $i$  at time period  $t$ ,  $K_i(t)$  is the capital stock of region  $i$  at time period  $t$ ,  $A_i(t)$  is the total factor productivity of region  $i$  at time period  $t$ , and  $\alpha_i$  is the capital value share parameter of region  $i$ .<sup>8</sup> In the model, I also assume  $A_i(t)$  will grow at a rate of  $\eta_i(t)$  and the growth rate  $\eta_i(t)$  is decreasing over time at a constant rate of  $\eta_i^d$ .<sup>9</sup> Let  $\overline{\eta_i}$  denote the initial productivity growth rate for region  $i$ , then the productivity growth rate at any given period can be determined by

$$\eta_i(t) = \overline{\eta_i} \exp(-\eta_i^d t) \quad (6)$$

and therefore the total factor productivity is gradually increasing over time at the rate of  $\eta_i(t)$ :

$$A_i(t) = \overline{A_i} \eta_i(t) \quad (7)$$

Because energy is not included as a primary input in the production function, here I simply assume that CO<sub>2</sub> emissions associated with production activities can be obtained by multiplying output by the emission/output ratio

$$E_i(t) = \phi_i(t)Q_i(t) \quad (8)$$

where  $E_i(t)$  is the new global CO<sub>2</sub> emissions of region  $i$  at time period  $t$ , and  $\phi_i(t)$  is the emission/output ratio for region  $i$  at time period  $t$ .<sup>10</sup> In the model, I also assume  $\phi_i(t)$  will decline at a rate of the autonomous energy efficient improvement,  $AEEI_i(t)$ , and that  $AEEI_i(t)$  is decreasing over time at a constant rate of  $AEEI_i^d$ .<sup>11</sup> Let  $\overline{AEEI_i}$  denote the initial AEEI for region  $i$ , so that  $AEEI_i(t)$  can be determined by

$$AEEI_i(t) = \overline{AEEI_i} \exp(-AEEI_i^d t) \quad (9)$$

and hence the emission/output ratio is gradually decreasing over time at the rate of  $AEEI_i(t)$ :

$$\phi_i(t) = \overline{\phi}_i AEEI_i(t) \quad (10)$$

Based on the assumptions of a single-commodity output and no international good trading, the regional expenditure constraint becomes

$$Q_i(t) = C_i(t) + I_i(t) \quad (11)$$

where  $C_i(t)$  is the consumption of region  $i$  at time period  $t$ , and  $I_i(t)$  is the investment of region  $i$  at time period  $t$ .

The level of consumption per capita is calculated by

$$c_i(t) = C_i(t) / L_i(t) \quad (12)$$

The evolution of capital over time is determined by the equation of motion

$$K_i(t+1) = K_i(t)(1 - \delta_i) + I_i(t) \quad (13)$$

where  $\delta_i$  is the annual depreciation rate of the capital stock for region  $i$  at time period  $t$  and  $\delta_i$  is assumed to be constant over time.

## 2.3 Climate Change Model

The climate system is a very sophisticated process, so most climate simulation models, such as Coupled Global Circulation Models (hereafter CGCMs) of the atmosphere and ocean, tend to be very complex and highly nonlinear. A number of sophisticated climate models based on CGCMs have been developed and well validated against the present climate (IPCC, 1996a). However, smaller-scale models are often able to provide a sufficiently close approximation (Peck and Teisberg, 1992). Therefore,

a highly simplified climate change model is used in this study to reflect the global climate system and transform an increase in CO<sub>2</sub> emissions into incremental atmospheric CO<sub>2</sub> concentrations and, in turn, temperature increases.

There are three major components included in the climate model: carbon cycle function, potential warming function, and actual temperature increase function. The carbon cycle function translates anthropogenic CO<sub>2</sub> emissions into atmospheric CO<sub>2</sub> concentrations. In this study, I apply the simple carbon cycle function estimated by Maier-Reimer and Hasslmann (1987) which approximates the behavior of a complex ocean-carbon cycle model:

$$CC_t = (1 - d)CC_{t-1} + \sigma GE_t \quad (14)$$

where  $CC_t$  is the atmospheric CO<sub>2</sub> concentrations at time period  $t$ ,  $d$  is the depreciation rate of the atmospheric CO<sub>2</sub> concentrations,  $GE_t$  is the new global CO<sub>2</sub> emissions at time period  $t$  and equals  $\sum_i E_i(t)$ , and  $\sigma$  is the conversion parameter used to convert emissions (measured in giga tons of carbon, hereafter GtC) into concentrations (measured in parts per million, hereafter ppm). The value of  $\sigma$  is about 0.47 ppm/GtC (IPCC, 1996a).

Based on Maier-Reimer and Hasslmann's carbon cycle function, some studies divide new carbon emissions into five classes, each with a different atmospheric lifetime ranging from two years to infinity (Peck and Teisberg, 1994; Tol, 1997). Then, the total atmospheric CO<sub>2</sub> concentration is calculated by taking the sum of atmospheric CO<sub>2</sub> concentrations across these five classes. To simplify the carbon cycle function, I adopt a simple approximation proposed by Peck and Teisberg (1992) that half of each year's new emissions are immediately eliminated from the atmosphere, while the other half remains in the atmosphere forever. The simplified carbon cycle function (equation (14)) becomes

$$CC_t = CC_{t-1} + \sigma(0.5GE_t) \quad (14a)$$

In this study, I use a logarithmic function estimated by Peck and Teisberg (1992) to calculate the potential global warming due to anthropogenic CO<sub>2</sub> emissions:

$$T_t = A \ln(CC_t) - B \quad (15)$$

where  $T_t$  is the potential temperature increase relative to preindustrial level at time period  $t$ , and  $A$  and  $B$  are constant parameters.

Assuming that climate sensitivity equals 2.5°C, the above parameters are fitted such that a potential temperature increase is zero at the preindustrial concentration (280 ppm), and a potential temperature increase is 2.5°C at 700 ppm, as forecasted by the IS92a scenario of IPCC (1996a). Under this assumption, the fitted values of the parameters are  $A = 2.7283$  and  $B = 15.3739$ .

Some recent studies simulate the actual temperature increase with coupled atmosphere-ocean models (Nordhaus and Yang, 1996; Tol, 1996). Instead of using such complex models, I use a simple lagged adjustment function estimated by Peck and Teisberg (1992) to calculate the actual temperature increase in each period.

$$T_t^A = T_{t-1}^A + 0.02(T_{t-1} - T_{t-1}^A) + T_{1990}^A \quad (16)$$

where  $T_t^A$  is the actual temperature increase relative to preindustrial levels at time period  $t$ ,  $T_{1990}^A$  is the actual temperature increase relative to preindustrial levels in the year 1990.

The change in actual temperature increase relative to preindustrial levels in a given period is 2% of the difference between the potential and actual temperature increase in the proceeding period. According to the IS92a scenario of IPCC (1996a), the actual temperature increase in the year 1990 relative to preindustrial levels is about 0.45°C.

It is well known that global warming damages depend on the level of actual temperature increase and that the relationship between temperature increase and damage is nonlinear. As a result, I use a quadratic function to evaluate global warming damages

$$\theta_i(t) = \omega_i (T_i^A / A)^2 \quad (17)$$

where  $\theta_i(t)$  is the global warming damage of region  $i$  at time period  $t$  and is measured as the percentage of output,  $\omega_i$  is the percentage loss of output for region  $i$  when the actual temperature increases reaches  $2.5^\circ\text{C}$ , and  $A$  (which equals  $2.5^\circ\text{C}$ ) is the actual temperature increases caused by an equivalent atmospheric  $\text{CO}_2$  concentration of 700 ppm.

Taking the global warming damages into account, the output that is available for consumption and investment becomes

$$Y_i(t) = (1 - \theta_i(t))Q_i(t) \quad (18)$$

where  $Y_i(t)$  is the net output for region  $i$  at time period  $t$ .

Then the expenditure constraint function (equation (11)) is modified as

$$Y_i(t) = C_i(t) + I_i(t) \quad (11a)$$

## 2.4 Mitigation Cost

The marginal abatement cost functions used in this study have the same functional forms as the logarithmic functions used in the Rose-Stevens model (itself patterned after Nordhaus, 1993)

$$MC_i(t) = \ln(1 - R_i(t)) / a_i \quad (19)$$

where  $MC_i(t)$  is the marginal abatement cost of CO<sub>2</sub> emissions for region  $i$  at time period  $t$ ,  $R_i(t)$  is the percentage emission reduction compared to business as usual emission levels for region  $i$  at time period  $t$ , and  $a_i$  is the constant slope parameter for region  $i$  at time period  $t$ .

The corresponding total abatement costs can be obtained by integrating equation (19) with respect to  $R_i(t)$

$$TC_i(t) = \overline{E}_i(t)[(1 - R_i(t))\ln(1 - R_i(t)) + R_i(t)] / \alpha_i \quad (20)$$

where  $TC_i(t)$  is the total abatement costs, and  $\overline{E}_i(t)$  is the business as usual emission levels for region  $i$  at time period  $t$ .

Therefore, the net output function (equation (18)) is modified as

$$Y_i(t) = (1 - \theta_i(t))Q_i(t) - TC_i(t) \quad (18a)$$

## 2.5 Permit Trading Scenarios

In this study, five step-wise simulations, starting from a no-trading simulation to a fully global-trading simulation, are performed to evaluate the dynamic efficiency of tradeable permits. When the exchange of emission permits between regions is allowed, as in the “flexibility mechanisms” of the Kyoto Protocol (Rose and Stevens, 2001), the expenditure constraint (equation (11a)) needs to be modified to take into account the revenue or cost from permit trading

$$Y_i(t) + PP_i(t)[\hat{E}_i(t) - E_i(t)] = C_i(t) + I_i(t) \quad (11b)$$

where  $PP_i(t)$  is the permit price at time period  $t$ , and  $\hat{E}_i(t)$  is the emission cap for region  $i$  at time period  $t$ . At time period  $t$ , region  $i$  is a permit seller if

$[\hat{E}_i(t) - E_i(t)]$  is positive and is a permit buyer if  $[\hat{E}_i(t) - E_i(t)]$  is negative.

The emission constraints and permit trading rules corresponding to alternative trading scenarios are discussed below (Stevens and Rose, 2002).

### 2.5.1 No-Trading between Annex B Countries

This case assumes Kyoto-based emission quotas for Annex B countries and no emission abatement requirements for non-Annex B countries. When permit trading is not allowed, the emission constraint for each Annex B country over the whole time horizon is

$$[\hat{E}_j(t) \geq E_j(t)] \quad (j = \text{Annex B countries}) \quad (21)$$

### 2.5.2 Trading between Annex B Countries

This case assumes Kyoto-based emission quotas for Annex B countries and no emission abatement requirements for non-Annex B countries. When permit trading is allowed, the emission constraint (equation (21)) for each Annex B country is modified as

$$[\hat{E}_j(t) + P_i(t) \geq E_j(t)] \quad (j = \text{Annex B countries}) \quad (21a)$$

where  $P_i(t)$  is the amount of emission permit purchased ( $P_i(t) > 0$ ) or sold ( $P_i(t) < 0$ ) for region  $i$  at time period  $t$ .

Two emission permit trading scenarios are performed in this case:

#### 2.5.2.1 Interregional Permit Trading among Annex B Countries

When interregional permit trading is allowed, the permit trading constraint at each time period is

$$\sum_j P_j(t) = 0 \quad (j = \text{Annex B countries}) \quad (22)$$

At each time period, the marginal abatement cost of each Annex B country will equal to the market-clearing permit price.

### 2.5.2.2 Interregional and Interperiod Permit Trading

When both interregional and interperiod permit trading are allowed, the permit trading constraint over the whole time horizon is

$$\sum_j \sum_t P_j(t) = 0 \quad (j = \text{Annex B countries}) \quad (23)$$

In equilibrium, the discounted present value of the market-clearing permit price at any time period will be the same.

### 2.5.3 International Trading between Annex B and Non-Annex B Countries

This case assumes Kyoto-based emission quotas for Annex B countries and the initial permit allocations for non-Annex B countries equal to their business as usual emission levels, the so-called No-Harm rule.<sup>12</sup> When the exchange of emission permits is allowed among all regions, two emission permit trading scenarios are also performed in this case:

#### 2.5.3.1 Interregional Permit Trading

The global permit trading constraint at each time period is

$$\sum_i P_i(t) = 0 \quad (24)$$

In equilibrium, the marginal abatement cost for each region will equal to the global market-clearing permit price at any given period.

### 2.5.3.2 Interregional and Interperiod Permit Trading

When both interregional and interperiod permit trading is allowed among all regions, the global permit trading constraint over the whole time horizon becomes

$$\sum_i \sum_t P_j(t) = 0 \quad (25)$$

At equilibrium, the discounted present value of the global market-clearing permit price at any time period will be the same.

## III. Socioeconomic Data and Parameter Calibrations

In this study, the global economy is divided into 17 countries/regions with a relatively disaggregated grouping for Asian countries: Africa, Australia/New Zealand, Canada, China, Eastern Europe, the Former Soviet Union, Hong Kong, India, Japan, Latin America, Middle East, South Asia, Singapore, South Korea, Taiwan, the United States, and Western Europe. 2000 is selected as the base year to perform alternative policy simulations. The simulation time horizon is from 2000 to 2100, and the model operates in periods of 5 years. All flow variables in the model are reported as flows per year, and stocks are measured at the beginning of each time period. A brief discussion of the base-year database and calibrations of key parameters used in the marginal abatement cost functions and global warming damage functions are present below.

Table 1 shows the basic socioeconomic and CO<sub>2</sub> emissions data for each country/region in the base year 2000. Columns 1 to 4 of Table 1 present the Gross Domestic Product (hereafter GDP) and population for each country/region. According to historical real GDP data (International Monetary Fund, 2004) and long-term annual real GDP growth rates forecasted by Energy Information Administration (hereafter EIA) (2004), developing countries' shares of world's GDP will nearly double by the year 2020. Among Asian countries, China and India are projected to have relatively higher growth rates of GDP than other countries during the period 2010 to 2035. All developed countries' projected population growth rates are lower than 1.0% per year. Most developing countries' projected population growth rates are below 1.5 % per year, except Africa (1.9% per year) and the Middle East (1.8% per year).

Columns 5 and 6 of Table 1 show CO<sub>2</sub> emissions for each country/region in the year 1990 and the base year 2000. The projected annual growth rates of CO<sub>2</sub> emissions for developed and developing countries are obtained from EIA (2004). The total CO<sub>2</sub> emissions of developing countries are about 30% of global CO<sub>2</sub> emissions in the year 1990. Because of the relatively high economic growth and population growth rates, total CO<sub>2</sub> emissions of developing countries will reach about 50% of global CO<sub>2</sub> emissions in the year 2035. Among developing countries, China will remain as the biggest CO<sub>2</sub> emitter for several decades. Africa, China, India, Latin America, Middle East, and South Asia are projected to have a CO<sub>2</sub> emission growth rate higher than 2.0% mainly because of their relatively high economic growth rates and population growth rates.

In the base year 2000, except for Eastern Europe and the Former Soviet Union (hereafter FSU), all countries/regions underwent a positive increase in CO<sub>2</sub> emissions relative to their 1990 emission levels. Because of its economic recession in the early 1990s, CO<sub>2</sub> emissions of the FSU had decreased from 1.036 GtC in the year 1990 to 0.638 GtC in the year 2000.



In the year 1990, the average CO<sub>2</sub>/GDP intensity for non-Annex B countries is about 0.5, which is nearly 2.5 times that for Annex B countries. In general, the average CO<sub>2</sub>/GDP intensity for non-Annex B countries is projected to fall in the future, mainly as a consequence of changes in economic structure and improvements in energy efficiency. Also, the average CO<sub>2</sub>/GDP intensity for Annex B countries is projected to fall gradually in the future, primarily as a consequence of the increasing share of natural gas in electricity generation.

Column 8 shows the CO<sub>2</sub> emission mitigation percentages of 1990 levels committed by Annex B countries in the Kyoto Protocol. Based on the projected business-as-usual CO<sub>2</sub> emissions, Column 9 of Table 1 presents the required CO<sub>2</sub> emission mitigation percentages for Annex B countries to achieve their Kyoto Protocol commitments in the year 2010. In the absence of CO<sub>2</sub> emission abatement commitments from developing countries, the global CO<sub>2</sub> mitigation percentage will be nearly 7.0% by the year 2010.

Several different methodologies have been used to estimate CO<sub>2</sub> emission mitigation costs. They can be grouped into two major categories: bottom-up and top-down models.<sup>13</sup> In general, bottom-up studies are based on engineering studies of detail options for energy efficiency improvements or renewable energy technologies and tend to conclude that emission reductions are either cheap or even beneficial.<sup>14</sup> On the other hand, top-down studies are based on more integrated economic analyses, which incorporate energy supply and demand in the context of a model of the entire economy. These studies tend to conclude that emission reductions are costly and the scope for cost-effective energy savings is limited (Hourcade and Robinson, 1996).

Ideally, I could apply econometric methods to estimate the value of  $a_i$  in equation (19); however, statistical estimation of  $a_i$  is not feasible because there are too few mitigation cost estimates currently available for most countries/regions. Therefore, I obtain the point estimates of  $a_i$  by substituting the available data of a specific CO<sub>2</sub>

percentage reduction ( $R_i$ ) and its corresponding marginal abatement cost ( $MC_i$ ) into equation (19).

Most studies on the assessment of climate change impacts have concentrated on the benchmark case of potential global warming damage from a doubling of atmospheric CO<sub>2</sub> concentrations (2xCO<sub>2</sub>), which is estimated to incur damage in the order of 1% to 2% of world GDP (Cline, 1992; Fankhauser, 1994; Nordhaus and Boyer, 1999; Tol, 1995). One important characteristic of global warming is that damage is not caused by the flow of greenhouse gas emissions, but by their accumulation in the atmosphere. Consequently, one ton of CO<sub>2</sub> emissions has an impact not only in the period of emission, but over several time periods. The marginal damage of an additional ton of CO<sub>2</sub> emissions is thus a discounted sum of future incremental damages. Current available estimates of marginal damages range from about \$5 to \$125 per ton of carbon, with most estimates at the lower end of this range.

The estimation of the percent of damages in terms of GDP ( $\omega_i$ ) at the time when the global mean temperature increase reaches 2.5°C are obtained directly from Fankhauser (1994) and Tol (1995). It is obvious that developed countries have a lower percentage loss of GDP than developing countries because it is relatively easier for the former to adapt to global warming.<sup>15</sup> Most estimates of global warming damages for developed countries range from 1% to 2% of GDP. With relatively high vulnerability to global warming, the estimates of global warming damages for developing countries range from a minimum of 2.8% of GDP to a maximum of 8.7% of GDP.

## IV. Global Simulation Results

The computations for the model use a nonlinear programming solver PATH in the General Algebraic Modeling System (hereafter GAMS). In order to compare the effectiveness of alternative CO<sub>2</sub> mitigation policies, three types of policy simulations

are conducted: 1) Business as Usual (hereafter BAU) – individual countries/regions maximize their own welfare without taking any mitigation policy to slow down global warming; 2) Global optimal policy – the optimal time path of CO<sub>2</sub> emissions for each individual countries/regions is determined when global social welfare is maximized; and 3) Emission limitations (Kyoto Protocol) – Annex B countries committed to stabilize their CO<sub>2</sub> emissions below certain levels without emission permits trading among Annex B countries.

Table 2 summarizes the simulation results for the mitigation policies described above. BAU GDP levels for each country/region are listed in the first column of Table 2. Global net GDP is the sum of the discounted present value of net GDP across regions over the time period 2010-2100. Net GDP equals gross GDP minus mitigation costs plus environmental benefits from reduced global warming damages. The difference of net GDP from BAU is calculated by subtracting the global net GDP of a simulation case from the global net GDP of the BAU policy. Compared to the BAU policy, the global optimal policy generates a global net GDP gain of \$0.802 trillion, while the Kyoto Protocol policy incurs a global net GDP loss of \$16.275 trillion. This means that the Kyoto Protocol policy could be very costly and inefficient. Theoretically, one would expect emission limitation policies like the Kyoto Protocol to incur a significant global net GDP loss when emission limitations are set without explicit regard to mitigation costs and global warming damages. Our simulation results show that this negative economic impact is likely to be further exaggerated when permit trading among countries is not possible.

Analysis of the impacts of the global optimal mitigation policy on individual countries/regions shows that most countries/regions, except four Annex B countries (the FSU, Japan, the US, and Western Europe), are better off compared to the BAU policy (see columns 2 and 3 of Table 2). Non-Annex B countries are the major gainers from the relatively lower global warming damage compared to the BAU policy, while Annex B countries are the major contributors to the CO<sub>2</sub> emission reductions. Among



non-Annex B countries, Africa, Latin America, and South Asia receive significant net GDP gains because of their high vulnerability to global warming. Japan, the US, and Western Europe are the major contributors to the reduction of CO<sub>2</sub> emissions to slow down the pace of global warming. All of them incur significant net GDP losses because their mitigation costs are much higher than their gains from modest global warming. In the case of the Kyoto Protocol, all non-Annex B countries would benefit from lower global warming damages without limiting their own CO<sub>2</sub> emissions. In contrast, all Annex B countries incur high mitigation costs and net GDP losses in order to fulfill their emission reduction commitments.

Figure 2 shows the projected global CO<sub>2</sub> emissions for different policies. The projected BAU global CO<sub>2</sub> emissions would reach 21.2 GtC in 2100, which is about 0.01% less than that forecasted by the IPCC IS92a scenario (IPCC, 1996a). In the global optimal case, emissions are stabilized at 18.5 GtC in 2100. In the Kyoto Protocol case, emissions increase gradually relative to the BAU case and reach 20.3 GtC in 2100. The time path of CO<sub>2</sub> emissions projected by the Kyoto Protocol policy is above the one projected by the global optimal policy and the deviation between them is gradually increasing over time. This implies further emission reduction commitments will be needed to stabilize global CO<sub>2</sub> emissions at the optimal level.

Figure 3 shows the effects of different policies on the time path of global mean temperature increase. Although, both global optimal and Kyoto Protocol policies could only reduce the global mean temperature increase by 0.47 °C and 0.21 °C, respectively, relative to the BAU policy in 2100, substantial reductions are likely to occur after 2100. Therefore, both global optimal and Kyoto Protocol policies will slow down the pace of global warming significantly in the long term.

In order to explore the dynamic efficiency of tradeable permits under the Kyoto Protocol, five step-wise simulations are conducted in this study. In each case, I assume Kyoto-based emission quotas are applied to Annex B countries and there are no emission abatement requirements for non-Annex B countries.





- Case 1. No permit trading (same as the Kyoto Protocol policy above)
- Case 2. Interregional permit trading among Annex B countries
- Case 3. Interregional and interperiod permit trading among Annex B countries
- Case 4. Interregional permit trading among all countries
- Case 5. Interregional and interperiod permit trading among all countries

Table 3 summarizes the simulation results for alternative permit trading scenarios described above. Incremental net GDP increases shows the extent to which the net GDP losses could be further reduced with more flexible trading scenarios. Cumulative net GDP increases represents the cost savings for alternative permit trading scenarios relative to a no permit trading case.<sup>16</sup>

#### 4.1 Interregional Permit Trading Among Annex B Countries

Column 1 repeats the same simulation results for the Kyoto Protocol policy described above. Column 2 shows the simulation results of Case 2. Under interregional cooperation, all Annex B countries are much better off and achieve a cost-effective distribution of burdens across Annex B countries at any given period. The FSU and Eastern Europe are the biggest permit sellers and they receive a net GDP gain of \$72 billion and \$25 billion, respectively. Japan, the US, and Western Europe are the biggest permit buyers and, through interregional permit trading, they effectively reduce their net GDP loss by \$893 billion, \$3,694 billion, and \$3,837 billion, respectively. Overall, this refinement increases global net GDP by \$8,614 billion compared to Case 1. In this case, the global permit price is \$58.24 per ton of carbon in 2010, and then increases gradually to \$151.08 per ton of carbon in 2100. The required emission reduction percentage for all Annex B countries is increasing over time in order to meet their Kyoto commitments (a fixed commitment in the context of economic growth translates into growing percentage emission reduction requirements). This explains why marginal abatement costs and market-clearing permit prices are increasing over time.



## 4.2 Interregional and Interperiod Permit Trading among Annex B Countries

Column 3 presents the simulation results of Case 3. In this case, each Annex B country can trade permits with one another and are also allowed to allocate their usage of permits freely through time. As the results show, all Annex B countries are better off compared to Case 2 due to the increase in the flexibility of trading. The FSU and Eastern Europe are the major permit sellers and receive a net GDP gain of \$342 billion and \$130 billion, respectively. Japan, the US, and Western Europe are the major permit buyers and receive a net GDP gain of \$991 billion, \$5,313 billion, and \$4,257 billion, respectively. Overall, when interperiod permit trading is allowed, it further reduces global net GDP loss by \$2,468 billion relative to Case 2. In this case, a single global permit price is solved when the present value of selling or buying an additional unit of a permit at any given period is equalized. The global permit price is \$115.58 per ton of carbon through the entire time horizon 2010-2100. However, one would expect this high permit price to decrease dramatically when relatively low cost emission permits are available from non-Annex B countries.

## 4.3 Interregional Permit Trading among All Countries

Column 4 shows simulation results of Case 4. By including developing countries into interregional permit trading, not only Annex B countries but also non-Annex B countries receive substantial net GDP gains compared to Case 2, in which permit trading is allowed only among Annex B countries. This implies non-Annex B countries would be able to enhance their economic growth by participating in the regional permit trading when their emission limitations are set at their business-as-usual emission levels (No-Harm rule). Compared to Case 2, Japan, the US, and Western Europe further reduce their net GDP loss by \$294 billion, \$1,657 billion, and \$951 billion, respectively, because of relatively low costs of permit purchases. Most

non-Annex B countries offer relatively cheap permits to potential permit buyers and benefit from selling permits as long as their mitigation costs are lower than permit prices. Countries/regions with high carbon density, high projected BAU CO<sub>2</sub> emissions, and low marginal abatement costs, such as, China, Latin America, the Middle East, and South Asia, are the major permit sellers among non-Annex B countries. The participation of non-Annex B countries in interregional permit trading would further reduce global net GDP loss by \$3,573 billion compared to Case 3. In this case, the global permit price is \$14.49 per ton of carbon in 2010, and then increases gradually to \$32.90 per ton of carbon in 2100, which is much lower than the permit prices in Cases 2 and 3.

#### 4.4 Interregional and Interperiod Permit Trading among all Countries

Column 5 presents the simulation results of Case 5. When interperiod permit trading is allowed among all countries, all Annex B countries are better off as compared to Case 4. For example, net GDP losses for Japan, the US, and Western Europe are decreased by \$98 billion, \$488 billion, and \$353 billion, respectively. In this case, all non-Annex B countries, except the Asian Tigers, are worse off compared to Case 4. This is because the amount of permits sold by the Asian Tigers is decreased due to increased sales of permits by other non-Annex B countries when interperiod permit trading is allowed. The incremental global net GDP increase for this case is \$1,251 billion. Therefore, from the perspective of global society, Case 5 is the most cost-effective permit trading scenario. In this case, the permit price is \$23.13 per ton of carbon through the entire time horizon 2010-2100.

## V. Impacts on Asian Countries

Figure 4 summarizes simulation results of alternative permit trading scenarios for Asian countries. In spite of different trading rules, regions with relative high vulnerability to global warming, such as China, India, and South Asia, receive significant net GDP gains across all five cases because of lower global warming damages projected by the Kyoto Protocol policy compared to the BAU policy. Furthermore, with relative high carbon intensity and low marginal abatement cost, these three regions could further enhance their economic growth by selling emission permits to Annex B countries in Cases 4 and 5. On the other hand, countries such as the Asian Tigers that have relatively low vulnerability to global warming, low carbon intensity, and high marginal abatement cost incur relatively lower net GDP gains from permit trading. Among the Asian Tigers, South Korea is the only one that receives significant net GDP gains through permit trading. In terms of the cost-effectiveness of permit trading, Japan is the biggest gainer from permit trading. Compared to Case 1, Japan effectively reduces its net GDP loss by \$893 billion in Case 2 and by \$1,285 billion in Case 5.

To further analyze the efficiency of different policies, Table 4 presents the breakdown of mitigation costs, environmental benefits, and net GDP changes compared to the BAU case of selected policy simulations for Asian countries. In the global optimal case, the reduced damages from slowing global warming, i.e., environmental benefits, ranges from \$16 to \$1,261 billion depending on the scale of economy and the vulnerability of climate change of individual countries. For example, China, India and South Asia receive much higher environmental benefits than the Asian Tigers due to their bigger economies and higher vulnerability towards climate change. Since the annual emission reduction levels for Case 4 are fixed at the same levels defined in Case 1, they produce the same amount of





environmental benefits. The environmental benefits are only about one third of those in the global optimal case due to the less strict global emission reduction target established in the Kyoto Protocol. With respect to mitigation costs, Japan incurs much higher mitigation costs in Case 1 than in the global optimal case. This is also true for other Annex B countries in general. However, through interregional permit trading, Japan could effectively reduce its mitigation costs by more than 80%. In terms of permit trading, China, South Asia, and India are the biggest permit sellers, with about 40%, 32%, and 23% of the total permits sold by non-Annex B Asian countries, respectively. Among Asian Tigers, South Korea is the biggest permit seller and receives \$36 billion from selling permits. Non-Annex B Asian countries as a whole account for more than 60% of total permits traded in Case 4. Therefore, from a global perspective, participation of non-Annex B Asian countries, especially China, India, and South Asia, in permit trading would be needed to effectively reduce the global net GDP loss incurred in the Kyoto Protocol policy.

Columns 4 and 12 of Table 4 show the benefit-cost ratios for the global optimal case and Case 4, respectively. In the global optimal case, the benefit-cost ratio is calculated as the ratio of environmental benefits to mitigation costs. It ranges from 0.85 to 4.95, which implies the global optimal case is a cost-effective policy for most Asian countries. In Case 4, the benefit-cost ratio is calculated by dividing the sum of environmental benefits and permit trading revenues by the sum of mitigation costs and permit trading costs. The benefit-cost ratios for non-Annex B Asian countries are all greater than 1.0, which indicates that participation in regional permit trading is a cost-effective policy for them. However, in contrast to non-Annex B Asian countries, the Kyoto Protocol is an inefficient policy for Japan even with the flexibility of trading permits with other countries.

To further analyze the impacts of different mitigation policies on the long-run economic growth for Asian countries, Figure 5 shows the average percentage



change of the net GDP gain or loss for selected policies compared to the BAU case. In general, both global optimal GHG emission reduction and Kyoto Protocol cases have modest impacts on the long-run economic growth of Asian countries mainly because the difference between these two cases and BAU case is rather small in terms of the time path of global warming. In the global optimal case, the impact ranges from -0.02% to 0.61%, depending mainly on the extent of the region's vulnerability to global warming. For example, the impact for China, India, and South Asia is bigger than 0.20%, while the impact for the Asian Tigers is only about 0.10%. Compared to the global optimal case, the Kyoto Protocol case has relatively lower impacts on most Asian countries, except Japan, due to the less strict mitigation goal established in the Kyoto protocol. The negative impact of the mitigation burdens of the Kyoto Protocol on Japan is about 0.55%. A comparison of the Kyoto Protocol and Case 4 shows that permit trading also only has modest impacts on the long-run economic growth of Asian countries. Among Asian countries, China, India, and South Asia attain significant improvement of their economic growth through permit trading. The net gains from selling permits generate about the same percentage of positive impacts on economic growth of the Asian Tigers. On the other hand, interregional permit trading effectively reduces the negative impacts of the Kyoto Protocol on Japan significantly, from 0.55% to 0.15%.

## VI. Conclusion

Under the Kyoto Protocol emission mitigation policy, my step-wise permit trading simulations show that net GDP loss for the group of Annex B countries could be effectively reduced by \$13,096 billion (see Table 3). About 85% of this cost savings could be achieved by permit trading among Annex B countries mainly because the FSU and Eastern Europe would be able to provide a large amount of

cheap emission permits to other Annex B countries. This seems to suggest the relatively less important role of non-Annex B countries in the attempt to reduce the total mitigation cost of Annex B countries. However, the shape of the global mean temperature increase curve shows that the rate of global warming will increase over time. Therefore, one would expect the temperature increase to be higher and faster beyond the year 2100. Global warming damages beyond the year 2100 would increase much faster than I observed in the simulation period 2010-2100 due to the nonlinear nature of the damage function I assumed in the model. In order to slow down the pace of global warming, it is important to create favorable incentives for non-Annex B countries to participate the Kyoto Protocol as well as new Protocol in the future. This will not only reduce their individual future global warming damages significantly because of their high vulnerability to global warming, but also benefit the entire global society in the sustainable development perspective.

I conclude with two observations regarding the impacts of different policies on Asian countries. First, in either the global optimal case or the Kyoto Protocol case, the impacts on the economic growth of Asian countries are modest. In the global optimal case, the impacts resulting from the reduced global warming damages range from -0.02% to 0.61%. Among Asian countries, China, India, and South Asia obtain relatively higher improvements of their economic growth because they are more vulnerable to global warming and thereby receive higher environmental benefits from slowing global warming than other Asian countries. In the Kyoto Protocol case, the impacts resulting from the reduced global warming damages range from 0.04% to 0.18% for non-Annex B Asian countries. They are only about half of the measured impacts in the global optimal case because of relatively low environmental benefits generated in the Kyoto Protocol case. Japan incurs a negative impact of 0.33% of its economic growth rate due to its commitments to cut carbon emissions in the Kyoto Protocol.

Second, when permit trading is allowed between all countries (Cases 4 and 5), the impacts of different permit trading scenarios on the economic growth of Asian countries are similar because the sizes of the permit trading market are about the same (see columns 4 and 5 of Table 3). In addition to the environmental benefits received in the Kyoto Protocol case, China, India, and South Asia could further improve their economic growth by selling permits to other countries. The magnitude of this positive effect ranges from 0.15% to 0.31% of their economic growth rate. Similar to other Annex B countries, Japan could reduce the negative impacts of emission mitigations on its economic growth effectively through buying permits from other countries.

## Endnotes

1. See IPCC (1996b, 2001a, 2001b, 2007b) for an overview of climate change impact analysis and mitigation cost studies.
2. In general, the major components of a dynamic optimal growth model include an output/cost function, a capital accumulation function, and a detailed energy industry model. A climate change model consists mainly of a carbon cycle function, a temperature change function, and a damage function.
3. Four core scenarios are typically simulated: business as usual, no cooperation, full Annex B cooperation, and full global cooperation.
4. Another key issue in a system of tradeable permits is the initial allocation of emission permits. Given the large total value of emission permits, significant transfers among countries would occur based on different emission allocation criteria (Rose and Stevens, 1993; Rose *et al.*, 1998). Therefore, it is important that the negotiated permit allocation criteria be equitable. However, given the fixed mitigation requirements of the Kyoto Protocol, alternative allocations are not considered here, and hence equity issues are not addressed.
5. The actual cost savings from trade in emissions are likely to be less than the theoretical savings shown in our analysis because our model does not include the various measurement, verification, trading, and enforcement costs that would characterize any real trading system.
6. The net abatement cost equals total emission mitigation costs plus the cost of permits purchased, minus the value of permits sold.
7. With the same level of consumption per capita, this assumption implies that the marginal utility of consumption per capita is higher for the current generation than for the future generation. The pure rate of time preference is one of the key factors that determine the optimal growth path (Nordhaus, 2009; Stern, 2007). It will be different between different regions for the same generation or among different generations for the same region. A broad survey on this field of study shows that a pure rate of time preference between 1% and 8% was often used in the economics of climate change. Because it involves very high uncertainties about the time-path of the pure rate of time preference for each individual country/region, I assume a medium-level pure rate of time preference (4%) for all countries/regions and that it remains constant across different generations.
8. The capital value share parameter is calibrated by using the value of output, capital input, and labor input data obtained from the Global Trade Analysis Project (hereafter GTAP) database (Center for Global Trade Analysis, 2009).

9. The value of  $\eta_i(t)$  and  $\eta_i^d$  are calibrated numerically such that the GDP growth rate in the business as usual case (base case) for each region is consistent with the projected long-term GDP growth rate estimated by EIA's reference case (EIA, 2004).
10. Without a separate energy sector in our model, the effects of the price changes of fossil fuels due to emissions control and permit trading on Annex B countries as well as non-Annex B countries are not characterized in the simulations. In general, energy-importing and energy-intensive non-Annex B countries would benefit from lower fossil fuel prices due to carbon emissions control.
11. The value of  $AEEI_i(t)$  and  $AEEI_i^d(t)$  are calibrated numerically such that the regional and global CO<sub>2</sub> emissions in the business as usual case (base case) are consistent with the IS92a scenario estimated by IPCC (1996a).
12. The No-Harm rule in this case means that non-Annex B countries are granted emission permits equal to their annual base case emissions and allowed to trade these permits internationally (Edmonds *et al.*, 1995; Rose and Stevens, 1998).
13. The major reason that bottom-up studies often arrive at more optimistic results of CO<sub>2</sub> emission reductions than top-down studies is that they typically neglect some implementation barriers and the interactions between the energy sector and the rest of the economy. On the other hand, top-down studies typically include relatively little detail on energy consumption and available technologies, compared with bottom-up studies (Repetto and Austin, 1997). In recent years, some top-down studies have incorporated detailed energy sectors to reflect more options for energy savings and fuel-switching possibilities (Kurosawa *et al.*, 1999).
14. This often refers to "no regrets" measures that have emission reduction benefits, such as reduced energy input costs and reduced emissions of local/regional pollutants, equal to or exceed their emission reduction costs.
15. As the IPCC Working Group II pointed out in their Fourth Assessment Report (IPCC, 2007a), there remains a lot of uncertainties relating to the assessment of global climate change damages. However, it is widely recognized that developed countries will incur a lower percentage loss of GDP than developing countries due to global climate change. Therefore, the simulation results will change significantly as long as the relative vulnerability to global climate change for developed and developing countries remains unchanged in the future.
16. When only interregional permit trading is allowed, which implies annual net permit trading (overall purchases minus sales) equals 0, the time path of global CO<sub>2</sub> emissions and global mean temperature increase is the same as the one projected in the no permit trading case. When interperiod permit trading is allowed, which implies annual net permit trading may not equal 0 in any given period, the time path of global CO<sub>2</sub> emissions and global mean

temperature increase will be different from the one projected in the no permit trading case (Kling and Rubin, 1997; Stevens and Rose, 2002). However, our simulation results show that this difference is relatively small because the amount of annual net permit trading is only a small portion of annual global emissions. Therefore, we consider the net GDP difference between different alternative permit trading scenarios are mainly from increases in economic growth due to reductions in net abatement costs and/or revenues from selling permits.

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# 京都議定書下二氧化碳排放權交易對 亞洲地區國家之影響

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本文以整合氣候變遷與經濟成長之動態最適化模型來模擬分析在不同的二氧化碳排放權交易制度下，當亞洲地區國家參與京都議定書二氧化碳排放減量協議時，對其經濟成長可能造成之影響。研究結果發現：(1) 比較僅允許區域間及同時允許區域間與跨時期排放權交易之情境模擬結果發現，此兩種排放權交易制度對亞洲地區國家經濟成長所造成之衝擊並無顯著之差別；(2) 在各種不同排放權交易制度下，中國大陸、印度及東南亞地區國家，將可藉由參與排放權交易所得之收益，提升其經濟成長；(3) 在允許區域間或同時允許區域間與跨時期排放權交易之情境模擬下，日本將可透過排放權交易，大幅減低二氧化碳排放減量對其經濟成長可能造成之負面衝擊。

**關鍵詞：**氣候變遷，經濟成長，二氧化碳排放權交易

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