GLOBAL WARMING: CONTRIBUTION BY AND IMPACTS ON CHINA -- AN APPLICATION OF THE DICE MODEL

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STATEMENT OF RESEARCH INTEREST

The Issue of Global Warming and Uncertainties Concerning Climate Change

Uncertainty has always been a factor that complicates the decision making process. Unfortunately, many decisions have to be made before there is certainty. Whether or not there should be policies regulating economic activities to reduce the potential damages of the possible climate change caused by global warming is a very good example of decision making with uncertainty.

There are many aspects of uncertainty concerning global warming. A slightly higher mean temperature on the earth's surface has been observed over the past several decades; however, it has not been confirmed whether this is just normal long-run variation or evidence of greenhouse warming. Many scientists believe that the earth is indeed on a warming trend as a result of the accumulation of greenhouse gases in the atmosphere, but so far not much is known for sure about what damages this warming and related climate change will do to the ecosystem of this planet or to human society. Much more information is needed to help us understand the issue better and to help us determine what should be done, how to do it, and how much it will cost to carry out the appropriate actions.

On the global level, because of the uncertainties, whether action is or is not taken today against the possibility of global climate change involves a risk of losing in terms of economic well-being. If we believe global warming is very likely to occur, and, when it does, that the damages will be tremendous, action now to prevent further climate change may be justified. Then, if climate change does not occur as we believe it would, we would be responding to a problem that does not exist after all. The efforts to avoid damages would incur costs in terms of abatement investments (consumption foregone) or slower growth in the production of normal goods and services (foregone GDP). When global warming does not occur as predicted (or, in the similar sense, if the impacts of global climate change are not as much as what we think they would be), these costs would produce net economic losses since there would be no benefits in terms of avoided damages (or the investments made according to our understanding today would not produce benefits as large as expected, which makes the investment worth less than we assume today).

On the other hand, if we do cling to the argument that there is currently no reliable evidence of global climate change therefore carry on economic activities as usual, we then take the risk of running into the consequences of the problem head on when global climate change does occur sometime in the future, without having sufficient knowledge and experience, or most importantly, without having sufficient time to deal with the consequences of the problem in a satisfactory way. The damages caused by climate change due to or related to global warming may turn out to be much larger than the costs of actions taken.

Because global warming and climate change would affect almost every country in the world, efforts to limit global climate change require worldwide cooperation. However, since the role of each country in causing climate change is different, and the consequences of global warming will not be felt equally by all countries or regions, any attempt to responsibility-sharing will be fruitless until there is a full assessment of how each country will be affected by the consequences of global climate change and how much it would cost each country to participate in abatement actions. As long as each country is a sovereign state, national interest will always be a powerful force affecting international cooperation. In fact, without better understanding and assessment of benefits and costs of abatement actions by a country, there would be incomplete commitment toward policy cooperation.

These uncertainties underscore the need for further research in all aspects of the issue. Many questions involving global warming and climate change as well as their economic consequences have to be answered to an acceptable degree before decisions concerning what should be done, and by whom, will be made.

Researches on Global Warming and Economic Consequences

Scientists have learned that carbon dioxide and other trace gases have accumulated in the atmosphere. These trace gases admit short-wave radiation from the sun to the earth but block the infrared long-wave radiation from the earth to outer space. The thermal radiation kept in the lower atmosphere by the trace gases warms up the earth and makes it more suitable for life to exist. This process is called the "greenhouse effect", and the trace gases are called greenhouse gases (GHGs).

Scientists also know that human activities such as fossil fuel (e.g. coal and oil) burning and deforestation increase the emissions of GHGs. When emitted, some portion of the GHGs accumulates and remains in the atmosphere for many years (from decades to more than a century, depending on the gas). This raises the concern that if we keep emitting GHGs the way we have been, excessive amounts of GHGs will accumulate in the atmosphere, and as a result, the mean temperature on the earth's surface will rise (global warming). Together with other climate change caused by or related to a warmer globe, there may be serious impacts on many aspects of daily living.

While scientists are working to find out more about our climatic system and the interactions between its different components, economists are working on other aspects of the issue. Some economists have focused on estimating the costs of emission reductions, others on the benefits from emission control actions. Progress in the policy arena requires the integration of the work of scientists and economists.

Fortunately, economists have developed models that capture some of the relationships between GHG emissions, climate change, and their economic consequences. These models are categorized as emission-climate-economic consequences models. These models typically incorporate a traditional economic sector that is linked to a simple climate factor or a very much simplified climate model. Their purpose is to capture the economic consequences of the climate change and to estimate the costs of abatement actions directed toward GHGs.

One of the most widely-cited models is the Dynamic Integrated model of Climate and the Economy (DICE) developed by Nordhaus. This is a general equilibrium optimization model which maximizes the present value of the world consumption over time subject to certain economic, emissions, and climate constraints. Nordhaus uses this model to evaluate the economic impacts of several policy options in terms of GDP foregone and changes in consumption levels. Based on these impacts, policies are ranked and suggestions for policy actions are made.

Most of the emission-climate-economic consequences models have several things in common. For one, they all agree that China will play a vital role in causing global warming, and that it will be a key player in curbing the problem. Yet, there has been no explicit and exclusive estimates of impacts done for China only, from the perspective of China's national interest, to provide the foundation for China's policy making concerning options for limiting global climate change. In fact, the focus of the estimates usually is a developed country or countries (most likely the USA or the OECD members, perhaps because of data availability and funding for research institutes in these countries). These estimates are often generalized and extended to a global scale based on the results for the developed country or countries. There have been few systematic quantitative estimates for developing countries, however, even though it is commonly agreed that they will contribute more to the problem given their large potential for future growth. The damages from climate change may also be more severe for developing countries both because climate-sensitive sector constitutes a larger share of their economies and they lack resources and technology to adapt to changing climate.

Importance of China's Role in the Issue

There are several reasons why China warrants special focus in the issue of global warming. China is known as a country with a long history and a huge population. Its current population of more than 1.2 billion makes up one-fifth of the world total. Recently, China has experienced rapid economic growth. This combination of a large population and rapidly increasing purchasing power promises enormous market potential. China is also a country with a rich endowment of natural resources, among them, coal reserves. According to the 1994 Statistical Yearbook of China, as of 1993, China had a coal reserve of more than 1000 billion tons, the largest in the world. In fact, since 1989, China has been the number one coal producer in the world. By 1995, coal production reached 1.28 billion tons. Still, the demand for energy outweighs the country's production capacity. With the expected fast growth of the economy in the next several decades and the relative lack of other major energy sources, the coal industry will be an important drive of the entire national economy. The high demand for power and energy will keep coal production at high levels, which will result in more carbon dioxide emissions.

With its large population, rapid economic growth, high and increasing demand for energy, and especially its rich endowment of coal reserves, China will play a critical part in the success (or failure) of the worldwide effort to limit global warming and climate change. China may have to make a special effort and commitment toward limiting carbon dioxide emissions if the global effort is to succeed.

China has much to lose if global climate change does occur as predicted. Global warming is expected to raise sea levels which is associated with land loss, species loss, increased flooding, water contamination, and loss of structures and recreational facilities in coastal cities and ports. China's most advanced economic areas are almost all along its coast. Coastal provinces like Guangdong and Fujian are pioneers in the economic takeoff over the past couple of decades and they host many Special Economic Zones that are designed as local or national economic driving forces. Hainan, the newly established province to attract foreign investment, is in fact a tiny island. Coastal cities are usually heavily populated and have already been experiencing difficulties in water supply and other living conditions.

Shanghai is a good example. In 1980, this city, with 0.06 percent of the national land area and 1.2 percent of the country's population, created more than 12 percent of the national industrial product and accounted for one-third of the central government's financial expenditures. In 1993, it contributed almost 5 percent of China's GDP. Shanghai is also the first consideration of many foreign investors when they try to locate new ventures in China. On the other hand, high population density, large scale industrial activities, and heavy construction have also created environmental problems for this crowded place. Housing , transportation and water supply have always presented serious problems. Heavy reliance on ground water has caused a severe land sinking problem. If increases in the sea level were added to all the problems it has now, Shanghai would face heavy losses in capital investment, infrastructure, and wetlands.

If the sea level does rise as a result of global warming, the large population in the coastal areas may have to relocate. The cost of migration could be tremendous. Various impacts of climate change, such as deterioration of living standards, shortages in water supply, and losses of valuable lands that are important in grain production (the Yangtze and Pearl deltas, for example) and for other purposes (i.e., wetlands) may develop into social chaos that would damage the ground for a stable society.

China was isolated from the rest of the world for almost 30 years. Instead of developing the economy and providing a good living environment and a higher living standard for its people, the country was engaged in one political "mass movement" after another, consumed by an ideological struggle. When China was finally able to break down the walls surrounding itself and face the world, it was stunned by the gap between the economic situation it was in and the living standard people in other countries enjoyed. There was a sense of urgency to catch up with the rest of the world. All of a sudden, economic development became the number one priority for everyone. Current government policies are in favor of anything that can stimulate economic growth, ordinary people are impatient to get rich, the temptations from material commodities are hard to resist, and no one ever feels rich enough soon enough. This feverish pursuit of economic well-being is so overwhelming that any attempt to slow it down is bound to be tough and time consuming.

In the middle of the rush for economic growth, at least two points have to be made firm and clear for China to be convinced to commit to the cause of limiting global warming and climate change. First, China would suffer huge losses if global warming does occur, and second, the potential losses caused by climate change would be larger than the cost of slower economic growth. The degree to which it is optimal for China to reduce GHG emissions by slowing economic growth in the coming decades depends upon the relative size of these losses.

Research Interest and Dissertation Structure

This dissertation will modify and apply the original DICE model developed by Nordhaus to the special case of China. Using the DICE-CHN model (the modified DICE model for China), the optimal path of GHG emissions by China will be estimated, given the objective of maximizing China's utility function only, rather than the common global social well-being. Since the DICE model has the built-in capacity of variable control, several policy options will be explored and the impacts of the various policy options on emission reductions, output, and consumption will be simulated. These results will provide information needed for policy evaluation and cost-benefit assessment. Based on this information we will evaluate policy options from the perspective of China's national interest.

The DICE-CHN model will be run in two different scenarios. The first scenario will reflect popular proposals to limit world total emissions, for example, to the 1990 world total emissions level, 80% of the 1990 world total emissions level, or the 1995 world total emissions level. The second scenario studies the cases when China takes no emission reductions or follows optimal emissions path. In each scenario, the focus will be on China's income levels and the optimal emission reduction rates as compared to the no control case. A comparison of results across the cases will determine the best policy option for China.

A sensitivity analysis will be done to determine the impacts on the results when different values are assigned to some of the key parameters, such as the rate of social time preference, the damage function coefficient, and the decline rate of the emission-output ratio. The model results may also be sensitive to the values of other parameters which warrants future studies and estimates.

The dissertation starts in Chapter I with information about scientific findings on the possibility of global warming and climate change, debates over immediate actions, and the potential damages that may be caused by global climate change, and an introduction of emission control methods suggested by other researches.

A general description of China is provided in Chapter II, to show the role of China in causing global warming and climate change and how vulnerable it is to the potential damages of global climate change. Included in this chapter are information concerning its geographical location and climate types, natural resources, population, and environmental limitations, current and potential economic growth and development, energy demand, energy production, and the role of its energy sector in global carbon emissions.

Chapter III contains a literature review which focuses on comparing and contrasting the basic structures of various emission-climate-economic consequences models. The original DICE model is introduced in this chapter. Modifications of that model will be detailed in Chapter IV, together with the estimates of the model's parameters.

A summary of the model results from DICE-CHN is presented in Chapter IV, with the focus on impacts of various policy options on China's income and consumption levels, and optimal emission reduction rates by China under various scenarios.

A sensitivity analysis in Chapter V determines the impacts on the model of changing assumptions about the values of some key parameters.

The final chapter discusses the policy implications of the findings, the strength and weakness of the approach, and suggestions for future research.

CHAPTER I

BACKGROUND INFORMATION ON GLOBAL WARMING

Origin of Concern: Scientific Findings on Global Warming

Scientists believe that there are at least five key factors that affect the climate of the earth: the slower-acting factors including the earth's orbital movements around the sun and the expansion and retreat of the polar ice caps, and the faster-acting factors such as atmospheric dust, feedbacks due to water vapor, clouds and snow, and the concentrations of GHGs in the atmosphere. Each of these factors operates on a very different time scale. The earth's climatic system is thus a complex outcome determined by complicated interactions between the atmosphere, oceans, ice-caps, living things (plants, animals, human beings, etc.), and even rocks and sediment. This complexity makes it extremely difficult to predict with high confidence the changes in the climatic system.

The methods applied in today's climatic change predictions are combinations of historical observations and theoretical calculations. In recent years, scientists have made tremendous progress with both of these techniques. Still, the unknown factors governing the climatic system are too much for the predictions to be accurate at very high confidence levels.

Researchers are now able to get information on millions of years of the earth's climate history. By studying ice-cores and sediment-cores, scientists can determine, among other things, the temperature on the earth and the carbon dioxide content of the air at different times. These researches confirm that the carbon dioxide content of the atmosphere and the air temperature on the earth are closely related; warmer periods are associated with high carbon dioxide content, and there is usually less carbon dioxide in the air when the world is cool. In the interglacial (warmer) periods, the carbon dioxide content averages around 280 part per million (ppm), or, 0.028 percent of the air in the atmosphere is carbon dioxide, while in the glacial (cooler) periods, the average goes down to 210 ppm, and may even fall to 180 ppm (Leggett, 1990, p. 19).

Table 1.1 on page 13 shows several "warm" periods on the earth, with the temperatures and carbon dioxide concentrations at each time compared to today's observations. These records make scientists believe that, while changes in the way the earth orbits the sun switches the planet between glacial periods and interglacial periods, the orbital parameters alone are not strong enough to explain the rapidity and magnitude of the switches seen in the ice-cores and sediment-cores. There has to be other factors that amplify the speed and magnitude of the changes, and the GHGs accumulated in the atmosphere is believed to be one of the most important factors.

The mere existence of GHGs in the atmosphere and the greenhouse effect are themselves not worrisome. In fact, it is the very existence of the GHGs and the greenhouse effect that brings the mean temperature on the earth's surface to a currently comfortable 15° C. Without the GHGs in the atmosphere, that temperature would be about 35° C lower than it is, which would make the earth much less habitable for human and other life. What worries the scientists is the fact that, because of human activities, GHGs have been accumulating in the atmosphere at a pace that is unprecedented in the 10,000 years of human development. They fear that a large amount of GHGs accumulated in the atmosphere over a short period of time

Table 1.1 Warmer Periods on the Earth

Years Ago	Temperatures Compared to Today	CO_2 Concentration in the Atmosphere	CO_2 Concentration Compared to 1989
140 - 66 million (dinosaur age)	10 - 15° C higher	1410 - 2820 ppm	4 - 8 times higher
4.3 - 3.3 million (Pliocene)	3 - 4° C higher	450 ppm	1.3 times higher
125,000 (mid point) (Eemian)	2° C higher	280 - 300 ppm	82%
6,000 - 5,000 (Holocene)	1° C higher	270 - 280 ppm	80%

Sources: National Academy of Sciences, 1991, p.87.
Leggett, 1990, P. 28.
Note: Modern mean temperature is 15° C, and CO_2 concentration in the atmosphere, as of 1989, was 353 ppm.

may cause irreversible changes in the climatic system and damages to the ecosystem of the earth and to many aspects of human life.

Among the GHGs, carbon dioxide is believed to be the largest contributor to total radiative forcing (the factors that perturb the balance between the solar energy absorbed by the earth and the radiation emitted to space from the earth). According to the International Panel on Climate Change (IPCC) report in 1990, methane contributes about 15 percent to total radiative forcing, and the contribution of nitrous oxide is only 6 percent. Chlorofluorocarbon (CFCs) were previously thought to contribute about 24 percent to total radiative forcing, but new findings suggest that CFCs' share may be much smaller since the build-up of CFCs removes lower ozone, another greenhouse gas, thereby offsetting the greenhouse effect caused by CFCs themselves. It is estimated that carbon dioxide has historically contributed at least two-thirds to 80 percent of total radiative forcing, and this fraction is expected to be maintained in the future.

The major sources of carbon dioxide emissions due to human activities are the burning of fossil fuels and deforestation. IPCC (1990) reports that the carbon dioxide content in the atmosphere before industrialization was about 280 ppm, or the equivalent of 570 Gts (gagitons, or billion tons) of carbon. Since 1860, human activities have added more than 175 Gts of carbon to the atmosphere, resulting in a carbon dioxide content of 315 ppm in 1958 and 353 ppm in 1989. Using climate models, scientists predict that a carbon dioxide content of twice the preindustrialization level will result in a 1.5-4.5° C increase in the earth's mean surface temperature, with the best guess at 2.5° C. The doubling of carbon dioxide in the atmosphere is expected to be reached some time before the middle of the next century if nothing is done to slow the carbon dioxide emissions trend.

To make the situation more worrisome, there are still plenty of carbon-rich fossil fuel reserves available on the earth. Among all the fossil fuels, coal has the highest concentration of carbon. With modern technology, about 20,000 Gt of coal can be mined at costs that are considerably lower than the price levels required to suppress demand to the level that is necessary for the stabilization of global carbon dioxide emissions. Leggett (1990) estimated that about 5,000 to 10,000 Gt of carbon are contained in fossil fuel reserves, 4,000 Gt in proven coal and oil reserves, with at least 730 Gt in China alone. If the fossil fuel reserves are consumed at a speed that would exhaust them in 300 years, Sundquist (1990) projected that the atmosphere concentration of carbon dioxide would rise to 1600 ppm in 250 years (5.7 times the preindustrial level) and level out at about 700 ppm 50 years after that.

As noted, a high concentration of carbon dioxide in the air is accompanied usually by high temperatures on the earth. A higher mean temperature is only one consequence of high concentrations of carbon dioxide, however. Others are more serious changes in precipitation, and in the intensity and frequency of hurricanes and storms.

Some scientists believe that there are already early signs of global warming. According to the IPCC Report (1990), over the past 100 years or so, while the carbon dioxide content in the atmosphere has gone up by 25 percent (from 280 ppm to 353 ppm and accordingly the amount of carbon accumulation in the atmosphere increases from 570 Gts to 750 Gts), the average world surface temperature has risen by 0.3-0.6°

C, compared to a 2° C increase in the last 10,000 years. In the meanwhile, the global mean sea level has risen by about 15 cm, or about 1-2 mm per year. Precipitation patterns have also changed in some regions. The incidence of light and moderate rainfall has declined sharply, while one-day downpours of 2 inches or more have become increasingly common in the past two decades. The frequencies of severe floods and hurricanes have also increased, causing significant damages to property, crops and lives.

This evidence and the predictions from theoretical models have made many scientists and nonscientists believe that it is necessary and urgent for human beings to change their behavior in order not to destroy the very planet they live on. However, there are also many people who don't hold the same views on the issue. Although the evidence described above is consistent with the climate models' predictions of the changes due to increased GHG concentrations in the atmosphere, they are also within the boundary of natural variations. The available evidence is not strong enough to confirm that these events indeed are the results of greenhouse warming rather than natural variations. Given the likely magnitude of the potential costs of any action taken to reduce GHG emissions, many people are hesitant to advocate or to make immediate policy responses. Some suggest (as advocated by the U.S. government during the Bush administration) that it might be beneficial to wait another decade or so before we commit a large amount of resources to emission reduction related investments. Others believe that there are too many other obvious and serious environmental problems, and that we can much better utilize available resources solving these problems.

The key problem here is uncertainty. It is unlikely for people to be convinced that it is necessary and urgent to make a commitment to the cause of emission control or abatement without knowing clearly that, if we do not change our behavior now, the temperature will surely rise, climate change will surely come, and the change will surely cause severe damages to our lives.

While most people agree that there is much research concerning global climate change that needs to be done, some precautionary actions may be needed now to reduce the possibility of climate change before it is too late. Human lives may be too valuable to be put at unknown risk of irreversible damages, and so also may be the natural ecosystems associated with various plant and animal species.

Potential Impacts of Global Warming and Climate Change

When assessing the impacts of climate change on economic activities, the most commonly used benchmark is the doubling of carbon dioxide equivalent in the atmosphere relative to the preindustrial level. It is estimated by the IPCC that, when the doubling of carbon dioxide equivalent is reached, the global mean temperature on average would increase 1.5-4.5°C, with the best guess of 2.5°C. This would be a global mean surface temperature unprecedented in human history. By 1986, the carbon dioxide in the atmosphere was already 25 percent higher than the preindustrial level. The doubling of carbon dioxide in the atmosphere is expected to be reached before the middle of the next century.

It is expected that most of the warming would happen in the high latitudes, especially in the northern polar region. The northern polar surface temperature may increase 2-3 times more than the global average increase, which imposes a great threat of the melting of the ice sheet and ice caps in that region. Global warming may increase sea levels in two ways: through the thermal expansion of ocean water, and through the shrinking of ice caps and mountain glaciers. IPCC expects the sea level to rise about 65 cm from the current level by the year 2100 if no action is taken to abate GHG emissions. Warmer air increases evaporation, and a warmer atmosphere is able to hold more moisture longer, thus the frequency of heavy rainfall in very short period (i.e. one-day downpours of 2 inches or more) increases. Since the frequency of hurricanes is closely and exponentially related to the area of the ocean with a temperature over 26.8°C, when the oceans are warmer, more hurricanes are likely.

Taking into consideration the feedback processes of the climatic system, the effects of global warming may be even more serious. At higher temperatures, more methane (a GHG) will be released faster from the ocean sediments. Oceans may also not have as much capacity to absorb carbon dioxide when they become warmer. If the assumption of continuity is not true, climate changes may come in sudden jumps rather than gradual transitions, leaving little time for people to react or adapt. These surprises may be catastrophic and the damages significantly larger.

With business as usual, the emissions and accumulations of GHGs may cause a 5°C increase in global mean temperature by the end of the next century, which would mean a 0.8°C increase in the mean temperature per decade. At this speed, there may be extreme shifts in the temperature at high latitudes, more rain in the wet tropics, and a sea level rise of 1.5 meters by the middle of next century (World Resource Institute, 1990, p.15). Historically, a 5°C increase in the global mean temperature occurred

15,000 - 5,000 years ago and it was accompanied by a 100 meter rise in sea level, the migration of forest species over thousands of kilometers, radically altered habitats, species evolution and extinction, and other catastrophic environmental changes (Leggett, 1990, p.58).

A rise in the sea level would threaten low lying coastal areas and small islands. If the sea level rises as predicted by the IPCC, it would put millions of people and millions of square kilometers of land at risk. The most vulnerable areas would be the unprotected, densely populated and economically productive coastal regions of countries with poor financial and technological resources. Tourist beaches, cultural and historical sites, fishing centers and other areas of special value would all be at risk. Valuable wetlands and lowlands may be destroyed. Coastal structures may be damaged. Groundwater in the coastal areas would become more saline and coastal farming may face the triple threat of inundation, freshwater shortage, and salt damage. Warmer water and a resulting increase in humidity over the oceans might even encourage tropical cyclones, making damages caused by more frequent floods and storms even worse. Plant and animal species may suffer serious losses, along with damages to wetlands which are critical to biodiversity and to the life-cycles of many species.

Species losses may also happen during the poleward migration of forests, when tropical forests increase and temperate and boreal forests decline as a result of changes in temperature, precipitation, soil moisture, and heat stress (Leggett, 1990) . Changes that affect the forest industry would also affect the agricultural sector. Besides the damages from inundated farmland and saltier groundwater related to sea level rising, extreme whether events, shifting climate zones and changes in soil moisture may cause further losses in agriculture. Although some researchers suggest that the fertilization effect of carbon dioxide and longer growing seasons in the northern areas may increase agricultural production, the unfavorable changes in heat stress, soil moisture, and less time for plant development before maturity would reduce yields in many other regions. Also, the fertilization effect is more significant for the mid-latitude food staples, such as wheat, rice, and soy beans, but not so for low-latitude crops such as maize, sorghum, sugar-cane, millet, and many pasture and forage grasses. Poor soil in the north may also offset some of the benefit from the fertilization effect of the mid-latitude crops.

The fertilization effect would require ample water to be effective (Leggett, 1990). However, even without climate change, there have been increasingly serious problems with water supply in many areas. Demand for water increasingly exceeds local supplies in many regions. Water pollution and poor irrigation practices put even greater pressure on water resources. With global warming, precipitation is expected to rise in some areas and fall in others, but the evaporation rate would be higher and snow accumulation would be less everywhere. These would both result in a reduction in river run-off. Large variations in precipitation from year to year and an increase in extreme events such as droughts and floods would cause critical problems in the reliability of water sources. As the water supply is reduced, there may not be enough freshwater or groundwater suitable for household and agricultural use in some areas. Croplands, forests, and other ecosystems may be damaged. Falling water levels would also require adjustments in urban settlement, upgrading of water storage infrastructure, and the implementation of public policies on water usage and waste control.

Other economic sectors may also be affected. Tourism may decrease because of very high temperatures in the low latitude areas and warmer winters with less snow accumulation in the high latitude areas. Neither very hot days nor very heavy rains are favorable for the construction sector. The increase in demand for electricity for cooling is expected to exceed the reduction in the demand for electricity for heating, leading to a overall higher demand for and spending on energy. Serious stress may be put on urban structures such as reservoirs, storm sewers, canal controls, drainage systems, dams, etc.. Discomfort from the very hot and longer summers, in addition to sea level rising, may increase migration and increase pressure on capacity in the host areas. Longer and warmer summers may also increase heat-stress-related illness and other diseases caused by increased pollution.

Abatement Options and Policy Implications

With the knowledge that global warming is mainly caused by the increase in the emission and accumulation of GHGs in the atmosphere, the suggested abatement actions primarily focus on reduction of these emissions. The most cost-effective way to reduce emissions is by improving energy efficiency. Cline (1992) and others, estimate that GHG emissions may be reduced by about 20% of the 1990 level at zero cost through many engineering approaches. Window glazing, weather stripping, better insulation and more efficient cooling and heating systems could significantly reduce electricity use in residential and commercial buildings. Even replacing incandescent light bulbs with fluorescent bulbs saves significant lighting energy. More fuel-efficient car and airplane engines, together with mass transportation systems, car pooling and other means of transportation, could reduce energy demand and hence fossil fuel burning. Technological innovation and improvement and international information exchange could enable manufacturing industries to produce more goods per unit of energy used.

Although some of these approaches do suggest easy and inexpensive energy saving tips, such as weather stripping and car pooling, others may involve more complicated and high cost processes. Research and technology innovation are needed to develop and adopt many energy saving options, such as more efficient heating and cooling systems, fuel saving motor engines, and more energy efficient buildings. It would take even more effort and resources to find more efficient technologies for manufacturing processes.

Another way to reduce atmospheric GHG accumulations is to switch away from GHG emitting processes and products. The first step of the switch is to phase out CFC-11 and CFC-12, and replace them with safer CFCs. CFCs have many industrial uses, as blowing agents in packing materials and other plastic foams, as solvents for cleaning electronic circuits, and as the coolants in refrigerators and air-conditioners. CFCs account for smaller share than does carbon dioxide of the total GHG accumulations in the atmosphere. However, the radiative forcing per unit of mass change (molecule) from CFCs is 4,000-20,000 times more than carbon dioxide, and it stays in the atmosphere for 60-130 years (Cline, 1992). Another danger of CFCs is that they deplete the ozone layer and allow ultra violet rays to come close to the earth creating a great health risk. Since the 1987 Montreal Protocol, many new forms of CFCs have been developed and used in place of CFC-11 and CFC-12. These new forms of CFCs are believed to be easier to break down and they stay in the atmosphere for much shorter times, thus causing less serious damage to the ozone layer and trapping less radiation.

Given the large share of carbon dioxide in the accumulated GHGs, the major attention of fuel switching to reduce emissions is focused on replacing high carbon fuels with lower carbon fuels, such as replacing coal with oil or natural gas. To produce the same amount of energy, coal emits 1.5 times more carbon dioxide than oil and twice as much as natural gas. However, natural gas has a much higher concentration of methane, another GHG that traps more heat than carbon dioxide per unit. A even better or cleaner choice of fuel would be hydrogen, which may be obtained by passing electricity through water to split it into hydrogen and oxygen, although the current cost of producing hydrogen this way is too high, primarily because of high electricity costs (World Resources Institute, 1990).

Since fossil fuel burning is a major source of carbon dioxide and other GHG emissions, switching toward energy sources that do not involve fossil fuel burning would reduce emissions dramatically. Non-fossil-burning sources include hydro, solar, wind, biomass, and nuclear energy. With currently available technology, these energy sources may be used either to partially replace fossil fuels in some sectors, or to completely replace fossil fuels in some applications. Solar energy may be used for water heating, pool heating, space cooling or heating. It can also be used to provide heat for industrial processes, to meet building energy needs, and to generate electricity.

Biomass is another source of thermal energy. It can also be transferred into liquid or gaseous fuels. Wind, hydro, and nuclear energy can all be used to generate thermal capacity or electricity.

Deforestation is another major source of man-made carbon dioxide emissions. Therefore, to reduce emissions, deforestation could be reduced and/or afforestation could to be increased. These options constitute the forestation approach of emission abatement.

Also, since emissions are closely related to energy consumption, which in turn is directly related to the size of the population, it may be important to control population growth if emissions are to be limited. Uncontrolled population growth may also contribute to carbon dioxide emissions through human respiration. Zhuang and Zhai (1991) estimated that each person produces 0.07 tons of carbon per year. With a total world population of 5.7 billion in 1995, this source accounts for about 400 million tons of carbon per year.

Government policies can play an important role in many areas to provide incentives for emissions reduction. Policies can be directed to support and sponsor research in the development of better materials, techniques, and more efficient systems and technologies. Taxes and other regulations may be used to steer energy-users away from high GHG content fossil fuels to lower content fuels or to non-fossil fuel renewable energy sources. Population policy could also play a critical part in countering the problem.

CHAPTER II

CHINA OVERVIEW

General Introduction

Geography and Climate China is located in Eastern Asia, with the Pacific ocean on its east and southeast. It stretches in latitude from 3°N (Nan Sha Islands) to 54°N at the border of Helongjiang Province with the former Soviet Union. Even when the southern islands are not included, the mainland of the country still covers 36° in latitude, from 18°N at Hainan province northward, a stretch of about 4,400 km (2,750 miles). The west-east distance is about 4,500 km, starting from 71°E in longitude at the western most point between Xinjiang Autonomous Region and the former Soviet Union in the west, and going to 135°E at the Ussuri River bordering Helongjiang province and the former Soviet Union in the east (Manfred and Peng, 1988).

Because of its latitudinal position, China is mostly a mid-latitude subcontinent with mainly temperate climate and certain subtropical areas. However, the geographic location and landform of the country makes China's climate a much more complicated system.

Facing the Pacific ocean on the east while the other three sides are encompassed by continental Asia, China presents a sharply contrasting and highly diversified surface configuration. There are three natural steps determined by elevation. On the southwest side is the highest step known as the "roof of the earth", which consists of the gigantic Qinghai-Xizang (Tibetan) Plateau. Going north and eastward, the medium step in altitude is mainly formed by vast plateaus and enormous intra-

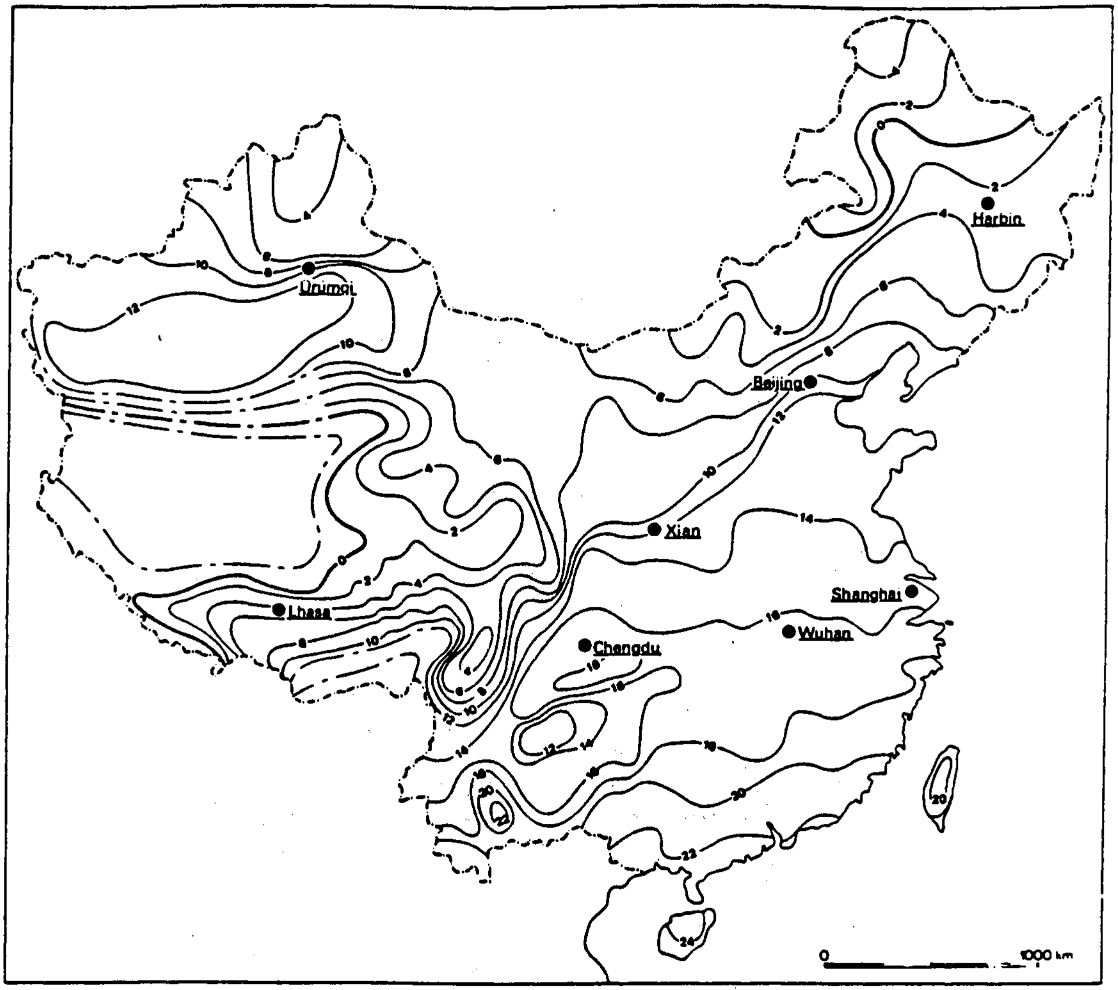
Mountain basins. The third step is on the east side with plains and lowlands and thousands of islands.

Combining the impacts of latitude, longitude, and landform on the climate system, China has a temperature distribution system that exhibits large variations with respect to both latitude and longitude (see figure 2.1 on page 27). The total annual precipitation distribution is also extremely variable, as shown in figure 2.2 (page 28). Following the northwest-southeast gradient, the country may be roughly divided into two parts, with the west part dry and warmer, and the east side relatively wet and cooler. However, the large variations in temperature and precipitation allow numerous combinations of the two, thus all five climate types defined by the Koppen classification system are present in China (see figure 2.3 on page 29 and table 2.1 on page 30 for details).

<u>Natural Resources, Population, and the Environment</u> China is ranked the second largest country in the world with a land area of more than 9.6 million square kilo-meters, and another 4.73 million km^2 of sea surface. The country is surpassed in size only by Canada after the disintegration of the former Soviet Union. With more than 5,400 islands, its island coastline comes to a total of 14,000 kilometers, while the length of its mainland shore extends more than 18,000 kilometers.

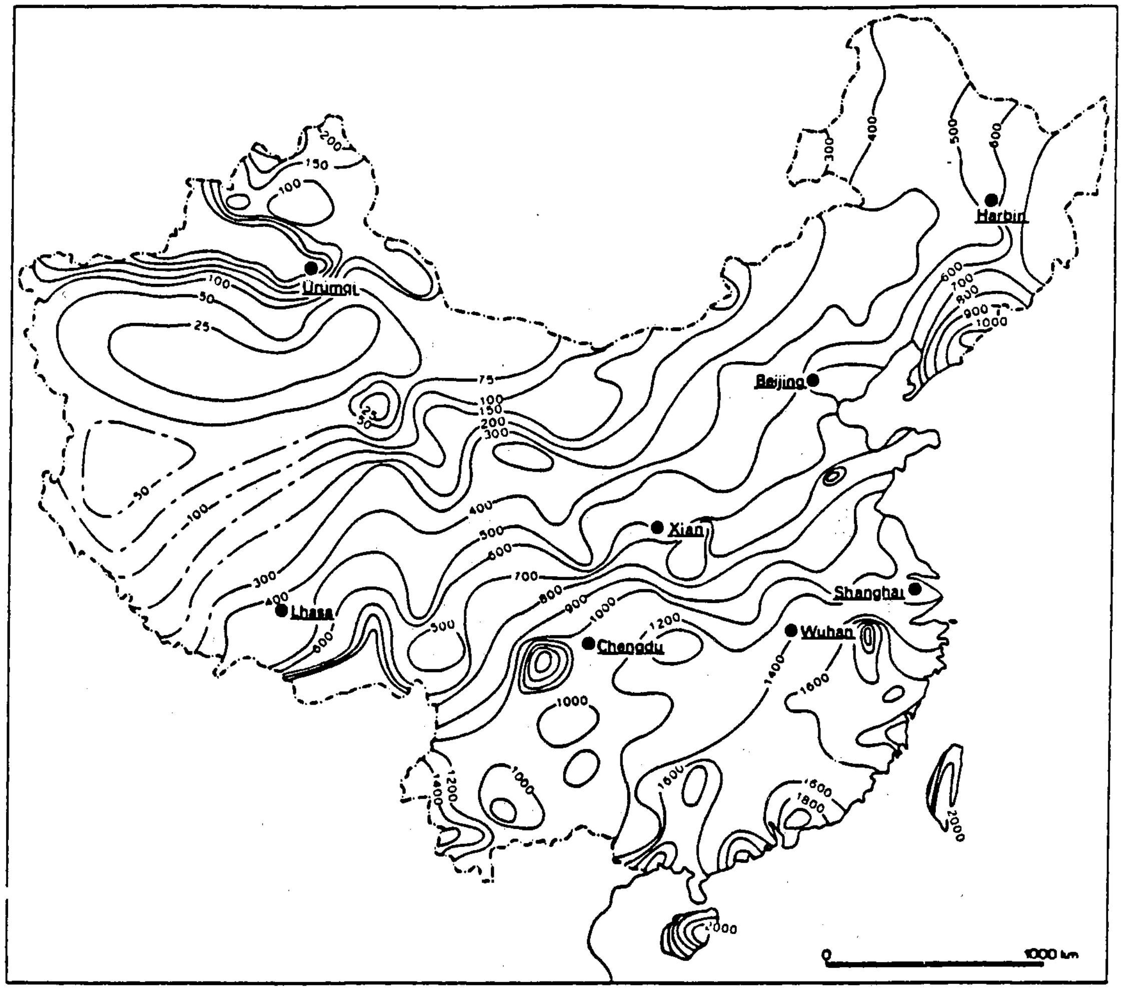
The official estimate of cultivated land in 1993 was 95.1 million hectare, which is less than 10 percent of its total land area. There is another 108 million hectare of undeveloped land, with about 35.35 million hectare arable. Forests cover 128.63 million hectare, or 13.4 percent of the country. Mountains and plateaus with elevation of 1000 meters and above make up 60 percent of the total area of the country. The

Figure 2.1 Mean Annual Air Temperature Distribution of China



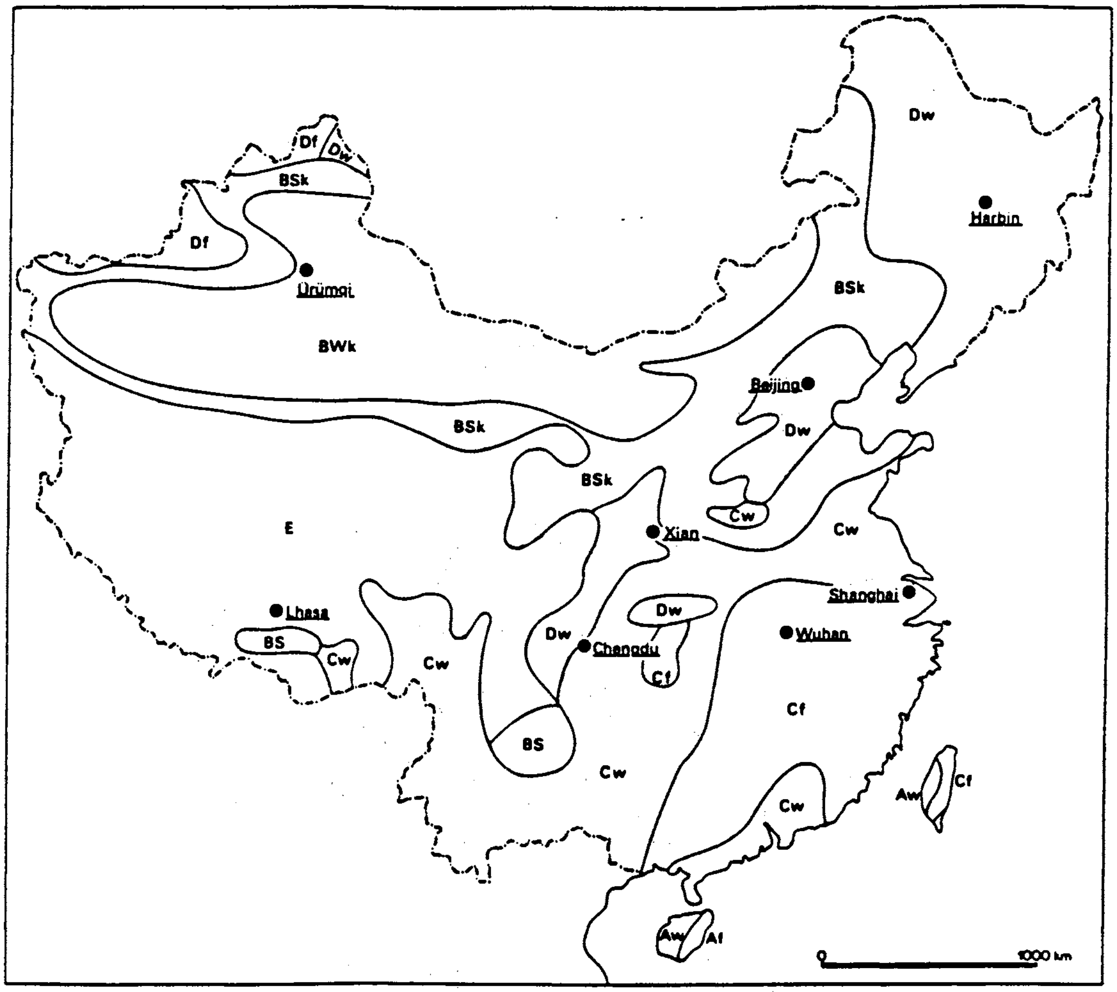
Source: Manfred and Peng, 1988, p. 78.

Figure 2.2 Mean Annual Precipitation Distribution of China



Source: Manfred and Peng, 1988, p.140.

Figure 2.3 The Climate Division of China according to the Köppen Classification



Source: Manfred and Peng, 1988, p. 235.

Table 2.1 Koppen Climate Classification System

Letter	Symbol	Explanation
A		Average temperature of coolest month 18°C or higher
	f	Precipitation in driest month at least 60mm
	m	(100-r)/25 ≤ Precipitation in driest month < less than 60mm
	w	Precipitation in driest month less than (100 -r)/25
B		70% or more annual precipitation falls in the warmer 6 months (April to September in the northern hemisphere) and r/10 less than 2t+28
		70% or more annual precipitation falls in the cooler 6 months (October to March in the northern hemisphere) and r/10 less than 2t
		Neither half of the year with more than 70% annual precipitation and r/10 less than 2t+14
	W	r less than one half of the upper limit of applicable requirement
	S	for B
		r less than upper limit for B, but more than one half of that amount
C		Average temperature of warmest month greater than 10°C and of coldest month between 18° and 0°C
	s	precipitation in driest month of the summer half of the year less than one-tenth of the wettest summer month
	w	Precipitation in wettest month of the summer half of the year more than 10 times of driest month of winter half
	f	Precipitation does not meet conditions of either s or w
D		Average temperature of warmest month greater than 10°C and of coldest month 0°C or below
	s	Same as under C
	w	Same as under C
	f	Same as under C
E		Average temperature of warmest month below 10°C
	T	Average temperature of warmest month between 10° and 0°C
	F	Average temperature of warmest month 0°C or below

Source: Manfred and Peng, 1988, p. 234.
Note: In the formula, t is the average annual temperature in °C, the average annual precipitation is in mm.

country has more than 1000 billion tons of coal reserves, more than 48.7 billion tons of iron ore, and some amount of many other minerals. Surface water resource is estimated at a total of more than 2,800 billion cubic meters. (China Statistical Yearbook, 1994)

China has always been a populous country. During the first two decades of the People's Republic, population growth was astonishing. In 1949, the year of the establishment of the People's Republic, total population of the country was about 540 million. Although population control efforts started in the early 1970s and became very rigid in the late 1970s and early 1980s, the fast population growth in the decades of 1950s and 1960s led to the doubling of the already large population in just over three decades. By 1982, the country's population surpassed the 1 billion mark. Its current population of more than 1.2 billion makes up one fifth of the world's total. It is projected that by the year 2000, China's population will be more than 1.25 billion (see tables 2.2 and 2.3 on pages 32-33 for population statistics and projections).

Dividing the available resources by the huge population, per capita resources become trivial, especially in the case of energy. In 1992, annual per capita electricity consumption was 54.6 kwh, with annual per capita energy consumption of 133.4 kg of standard coal. Lu (1989) estimated that even with very fast economic growth, China's per capita energy consumption in 100 years would come to only 1/5 of the level enjoyed by people in the US today. In areas where coal is not abundantly available and hydropower is not reliable, people depend heavily on biomass to bring heat and light. Deforestation becomes a means of living. In the rural areas of Yunnan Province, as in other regions of china, during the dry seasons when hydro-power is not available,

Table 2.2 China's Population: millions

Selected Years	China's Population	
	Year-End Total	Natural Growth Rate
1952	574.82	20.00
1957	646.53	23.23
1962	672.95	26.99
1965	725.38	28.38
1970	829.92	25.83
1975	924.20	15.69
1978	962.59	12.00
1980	987.05	11.87
1983	1030.08	13.29
1984	1043.57	13.08
1985	1058.51	14.26
1986	1075.07	15.57
1987	1093.00	16.61
1988	1110.26	15.73
1989	1127.04	15.04
1990	1143.33	14.39
1991	1158.23	12.98
1992	1171.71	11.60
1993	1185.17	11.45
1994	1198.50	11.21
1995	1212.00	11.21

Source:
1994: People's Daily, Mar. 2, 1995.
1995: People's Daily, Jan. 3, 1996.
Rest: China Statistical Yearbook, 1994.

Table 2.3 Population Projections

Year	China			World		
	high	medium	low	high	medium	low
1995	1244.16	1238.32	1231.99	5782.60	5759.28	5731.30
2000	1327.10	1309.74	1290.76	6300.58	6228.25	6150.79
2005	1395.40	1361.83	1325.16	6828.91	6688.16	6540.67
2010	1456.17	1409.95	1355.61	7368.84	7149.50	6916.42
2015	1519.43	1458.44	1384.43	7927.80	7608.97	7270.62
2020	1583.89	1504.18	1407.22	8498.18	8049.92	7581.03
2025	1642.23	1539.76	1417.07	9079.69	8472.45	7851.92
2050		1.52		12.5	10.0	7.8
2100		1.41		19.2	11.2	6.0

Sources:

1. 1995-2025: in millions, *World Population Prospects, the 1992 Revision*, Department for Economics and Social Information and Policy Analysis, united Nations, 1993.
2. 2050-2150: in billions, McNicoll, 1992.

Note:

Assumptions for total fertility rates are: high: 2.5; medium: 2.06; and low: 1.70.

people can afford only two hours of electricity every day. There are situations when people are rich enough to buy refrigerators and washers, only to use them as cabinets and storage spaces because of a shortage of electricity.[1]

With 20 percent of the world population, China has 7 percent of world's land area, and only 10 percent of it is cultivable. The increase in population has put serious pressure on food production, yet cultivated land area has been declining for various reasons, such as increased land needed for housing, industrial and urban expansion, extension of transportation links, construction of irrigation and power generation reservoirs, and natural degradation caused by heavy erosion, desertification and salinization.

North China has 60 percent of the country's area but only 20 percent of its water resources. Cities like Beijing, Tianjin, and some provincial capitals, experience serious water shortages all the time. Residential water supply may be rationed to different areas at different hours of the day even in provincial capital cities such as Taiyuan in Shanxi Province. Even in the southern part of the country where water is relatively abundant, underground water is constantly over-exploited. The water table of the entire region has dropped to 30, 40, in some areas even 70 meters below ground, causing land sinking problems, in cities such as Shanghai.[2]

The large and fast growing population, limited land and water resources, and the desperate need for energy results in activities that cause serious damage to the environment. Deforestation, the destruction of natural vegetation, the conversion of

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[1] Personal contact with Yunnan delegation on Biomass-To-Electricity project sponsored by Joint Institute of Energy and Environment, University of Tennessee at Knoxville.

[2] For detailed discussion of China's environment, see Vaclav Smil, *China's Environmental Crisis*, 1993, and *The Bad Earth* by the same author, 1983.

lakes to cultivable land, and other activities have led to "further damages of vegetation cover, destruction of ecosystems, erosion, aggravation of natural disasters, shortage of fuel, feed, and fertilizer, exacerbation of production problems, and difficulties in increasing food production".[3]

Economy, Energy, and Emissions Since the end of the 1970s, after China finally tore down the walls that had isolated the country from the rest of the world for about 30 years, the country has strived for fast growth in every sector of the economy. GDP has been increasing at double digit growth rates in most of the years since 1978, and it is expected to grow at a rate higher than most of the countries in the world for several decades to come (see table 2.4 on page 36 for growth rate of real GDP, agricultural, and industrial sectors).

Fast growth of population and the economy requires fast growth of the energy industry. Because of the limited availability of other energy resources and the abundance of coal reserves in the country, China's economic development plan is based on coal as the major energy source, and this situation will not change in the near future. China has the largest coal reserves in the world. Coal makes up more than 70 percent of its total energy production and consumption. Since 1989, China has been the number one coal producer in the world. Annual production that year passed the 1 billion tons milestone (see tables 2.5 and 2.6 on pages 37 and 38). Still, the demand for energy outweighs production capacity. Since 1993, China has been a net importer of oil, and oil imports have been rising.

[3] Fu, Lixue, et al, *Improving the Environment*, Academic Publisher, in Chinese, Beijing, 1989, p. 215.

Table 2.4 China's Economic Growth 1978-1994

year	GDP value	GDP growth rate (%)	Agriculture value	Agriculture share in GDP	Agriculture growth rate (%)	Industry value	Industry share in GDP	Industry growth rate (%)
1978	358.81	11.70	101.84	0.28	4.10	174.52	0.49	15.00
1980	447.00	7.90	135.94	0.30	-1.50	219.20	0.49	13.60
1983	578.70	10.20	196.08	0.34	8.30	264.62	0.46	10.40
1984	692.82	14.50	229.55	0.33	12.90	310.57	0.45	14.50
1985	852.74	12.90	254.16	0.30	1.80	386.66	0.45	18.60
1986	968.76	8.50	276.39	0.29	3.30	449.27	0.46	10.20
1987	1130.71	11.10	320.43	0.28	4.70	525.16	0.46	13.70
1988	1407.42	11.30	383.10	0.27	2.50	658.72	0.47	14.50
1989	1599.76	4.30	422.80	0.26	3.10	727.80	0.45	3.80
1990	1768.13	3.90	501.70	0.28	7.30	771.74	0.44	3.20
1991	2018.83	8.00	528.86	0.26	2.40	910.22	0.45	13.30
1992	2436.29	13.60	580.00	0.24	4.70	1166.95	0.48	21.80
1993	3128.03	13.40	665.00	0.21	4.00	1624.50	0.52	20.40
1994	4380.00	11.80	823.10	0.19	3.50	2125.90	0.49	17.40
1995	5773.30	10.20	1136.50	0.20	4.50	2827.40	0.50	13.60

Sources:
1994: People's Daily, March 2, 1995.
1995: People's Daily, March 5, 1996.
Rest: China Statistical Yearbook, 1994.

Notes:
1. Values are in billion yuans.
2. Growth rates are over preceding years based on comparable prices.
3. Share in GDP are calculated from data in values.

Table 2.5 China's Energy Sector: Production and Consumption

	Production			Consumption		
year	total	growth rate	elasticity	total	growth rate	elasticity
1978	627.70			571.44		
1979	645.62	2.9		585.88	2.5	
1980	637.35	- 1.3		602.75	2.9	
1981	632.27	- 0.8		594.47	- 1.4	
1982	667.78	5.6		620.67	4.4	
1983	712.70	6.7	0.66	660.40	6.4	0.63
1984	778.55	9.2	0.64	709.04	7.4	0.51
1985	855.46	9.9	0.77	766.82	8.1	0.63
1986	881.24	3.0	0.35	808.50	5.4	0.64
1987	912.66	3.6	0.32	866.32	7.2	0.64
1988	958.01	5.0	0.44	929.97	7.3	0.65
1989	1016.39	6.1	1.42	969.34	4.2	0.98
1990	1039.22	2.2	0.58	987.03	1.8	0.47
1991	1048.44	0.9	0.11	1037.83	5.1	0.64
1992	1072.56	2.3	0.17	1091.70	5.2	0.38
1993	1112.63	3.7	0.28	1117.68	2.4	0.18
1994	1120.00	4.7	0.40			

Source:
1994: People's Daily, March 2, 1995.
Rest: China Statistical Yearbook, 1994.

Notes:
1. Total energy production and consumption are in million tons of standard coal.
2. Growth rates are over preceding year.
3. Elasticity = annual growth rate in energy / annual growth rate in GDP.
4. 1994 uses 10 kwh = 1.229 tons of standard coal equivalent to convert electric power into SCE. Other years uses 10 kwh = 4.04 tons of SCE. (A 70% improvement in efficiency?)

Table 2.6 China's Energy Components

		Share in Energy Production				Share in Energy Consumption			
year	Raw Coal production	Raw Coal	Crude Oil	Natural Gas	Hydro-Power	Raw Coal	Crude Oil	Natural Gas	Hydro-Power
1978	618	70.3	23.7	2.9	3.1	70.7	22.7	3.2	3.4
1979	635	70.2	23.5	3	3.3	71.3	21.8	3.3	3.6
1980	620.15	69.4	23.8	3	3.8	72.2	20.7	3.1	4.0
1981	621.64	70.2	22.9	2.7	4.2	72.7	20.0	2.8	4.5
1982	666.33	71.3	21.8	2.4	4.5	73.7	18.9	2.5	4.9
1983	714.53	71.6	21.3	2.3	4.8	74.2	18.1	2.4	5.3
1984	789.23	72.4	21.0	2.1	4.5	75.3	17.4	2.4	4.9
1985	872.28	72.8	20.9	2.0	4.3	75.8	17.1	2.2	4.9
1986	894.04	72.4	21.2	2.1	4.3	75.8	17.2	2.3	4.7
1987	928.08	72.6	21.0	2.0	4.4	76.2	17.0	2.1	4.7
1988	979.88	73.1	20.4	2.0	4.5	76.2	17.0	2.1	4.7
1989	1054.14	74.1	19.3	2.0	4.6	76.0	17.1	2.0	4.9
1990	1079.88	74.2	19.0	2.0	4.8	76.2	16.6	2.1	5.1
1991	1087.41	74.1	19.2	2.0	4.7	76.1	17.1	2.0	4.8
1992	1116.38	74.3	18.9	2.0	4.8	75.7	17.5	1.9	4.9
1993		73.8	18.6	2.0	5.6	72.8	19.6	2.0	5.6

Sources:
China Statistical yearbook, 1993 and 1994.

Note:
Raw coal production is in million tons.
Others are in percentage.

As Lu (1991) pointed out, China has considerable potential to develop non-carbon sources, such as hydropower and nuclear energy. Currently, China is utilizing only 6 percent of its hydro potential, and there is no public hostility against nuclear energy development. However, there are various drawbacks and obstacles to exploiting these energy sources. For hydropower, the capital requirement is generally 50 percent higher than for fossil-fuel power plants, and there are more direct environmental impacts involved in the development of hydropower projects, such as the inundation of large areas of arable land, the relocation of millions of people, and the obvious disruption of the ecosystem. Besides, more than 25 percent of China's hydro sources are in the remote Tibet Plateau, and exploiting these resources would require the construction of long-distance ultra-high voltage transmission lines which require additional investment.

In the case of nuclear energy, an absolute safety guarantee is required if China is to rely on nuclear energy on a large scale. Given the magnitude of energy consumption, a small amount of nuclear energy will not solve the problem of GHG emissions from fossil fuel burning, but large scale nuclear energy imposes a serious safety threat to the public. Also, since nuclear power plants cost 50-100 percent more than conventional fossil-fuel plants, it is not economically sound to replace fossil-fuel plants with nuclear plants when there is a capital shortage.

Based on the availability of other energy sources and limitation on capital and technology, although China has the potential to exploit non-carbon energy sources, in the near future, coal will probably remain the major source of energy. Lu (1991) projects that , even by 2050, more than 50 percent of China's energy demand will continue to be satisfied by coal, with coal's share in energy consumption ranging from 50-70 percent depending on the scale of nuclear energy.

China already faces various serious environmental problems or, as Smil (1993) claimed, environmental crises, such as a shortage of water resources, desertification, soil erosion, acid rain, and air and water pollution. All of these problems are exacerbated by the huge population and large scale fossil fuel burning. The high demand for energy and the inefficient use of energy resources makes China one of the major contributors to world carbon emissions. Its carbon emissions in 1992 reached 728 million tons, which makes up about 12 percent of the world total (table 2.7 on page 41). The lack of other energy sources makes it impossible for China to reduce its GHG emissions significantly in the near future. Given the expected fast growth of the economy and a heavy dependence on coal as an energy source, China's carbon emissions are expected to increase still faster unless the country makes a commitment to carbon emission reductions through efficiency improvements and various policies.

Potential Impacts of Global Warming on China

The huge population of China is unevenly distributed, with over 90 percent of it occupying 43 percent of the land area concentrated in the southeast and east regions since a large part of the west and northwest is mountains or deserts that are less suitable for inhabitation. The agricultural sector still makes up about 20 percent of the economy and depends very much on natural climate conditions. In recent years, the coastal regions has been the site of the most advanced and fast growing economic zones, cities, ports, and other important facilities and structures.

Table 2.7 CO_2 Emissions from Fossil Fuel Burning and Cement Production: 1950-1992

	China		USA		world	
year	total	per capita	total	per capita	total	per capita
1950	21,713	0.04	696,069	4.57	1,638	0.65
1951	28,083	0.05	716,717	4.63	1,775	0.69
1952	35,396	0.06	697,920	4.44	1,803	0.69
1953	37,016	0.06	714,462	4.46	1,848	0.70
1954	44,508	0.08	680,491	4.18	1,871	0.69
1955	52,683	0.09	745,973	4.50	2,050	0.74
1956	59,702	0.10	781,912	4.63	2,185	0.78
1957	70,742	0.11	775,115	4.51	2,278	0.80
1958	145,012	0.23	750,766	4.29	2,338	0.80
1959	199,043	0.31	781,360	4.40	2,471	0.83
1960	215,259	0.33	799,544	4.43	2,586	0.86
1961	152,218	0.23	801,875	4.37	2,602	0.85
1962	121,402	0.18	831,489	4.46	2,708	0.86
1963	120,384	0.18	875,633	4.63	2,855	0.89
1964	120,432	0.17	912,912	4.76	3,016	0.92
1965	131,182	0.18	948,264	4.88	3,154	0.95
1966	144,066	0.20	999,673	5.08	3,314	0.97
1967	119,369	0.16	1,039,174	5.23	3,420	0.98
1968	129,195	0.17	1,080,969	5.38	3,596	1.01
1969	159,014	0.20	1,132,028	5.58	3,809	1.05
1970	211,607	0.26	1,165,477	5.68	4,084	1.10
1971	240,461	0.29	1,173,242	5.66	4,235	1.12
1972	255,513	0.30	1,227,346	5.86	4,403	1.14
1973	265,676	0.30	1,275,365	6.03	4,641	1.18
1974	270,967	0.30	1,231,098	5.76	4,649	1.16
1975	314,304	0.34	1,179,027	5.46	4,622	1.13
1976	328,181	0.35	1,262,745	5.78	4,889	1.18
1977	366,184	0.39	1,270,549	5.76	5,028	1.19
1978	407,398	0.43	1,293,945	5.80	5,076	1.18
1979	416,244	0.43	1,303,822	5.78	5,358	1.23
1980	406,440	0.42	1,236,297	5.43	5,290	1.19
1981	402,598	0.41	1,195,706	5.20	5,119	1.13
1982	431,541	0.43	1,139,230	4.91	5,080	1.10
1983	455,215	0.45	1,143,714	4.88	5,070	1.08
1984	494,786	0.48	1,184,227	5.01	5,242	1.10
1985	536,666	0.51	1,202,453	5.04	5,417	1.12
1986	564,391	0.53	1,224,096	5.09	5,609	1.14
1987	602,467	0.56	1,268,062	5.22	5,736	1.14
1988	646,047	0.59	1,340,168	5.47	5,961	1.17
1989	657,086	0.59	1,347,634	5.44	6,070	1.17
1990	660,726	0.58	1,322,212	5.29	6,099	1.15
1991	694,154	0.60	1,317,297	5.22	6,172	1.15
1992	728,161	0.62	1,332,246	5.22	6,097	1.12

Source: Gregg Marland, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

1. Carbon dioxide emissions for the world are expressed in million metric tons of carbon
2. Emissions for individual countries are expressed in thousand metric tons of carbon
3. Annual per capita estimates are expressed in metric tons of carbon per person

The IPCC projected that atmospheric carbon dioxide concentration will be double the preindustrial level by 2030, that the global average temperature by then will rise by 1-2°C, and that the sea level will rise 20 cm compared to 1990 levels. Basedon these projections, China's scientists have done many studies of the impacts of climate change on the economy. Among these are studies by Peng (1991) and Ren(1990) focusing on the impacts of climate on China's environment. Xia (1991) studied the Chinese population-environment relationship and the climate impacts.

In a paper published as proceedings of a workshop in Austria in 1993, Xia and Wei summarized the impacts of climate change on China in the following terms:

<u>Agriculture</u> The positive impact of global warming is mainly from the longer growing season in the northern regions due to higher temperatures. However, higher temperature also increases evaporation, resulting in drier winters and more arid summers. The shortage of water resources will be worsened in most regions, which will negatively affect agricultural activities, as well as reduce the benefits of the fertilization effect of carbon. Soil erosion, salinization, and land degradation will continue to cause losses of cultivated land. In general, climate change will reduce agricultural production in China by at least 5 percent (See table 2.8 on page 43 for details).

<u>Water Resources</u> China has the least water resource per capita of all major countries in the world. While its population makes up one fifth of the world total, its freshwater accounts for only 5 percent of the world's total volume. The uneven distribution of water resources causes other related problems, such as frequent floods and droughts. Global warming and climate change is expected to seriously affect

Table 2.8 Impact of Climate Change on China's Agriculture

Higher Temperature			Impacts on Output
Southwestern Northwestern Other	3°C or more 3°C or more 2-3°C	average effective growing season increases by one month	ag: increase by 2% (8 million tons) southeast: 4 million tons, northeast: 1 million tons, south: 1 million tons or more, also increases productivity of biomass and economic crops.
Evaporation			
mid-latitude (north and northwest)	increase 20% (300-400 mm)	13 million ha of cultivated land lost	
west		9 million ha of cultivated land lost to sanilization	
Drought			
Spring: north, west, mid-north			drought damage increases by 5%, 4 million tons of lost output (wheat)
Summer: south			rice output reduced by 20% (6 million tons)
Autumn: west north			grain output reduced by 20% (4 million tons) grain output reduced by 5 %
pest control cost			increase by 10-15%
Total Impact:			at least 5% reduction in ag output

Source: Xia and Wei, 1993.

precipitation, river run-off, and groundwater levels, especially in the central and eastern part of the country, where water supply is already in severe shortage.

As shown in table 2.8, global warming is expected to increase evaporation in north and northwest China by 30-40 percent. This is already an arid and semi-arid region. The Yellow River is the principle stream in this region. However, it can provide only one-fourth of the water per hectare of cultivated land as compared to the Yangtze River area in the south. During the dry season in the 1980s, its runoff dropped to two-fifth of its normal average, causing serious reductions in crop yields, disruption of industrial production, and enormous difficulties in urban living. A reduction in runoff necessitates heavy reliance on underground water reserves. Excessive pumping causes surface subsidence that affects virtually every major city in the north. In addition, soil erosion has always been such a serious problem in the Yellow River region that the river's silt load has been increasing the average river bed by 1 meter per decade. While an increase in evaporation and a decrease in precipitation in this region may cause more severe water shortage and drought damages, the increased intensity of rainfall coming as one-day downpours will cause river flooding that may affect most densely populated areas along the river.

Although water resources have been relatively abundant in the south, such as in the Yangtze valley, this region faces the same problem as the north of erosion and silting. Increased silting raises river beds and causes the disappearance of some lakes, reducing the natural flood-storage capacity. This region is densely populated and economically more advanced. If global warming increases precipitation intensity as predicted for this region, larger flooding damages may affect many people.

Sea Level Rise The southeastern coast of China is the most developed industrial and agricultural area, with many seawater breeding farms that are the most important non-staple food base for the coastal cities, the fertile river delta farmlands that are important grain production bases, and industrial and economic centers that have been the driving force for China's recent economic growth. A 20 cm sea level rise would flood or destroy most of the seawater breeding farms and half of the Pearl River delta would be inundated. There would be production losses, land losses, and damage to infrastructure. In Shanghai, the largest city and one of the most advanced areas of China, the business district is crowded with high buildings along the Huangpu River and the world's highest building is to be put up in the next few years. However, the average elevation of the city is only 1.8 meters above sea level. If the sea level rises as predicted, damages to the city and other similar areas would be tremendous. A higher warming rate in the summer would increase the frequency and intensity of typhoons that affect many coastal areas in China.

Forest Leggett (1990) cited a study sponsored by the Chinese government. The study found that reductions in soil moisture would produce large reductions in major tree species. Four of the six principle timber species in China would be severely affected or decimated.

China's Participation in Research on Global Climate Change

As in other countries, the issues of global environmental and climate change have engaged members of the scientific community in China. As a result, a policy approach to global change issues is evolving. In 1991, China signed the Montreal

Protocol on Substances that Deplete the Ozone Layers and Chinese scientists are researching and developing CFC-alternative technologies. Governmental support for other global change scientific research is also emerging.

In the area of global warming, China, like other developing countries, believes that wealthy industrialized nations should help finance developing countries' participation in addressing the problem. Chinese research on the global warming issue has a definite national focus. It is focused primarily on the possible impact of climate change on the country's prospects for economic development and on its existing problems such as deforestation, soil erosion, and soil degradation. China has also emphasized studies of historical changes and land use problems.

China has been involved in two major international global change programs since their early stages: the International Geosphere-Biosphere Program (IGBP) sponsored by the International Council of Scientific Unions (ICSU), and the World Climate Research Program (WCRP) jointly sponsored by ICSU and the World Meteorological Organization (WMO). China also participates in and cooperates with many other international global change projects, such as the International Global Atmospheric Chemistry Project, Global Change and Terrestrial Ecosystems, Biospheric Aspects of the Hydrological Cycle and Global Energy and Water Cycle Experiment, and Global Analysis, Interpretation, and Modeling, and others.

One aspect of the issue that has a relatively low priority in China's global change research agenda is China's contribution to global environmental change. Data on China's biogenic and industrial emissions, for example, are not readily available. Given the national focus in China's research on the global change issue, it is important to estimate the costs of global warming and climate change to China's economy, and China's benefits from emission abatement actions, so that emission control policy suggestions can be more persuasive to the policy makers in China.

CHAPTER III

LITERATURE REVIEW

Several studies have examined the issues of GHG emissions and possible climate change caused by the accumulation of GHGs in the atmosphere, and the potential impacts of climate change on economic activities. However, the results from these studies are far from close to each other, with the estimated GHG emissions and GDP losses in different regions covering a very wide range. Based on these studies (some of them to be reviewed below), global emissions in 2100 under the scenario of "business as usual" ranges from 22.5 billion tons of carbon (GtC) to 40 GtC. The estimated losses of GDP in 2020 range from 0.5 percent to 2 percent for OECD countries, 0.5 percent to 3 percent for China, and even larger for oil-producing developing countries. With a longer time horizon, the differences between these estimates are even bigger.

One most important reason for the big differences in the estimates from these studies lies in the different assumptions of these models, including, among others, the values for parameters such as primary energy demands, relative energy prices, energy efficiency improvement; the degrees of substitution between fossil fuels, between fossil and non-fossil fuels, and between energy and other production factors; and the availability of carbon-free backstop technologies. The differences in results of these studies underscore the uncertainty that characterizes global climate change and associated economic impacts. They also reveal the need for further scientific and economic researches.

This chapter compares and contrasts some of the important emissions-climate-economic consequences models. It also introduces the basic logic of Nordhaus DICE model and discusses the ground for modification of the DICE model to make the global model applicable to a one country case.

Edmonds & Reilly Model (ERM)

According to the manual prepared by Edmonds and Reilly (1986) to accompany for the PC version of their model, the ERM was originally written in 1984 using FORTRAN IV for mainframe adaptation, then modified in 1985 for use on IBM personal computers. The PC version allows users to modify a total of 39 different major assumptions interactively from 12 categories through the use of an internal data editor. It provides both graphical and tabular results. These easy-to-use features make the model widely and frequently applied.

The title of the model, "Long-Term Global Energy-CO_2 Model", clearly describes the model's primary focus; i.e., how carbon emissions are related to the energy sector. The model mathematically integrates economic, demographic, technological and geological factors to make long-term projections about global energy consumption and carbon dioxide emissions. The time horizon is from 1975 to 2100, in 25 year intervals. It divides the world into nine global regions, and includes six major energy sources. Energy demand in each region is a function of population, labor productivity, economic activity, technological change, energy prices, and energy taxes and tariffs. The supply of energy has two categories, renewable and non-renewable, and it is determined by resource constraints, behavioral assumptions, and energy prices. The model applies iterative price adjustments to achieve equilibrium of each energy market in each region within pre-specified bounds. After the energy markets are balanced, the carbon dioxide emissions are calculated for the regions according to how much gas, oil, and coal is consumed in that region.

As a partial equilibrium energy model aimed at projecting global energy and carbon dioxide emissions, ERM looks at only energy markets and does not consider any non-energy market explicitly. The only linkage between the energy sectors and the entire economy is through a feedback parameter which is used to capture the interdependence of GNP and energy prices. This parameter is based partly on the notion that GNP is a proxy for the overall level of economic activity and an index of income, and thus an important determinant of energy demand. It is also intended to capture supply aspects; that is, as energy resources are depleted, and energy prices rise, to keep energy production from falling, other resources are shifted away from other uses to energy sectors, slowing economic growth. The model allows this two-way interaction between GNP and energy by entering the GNP that would obtain if energy prices remained constant at 1975 levels (a base line GNP) as a model input and taking the GNP that is consistent with actual energy prices in the forecast year (the realized GNP) as a model output.

Although the losses in GNP due to reduced energy use (e.g. for the purpose of emission reductions) may be calculated by comparing the base line GNP and the realized GNP, when used to estimate economic impacts of climate changes due to global warming caused by emission accumulations in the atmosphere, this linkage between emissions and GNP appears to be over-simplified. It follows only the simple reasoning that to reduce emissions, energy consumption has to be reduced, therefore GNP has to be lowered as a result of lower energy consumption. However, this reasoning is not expressed as a production function process, and it does not capture the relations between emissions and climate changes, and between climate changes and other non-energy economic sectors. It cannot be used to produce reliable estimates of impacts of global climate change on overall economic activity.

ERM is a global model that is intended to project energy and emissions on a global scale. Although the model divides the world into nine regions and results are reported for each region, it is not suited for forecasting emissions of individual countries in a defined region. For example, China is included in the Asian Centrally Planned Economies, one of the nine regions in the model. The ERM model cannot be used, however, to disaggregate the projections for the region to get estimates of China's emissions and the economic costs of emission reductions in China. In other words, disaggregation beyond the regional level is not appropriate, neither is disaggregation beyond the specified level of energy services.

The ERM has been applied by many users under different assumptions for the values of the parameters, hence they produce different results in terms of emissions, GDP losses and carbon tax rates sufficient to keep emissions to a certain level.

IEA Medium Term Energy Model (IEA)

OECD (1993) includes IEA as one of the models that estimates costs of emission reductions. IEA is another partial equilibrium energy model with the objective of examining the trends in energy markets and carrying out sensitivity analysis of the energy system. It consists of five sub-models, four of which are interdependent, each of which is strictly energy related, and one of which is relatively self-contained activity sub-model. The primary interest is to study the impact of carbon taxes on the global energy system.

The final demand sub-model includes three final demand sectors (transportation, industry, and other, which is a combination of residential and commercial demand). All end-use products are energy related. There are seven oil products, two types of gas and electricity (industrial and other), and three coal sectors (industrial, coke, and other). The final demand sub-model solves for the final energy demand on the basis of sector activity, the end-user prices, and assumptions about other sector-specific variables. The result is a set of primary fuel demands.

The supply sub-model produces a set of primary fuel supplies under various assumptions regarding reserves, discovery rates, and energy prices from the price sub-model, plus other relevant variables. The demand for primary fuels from the final demand sub-model and the supply of primary fuels from the supply sub-model are then fed into the price sub-model. The interdependence between the price sub-model and both the final demand sub-model and the supply sub-model is easy to understand since the energy demand and supply are inputs into the price sub-model, and the prices are inputs into the final demand sub-model as well as the supply model.

Another sub-model is the transformation sub-model which converts the demand for electricity into primary fuel demand, given the structure of the electricity industries, conversion efficiencies, and assumptions about non-fossil fuels. Thus, the total primary fuel demand is the summation of the results from the final demand sub-model and the transformation sub-model. The interaction between the transformation sub-model and the other three sub-models is through the set of primary fuel demands to the price sub-model, therefore to the final demand and supply sub-models.

The one relatively self-contained sub-model is the activity sub-model which serves as the only linkage between the energy sectors and the macroeconomic setting. This sub-model converts exogenous assumptions on GDP and population into variables such as personal expenditure and industrial production by a non-energy sector, so that the assumptions about macroeconomic settings are translated into factors that have impacts on the sectors whose energy demand is endogenous.

As can be seen from the basic structure of the model, the linkage between the energy sectors and the general economy is a very simple and limited one-way process, and there is no feedback from the energy sectors to the economy. This means that the model is not suitable for estimating the economic impacts of reductions in energy consumption. There is no estimate of the economic cost of carbon emission reductions. There is no linkage between emissions and no impacts of emission accumulations on other non-energy sectors through climate changes, either.

One important feature of the IEA model is that most of the parameters are estimated econometrically using historical data. This feature imposes a limitation on the time horizon of the model. The model is designed to capture the short- and medium-term rigidities of energy markets. The results are reported in one year intervals for the period shortly after the beginning of the next century (2005). Although extension of the time horizon of the projections is technically possible, the confidence attached to the results would be very limited.

The econometric feature of the IEA model also imposes a limitation on its regional aggregation. The model divides the OECD countries into three groups (North America, Europe, Pacific), the former centrally planned economies into two parts (ex-USSR and Eastern Europe), and the developing world into three continental regions (Africa, Asia, Latin America) and the Middle East area. China is listed as the only one country region. However, because of difficulties with data availability, only OECD countries are covered in detail in the model. The data for the other regions are much weaker. In the case of China, the energy system is exogenously imposed on the model, rather than endogenously determined.

Global 2100 (The MR Model)

The name of the model (Global 2100) emphasizes the global nature of the carbon emissions problem and implies the need for research from a long-term perspective. The model covers the time span of 2000 to 2100, in 10 year intervals, with 1990 as the base period. This model is also referred to as the MR model because it was jointly developed by Manne and Richels (Manne and Richels, 1990b).

The MR model is a general equilibrium model combining process analysis of major individual energy sources with a production function approach. Both energy and non-energy sectors are summarized in the model, and the discounted value of consumption utility is maximized over time, using nonlinear programming, subject to carbon constraints. An energy technology assessment (ETA) sub-model provides the supply side of analysis, while the other sub-model, MACRO, which is a continuously differentiable macroeconomic production function describing the balance of the economy, determines the demands. Prices are determined so as to allow the two-way linkage between the ETA and MACRO sub-models. The energy supplies include both exhaustible resources and "backstop" technologies, with the latter available in unlimited quantities at constant marginal costs. For each technology, carbon emissions per unit of the activity level is described in the coefficients.

The energy demands are divided into two categories, electric and non-electric. The economy-wide macroeconomic production function has three basic inputs: labor, capital, and energy. Therefore, energy demand or consumption is closely linked to GDP, so are carbon emissions. However, over time, due to autonomous energy efficiency improvement and the price-induced substitution between energy and other inputs, the linkage between energy/emissions and GDP may be decoupled.

The model divides the world into five regions: USA, Other OECD Countries, USSR, China, and the rest of the world. A carbon emissions quota is exogenously determined for each region and can be traded on an international market. Within each region, supplies and demands are equilibrated for each period, but forward-looking features are also incorporated to allow for interactions between periods. Saving and investment are determined by optimization (maximization of the discounted value of consumption over time subject to carbon emissions constraints).

One feature of the MR model is its attention to substitution options. There are five existing technologies and four future technologies for electric energy, and six existing and two future technologies for non-electric energy. Each energy source is assigned a benchmark cost, and there are many possibilities for inter-fossil-fuel substitutions, fossil-fuel and non-fossil-fuel substitutions. The substitution between other factors and energy is explicitly modeled in the production function. Related to the availability of future backstop technology, the model sets an absolute limit on the carbon tax, since the backstop allows the emission level to be lowered without having to depend on higher carbon tax rates.

As in the models mentioned above, the MR model does not include climate changes, and there is no parameter that links emissions to climate changes, or climate changes to economic activities. The linkage between emissions and GDP is through energy as an input. Reducing carbon dioxide emissions requires the reduction of the consumption of carbon rich energy, which would affect economic activities. The model does not include assessment of the benefits from emission reductions.

The Recursively Dynamic Trade Model (CRTM)

The OECD (1993) survey also includes the CRTM (Carbon Rights Trade Model), nicknamed for its feature of allowing the trading of carbon emissions rights. CRTM is a recursively dynamic general equilibrium model designed to identify the economic channels through which restrictions on carbon dioxide emissions affect international trade and the pattern of comparative advantage. The model simulates the economic costs and consequences of restricting carbon dioxide emissions, with special attention to the effects of unilateral reductions in the OECD countries.

The CRTM is partially based on the Global 2100 model by Manne and Richels and has several things in common with the structure of the MR model. Both of the models divide the world into the same five regions, cover the same time span with the same time intervals, and have the same objective of maximizing discounted utility.

There is a process sub-model in each model that represents the energy sector. Carbon rights are region-specific and internationally tradeable.

There are important differences, however, between the CRTM and the MR models. Unlike the MR model, CRTM is recursive rather than forward=looking, with savings as an input that is not affected by changes in the real interest rate. Also, the energy sector responds to current prices only.

Aggregate output in CRTM is determined by three factors: the supply of primary factor inputs (labor and capital), the supply of "basic intermediate materials" (steel, plastic, chemicals, and other relatively energy-intensive goods), and the supply of energy resources. For each region, two traded energy goods and two non-traded end-use energy goods are included in an energy sub-model that describes current and future energy supply, with 15 alternative energy production technologies. Oil, carbon rights, basic intermediate materials, and other outputs are internationally traded. Restrictions on emissions require limitations on energy consumption, which may cause reductions in GDP through both direct losses from lower energy production and indirect losses from lower production of basic intermediate materials.

As in the MR model, CRTM does not include climate change factors, nor does it assess the benefits of reduced GHG emissions. The only linkages between emissions and GDP are through energy and energy-intensive goods supplies.

Cline's Cost-Benefit Analysis

In his 1992 book, William Cline presents an analytical survey of economic models of carbon reduction costs and reviews the estimates of carbon abatement costs.

He also considers the costs of afforestation and reduced deforestation. The economic damages from global warming are estimated at both the benchmarking carbon dioxide doubling level and at the very-long-term (250-300 years) warming level.

The basic approach of Cline is cost-benefit analysis, with somewhat more emphasis on the cost side. Cline provides sectoral estimates of damages from global warming, for about a dozen sectors and activities listed as being climate-sensitive, some of which are non-market sectors. He also takes into account the possible damages caused by catastrophe, i.e., those due to severe drought or flood. The result of this broad and detailed estimation is a suggestion of much more stringent emission control than suggested by others researchers.

For the calculation of benefits and costs, Cline divided the world into two groups: the developed countries and the less developed countries. For each group, future per capita income is determined by projecting base year per capita at assumed growth rates. Future population size is determined in the same way. The product of the projected per capita income and population yields the projected gross product of the group, and the sum of the two groups gives the gross world product.

Global carbon emissions are exogenously projected and compared to the target set in the aggressive abatement program. The difference is the amount to be reduced. Change in temperature (the degree of warming) is determined by the radiative forcing of the emissions accumulated in the atmosphere. The path of warming is assumed linear, determined by two reference points, one of which is based on the climate sensitivity parameter for carbon dioxide doubling in 2050, the other is based on the projection for the very long-term warming in 2275.

The economic damage from global warming is assumed to be geometrically related to the amount of warming, with the damage from carbon-dioxide-equivalent-doubling corresponding to a temperature increase of 2.5°C as the benchmark. The benefits of emission abatement are the damages that can be avoided as a result of abatement. The costs of abatement are determined by the cost of afforestation, the reduction of carbon released from deforestation, and losses of output in the rest of the economy due to reduced fossil fuel emissions. The cost function for carbon reduction in the general economy depends on the percentage cutback in carbon emission, but with adjustments that provide for an initial "free" reduction and a downward trend over time in costs because of improving technology. A carbon tax rate is determined that will achieve the required emission reduction. Carbon taxes are treated as a source of benefits on the assumption that they will be used to replace other taxes with excess burdens.

The overall cost of abatement equals the world GDP multiplied by coefficients representing the three cost sources (economywide output, afforestation, and deforestation reduction). The overall benefits are the gains from avoidance of warming (ultimately projected as multiplied by world GDP), expanded to include gains from investment and the benefits from taxes which reduce tax burdens.

Using empirically-estimated parameters, assuming a low 1.5 percent discount rate on consumption and a pure time preference rate of zero, assuming risk aversion to the possibility of catastrophe, and taking into account the possibility of very long-term warming, Cline concluded that the benefits in terms of avoided damages from emission abatement actions should be high enough to justify much more stringent emission control actions than suggested by other studies. Cline believes the difference between his results and those of other researchers is mainly from his consideration of long-term warming, while others argue that other factors (e.g., Cline's assumptions about the discount rate or the pure time preference rate) may contribute as much.[4]

The DICE Model

The DICE model (Nordhaus, 1994), or the Dynamic Integrate Model of the Climate and Economy, is a general equilibrium optimization global model. It calculates the optimal path for both capital accumulation and GHG emission reductions through the maximization of a utility function. The utility function in the DICE model represents the present value of the generalized (global) consumption level over time. The optimal paths are then compared to other scenarios, including cases where the objectives are to stabilize climate, to stabilize emissions at 80 percent of the 1990 level, to stabilize emissions at the 1990 level, to delay any action by 10 years, and to apply geoengineering controls over emissions. The optimal results are also compared to the no-mitigation base case. The results of simulation by Nordhaus show that the optimal path is better than the other alternatives in terms of reduced emissions and minimized climate change, except for the geoengineering option (which involves much unknown impacts and technologies).

The DICE model is established based on the following reasoning:

The level of consumption of goods and services by the entire population represents economic well-being and a higher level of consumption means a higher

[4] See Nordhaus, 1994, p. 56-8.

level of utility. The objective is to maximize utility of consumption subject to certain constraints. Consumption is a part of total production, which in turn is the result of the combined inputs of labor, capital and technology. Emission reduction policies have impacts on the supply of goods and services through a climate impact factor that is determined by both an abatement cost function and a damage function.

The level of GHG emissions is determined by an emissions-output ratio. Annual emissions, together with previous accumulations of GHGs in the atmosphere, determine the current atmospheric accumulations of GHGs. These accumulations are converted into radiative forcing, which results in projected changes in the mean temperatures of both the oceans and the earth's surface. When the global mean surface temperature on the earth changes, it causes other climate changes or other changes occur along with it. These changes cause damages to the climate sensitive sectors of the economic system, e.g., agriculture, water resources, coastal activities, the construction sector, etc..

To reduce the damages caused by climate changes, Nordhaus prescribes taxes that reduce GHG emissions. The required emissions-reduction rate is determined by the demand and supply of emission-intensive products. Both the demand for and supply of emission-intensive products are functions of the prices of the products. An emissions tax would change the equilibrium prices, production, and consumption of these product. The optimization process in the model solves for the optimal emission reduction rate that maximizes utility. This emission reduction rate is used to determine the optimal emissions path, the cost of emissions reduction, and the optimal output and consumption of goods and services.

For convenience in estimating, the abatement cost function is put in total cost form rather than in marginal cost form. Both the total cost of emissions reduction and damages avoided are defined as a function of the emissions reduction rate. According to economic theory, optimization (the optimal emissions reduction rate) is achieved when the marginal cost (of emission reduction) is equal to the marginal benefit (from damages reduced or avoided).

The DICE model allows some variables to be controlled and set at a predetermined level or within a specified range, which makes it possible to experiment with various policy options. A no-mitigation baseline case may be established by explicitly specifying a zero reduction rate. This results in an emission path which is determined only by the emissions-output ratio and the production level. Without the assumption of zero emission reduction rate, the model solves for the optimal emissions-reduction path that maximizes the economic well-being (utility) over time. The optimal case can be compared with the no-control case to determine the cost of emissions reduction.

Other policy options can also be studied by specifying explicitly controlled variables. For example, by specifying the emission level as a command or control variable and setting it equal to the 1990 level or 80 percent of the 1990 level, the model solves for the optimal paths of emission reduction rates, as well as the corresponding output and consumption levels, subject to the specified emission constraints. The results can also be compared to the results from the base case or the non-constrained optimal case to determine the extra cost of the more stringent constraints.

Based on the logic outlined above, the DICE model maximizes the utility of the present value of global total consumption over time. The present value of global total consumption over time is the product of the present value of per capita consumption over time and the population level. The size of population is determined by the initial level and projected growth rate, allowing the growth rate to decline over time.

Consumption is determined by production, which in turn is a function of labor, capital, and technology based on a Cobb-Douglas production function. Labor depends on population. Capital is determined by precious capital stock less depreciation plus investment. Technology (or total factor product) is projected based on an initial level and a growth rate, allowing a decline of the growth rate over time.

Climate impact on production hence consumption is through a climate factor that is determined by both an abatement cost function and a damage function. The abatement cost function is estimated using historical data and projections with the emissions reduction rate as the main determinant. The damage function is estimated with temperature change as the main determinant.

Carbon emissions are determined by production and emissions-output ratio. It also depends on a variable called the emission reduction rate, which may either be policy controlled ot optimally solved. Adding new emissions to previous accumulations in the atmosphere, taking into account of the atmosphere-ocean transfer, total atmospheric accumulation is determined. The radiative forcing of carbon dioxide accumulations plus the forcing from other GHGs produces the total radiative forcing, which causes the temperature to rise, and the damages to increase.

The careful study of the structure of the DICE model reveals the possibility of modifying the global model into one that focuses on the specific case of an individual region or country. The emissions equation can be disaggregated into regional or country by country emissions. Then, adding the emissions by the regions or countries gives the world total emissions, which in turn would determine the atmospheric accumulation of GHGs, radiative forcing of the accumulation, and temperature changes caused by the radiative forcing. Damages caused by higher global mean temperatures may be estimated for each region or country, and so may the abatement costs. Combining the country specific damage function and the country specific abatement costs produces the country specific climate impact factor. This factor would affect the income, consumption, hence utility level of this country only.

Given the structure of the DICE model, especially the possibility of modifying into to maximize the utility of one specific country, and my interest in analyzing China's role in generating as well as curbing global warming, this dissertation will capitalize on the features mentioned above of the DICE model in order to estimate China's contribution toward global warming and the impacts of climate change on China's economic well-being. Considerable modification is necessary to turn the global DICE model into the DICE-CHN model (the modified version of the DICE model). The details of the modifications and the structure of the DICE-CHN model are described in Chapter IV.

CHAPTER IV

MODEL RESULTS AND POLICY IMPLICATIONS

The DICE-CHN Model: Structure and Modifications

The computer-coded version of DICE-CHN is presented in Appendix A. The basic structure of DICE-CHN is described later in this section and the calculation of the DICE-CHN parameters in the next section. This section begins with a discussion of the differences between the original DICE model and the modified version, or DICE-CHN.

The DICE-CHN model uses the assumptions and logic of the original DICE model. Several modifications have been made, however.

The major difference between the original DICE model and DICE-CHN is that, while the former treats the entire world as one single entity and assumes that all countries behave in a way to maximize a common world utility function, the latter focuses on China alone. DICE-CHN treats the rest of the world as exogenous and develops an explicit utility function for China. The assumed objective function of DICE-CHN is to maximize China's economic well-being over time, given the behavior of the rest of the world, subject to certain economic and climate constraints.

DICE-CHN covers a time span of 250 years, starting the decade of 1970s (represented by 1975), instead of the 400 years projected in the DICE model. DICE-CHN divides this time span into 10 year intervals. A time span of 250 years is long enough to capture virtually all of the long-run aspects examined by Cline. Most results are reported up to 2115, that is 15 periods of 10 year interval.

The initial time period in DICE-CHN is designated as 1975 rather than 1965 as in the original DICE model. This is a better starting date for China, both in terms of data availability and accurate representation of the contemporary Chinese economy. Each 10-year interval is represented by the fifth year of the decade, e.g. 1985 for the decade of 1980-1989, 1995 for the decade of 1990-1999, etc. For the first period, some parameters use the 1978 values (not 1975 values) as the initial values because of data availability.

The original DICE model makes output a function of labor input, the capital stock, and technology, or total factor productivity, as determined by a Cobb-Douglas production function. The DICE-CHN model treats output exogenously. The real GDP in 1978 is used as the initial value of output, and the output level for each period thereafter is calculated by converting either the actual growth rate (before 1995) or the projected growth rates based on the Chinese government planning objectives into the multiple of 1978 GDP. This simplification seems essential, given the limitations on data on the Chinese economy.

Income is defined in the DICE-CHN model as output multiplied by the climate impact factor. Consumption is assumed to be 65 percent of income, since, historically, the investment rate is 35 percent in China. When calculating losses in terms of income and consumption, output determined by the planned growth rate alone (without climate factor impact) is used as the benchmark.

World total emissions in the DICE-CHN model consist of two parts: the emissions by China, which is determined by China's output, emissions-output ratio, and its emissions reduction rate, and emissions by the rest of the world, which is exogenously determined by the growth rate of emissions by the rest of the world, allowing the growth rate to decline over time. The emissions by the rest of the world is also affected by its emission reduction rate.

Finally, all monetary values are in Chinese yuans, to avoid the inconvenience caused by exchange rate conversions.

Given the above modifications, the basic structure of the DICE-CHN model is as follows:

$$\max_{c(t)} \sum_t U[c(t), L(t)] (1+\rho)^{-t}$$

subject to economic constraints

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

(2) $c(t) = C(t) / L(t)$

(3) $C(t) = 0.65\ Y(t)$

(4) $Y(t) = \Omega(t)\ Q(t)$

and the emissions-climate-economic constraints

(5) $\Omega(t) = [(1 - b_1\ \mu(t)^{b2}) / (1 + \Phi_1\ T(t)^{\Phi 2}]$

(6) $TC(t) = Q(t)\ b_1\ \mu(t)^{b2}$

(7) $MC(t) = Q(t)\ b_1\ b_2\ \mu(t)^{(b2-1)}$

(8) $D(t) = Q(t)\ \Phi_1\ T(t)^{\Phi 2}$

(9) $T(t) = T(t-1) + (1 / R_1) \{ F(t) - \lambda\ T(t-1) - (R_2 / \tau_{12}) [T(t-1) - O(t-1)]\}$

(10) $O(t) = O(t-1) + (1/R_2) [T(t-1) - O(t-1)]$

(11) $F(t) = 4.1 \log [M(t) / 590] / \log (2) + FO(t)$

(12) $M(t) - 590 = \beta\ E(T-1) + (1-\delta_M) [M(t-1) - 590]$

(13) $E(t) = [1 - \mu c(t)]\ \sigma(t)\ Q(t) + [1- \mu o(t)]\ EO(T)$

Definitions of the Variables and parameters:

Objective Function: maximize the present value of total consumption, measured as the product of per capita consumption and exogenously determined population, discounted at the pure rate of social time preference.

	t:	time periods in ten year intervals
	ρ:	the pure rate of social time preference
	U:	the level of utility
	c(t):	per capita consumption at time t
	L(t):	the population at time t; exogenously determined as a function of an initial level and growth rate
(1)	U(t):	utility at time t; equal to the population, L(t), times the utility of per capita consumption, or $U(c(t)) = \{[c(t)]^{1-\alpha} - 1\}/ (1- \alpha)$
	α:	a measure of the social valuation of different levels of consumption, or the rate of inequality aversion (the curvature of the utility function). This parameter reflects the extent to which society is willing to reduce the welfare of higher-income generations to improve the welfare of lower-income generations. α is the elasticity of the marginal utility of consumption. α is assumed equal to 1; thus, the utility function is the logarithmic or Bernoullian utility function, or $U[c(t), L(t)] = L(t)\ \{\log[c(t)]\}$
(2)	c(t):	per capita consumption, or total consumption, C(t), divided by total population, L(t)
(3)	C(t):	total consumption at t, or 65 percent of income (Y), because the

investment rate has been historically at about 35 percent of GDP

$Y(t)$: total income, or output (GDP) adjusted for climate impact

(4) $Q(t)$: output at time t, determined by an initial level and growth rate, with 1978 GDP as the initial value

Ω: the climate impact factor, or the impact of emissions reductions and climate change on output, determined by both the total abatement cost function, TC, and the damage function, D (see below).

(5) $\Omega(t)$: climate impact at time t. The numerator of the factor, $(1-b_1\ \mu(t)^{b2})$, is equal to $[Q(t)-TC(t)]\ /\ Q(t)$, and captures the negative impact of abatement on output, while the denominator, $(1+\Phi_1\ T(t)^{\Phi 2})$, which is equal to $[Q(t)+D(t)]\ /\ Q(t)$, captures the positive impact of the avoided climate change damages on output

(6) $TC(t)$: total cost of emissions reduction as a fraction of total output, where b_1 is the scale coefficient of the cost function and b_2 is the exponent of the cost function that reflects its nonlinearity.

$\mu(t)$: the emissions control rate (emissions reduction rate), or the fractional reduction of emissions relative to uncontrolled emissions (percentage reduction of emissions). This is a control variable determined by policy or optimization.

(7) $MC(t)$: marginal cost of abatement; or the first derivative of $TC(t)$ in (6)

(8) $D(t)$: damages to the economy as the fractional loss of output from climate change, where Φ_1 as the scale coefficient of the damage function and Φ_2 is the exponent of the damage function that captures nonlinearity.

(9) $T(t)$: the temperature in the atmosphere at time t, as determined by the atmospheric temperature of the previous period, $T(t-1)$, plus the warming effect. The warming effect depends on the thermal capacity of the atmosphere (R_1) coupled with the radiative forcing, $F(t)$, from GHG emissions, taking into account the transfer rate of thermal capacity between the atmosphere and the oceans.

$T(t-1)$ and $O(t-1)$: the temperature in the atmosphere and in the deep oceans, respectively, at time t-1.

R_1 and R_2: thermal capacity of the atmosphere and the oceans, respectively.

τ_{12}: transfer rate of thermal capacity from the atmosphere to the oceans.

λ: climate feedback parameter, captures the conversion ratio between radiative forcing (watts per square meter) and temperature change (degree C)

$F(t)$: the standard measure of radiative forcing in the atmosphere caused by accumulated GHGs relative to 1900 (the increase in surface warming per square meter (wm^{-2})).

(10) $O(t)$: the temperature in the deep oceans at time t, determined in a similar way as the temperature in the atmosphere, only that radiative forcing is not present.

(11) $F(t)$: the radiative forcing from carbon dioxide accumulations ($M(t)$) relative to the preindustrial level of 590 GtC. This measure is based on the benchmark of 4.1 wm^{-2} for CO_2 doubling. Also included is the radiative forcing from other GHGs, $FO(T)$.

(12) $M(t)$: the carbon dioxide concentration at time t, determined by adding part of the emissions during time t-1 to the accumulations at the beginning of time t-1.

$E(t-1)$: total world carbon dioxide emissions in t-1.

β: marginal atmospheric retention ratio, or the percentage of GHGs emissions that stays in the atmosphere . It is estimated using the actual data on emissions and concentrations of CO_2.

δ_M: transfer rate of carbon dioxide from the atmosphere to the ocean.

(13) $E(t)$: total emissions at time t, or the sum of emissions by China and by the rest of the world. Emissions by China is the product of the output level, Q(t), and the emissions-output ratio, $\sigma(t)$. $\sigma(t)$ is the ratio of emissions to output in the absence of controls on gross output. E(t) also depends on the emissions reduction rate, $\mu(t)$, which depends, in turn, on policies and optimization. Emissions by the rest of the world, EO(t), is determined exogenously, using an initial value and growth rate per decade.

Values of the DICE-CHN Model Parameters

T: time period 25 ten-year intervals to cover a time span of 250 years, starting with 1970s (represented by 1975), and ending with 2210s (represented by 2215).

ALPHA (α): elasticity of marginal utility Assumed to be equal to one to yield the logarithmic or Bernoullian utility function: $U[(c(t), L(t)] = L(t)\{\log[c(t)]\}$.

RHO (ρ): rate of social time preference Measured in percent per year, or 0.03 as in the Nordhaus DICE model.

M0: carbon dioxide equivalent concentrations in 1975 698 GtC, according to Nordhaus (Nordhaus, 1994, p. 88).

A1: damage coefficient for carbon dioxide doubling Carbon dioxide doubling is estimated to reduce China's agricultural output by 5 percent. In 1994, 5 percent of agricultural output was 0.94 percent of GDP. Accordingly, the value of A1 is assumed to be 0.0094. With economic development, the value of A1 should fall, but no provision has been made for this possibility.

B1 & B2: intercept and exponent of control cost function In an experiment with the Nordhaus DICE model, Bowman (personal contact) estimated the B1 for China (representing the developing countries) is 0.04, Nordhaus' estimate of B2 is 2.887. We use these values in this study.

L(T): population at time T L(t) is exogenously determined by projecting an initial value, L0, at a growth rate for each period, GL(T). L0 is the 1975 population of 924.2 million. GL(T) is determined by a combining a growth rate of population with a decline rate in the growth rate (DGL). The growth rate of population (in percent per decade) is assumed to be 0.16, an average of the growth rates of 1970-80 (0.189) and 1975-85 (0.145). DGL is assumed to be 0.164, or the percentage decline in the growth rate between the 1970-80 and 1980-90 time periods ((0.189-0.158)/0.189).

SIGMA(T): emissions-output ratio The emissions-output ratio is assumed to decline over time due to improved energy efficiency and switches between energy sources. The initial ratio (in 1978) was 1.135 tons of carbon dioxide emissions per thousand yuan of GDP. The emissions-output ratio in 1985 was 0.63 tons of carbon dioxide emissions per thousand yuan of GDP, a 45 percent decline over the 1978 ratio. Thus, DSIGMA0, the decline rate of emissions-output ratio for the initial decade is assumed to be 0.45. The cumulative improvement of energy efficiency at time T, represented by the decline of the emissions-output ratio, DSIGMA(T), may be estimated using the initial value of the emissions-output ratio, the decline rate of the ratio, and the decline rate of the decline rate, with the assumption that the growth rate of the emission-output ratio would decline over time at the same rate technology declines, which is 0.11 per decade. In other words, the emissions-output ratio will decline, as energy efficiency improves, at an initial rate of 0.45 per decade, and the speed of that decline will slow down by 0.11 per decade.

EROW(T): emissions by the rest of the world EROW(T) are exogenously determined by an initial level of the emissions by the rest of the world and a growth rate of emissions by the rest of the world. Nordhaus reported that world GHG emissions in 1975 were 5.89 GtC. China's share of total world emissions in 1975 was 6.55 percent (Lu, 1989, p. 50). Thus, emissions of the rest of the world in 1975 were 5.5 GtC, which is taken as the initial level (EROW0). By 1985, when world total emissions were 7.54 GtC, China's share increased to 10 percent, thus, emissions by the rest of the world were 6.79 GtC, a 23 percent increase for the decade (GEROW). In 1995, world emissions are expected to reach 9.28 GtC, and China's share will increase to 12 percent. Given these estimates, EROW would be 8.17 GtC, a 20 percent increase over 1985. Thus the growth rate of emissions by the rest of the world declined at a rate of 13 percent for the decade. Emissions by the rest of the world

(EROW) thus is estimated based on the initial value of 5.5 GtC in 1975, an initial emissions growth rate of 23 percent per decade, and the growth rate of emissions by the rest of the world declines at a rate of 13 percent per decade.

Q(T): output level without climate factor impact Q0 is 1978 Chinese GDP, or 0.359 trillion yuans. The growth rates of real GDP are reported in table 4.1 (page 76). In the computer program, growth rates are converted into multiples of 1978 GDP to simplify the equation used to calculate the output levels.

The rest of the parameters assumes the values estimated by Nordhaus (1994).

Model Results Report and Analysis: The First Run

The values of several major parameters in each period of time are summarized in table 4.1 (page 75), with China's population and emissions-output ratio, and emissions by the rest of the world, estimated as explained above. Radiative forcing from other GHGs is from Nordhaus. The average annual growth rates of output in the first two decades are historical data. Growth rates for output between now and 2050 are based on the Chinese government planning objectives (high growth rate scenario) as reported in Street, and in Xu; Growth rates for output are assumed to level out at 2.5 percent after 2050.

The DICE-CHN population projections are within the bounds of the United Nations projections (table 2.3 on page 33) at least up to 2025. After then, the United Nations projects the growth of China's population will level out then decline, while DICE-CHN projections show only a trend slowing growth. In DICE-CHN, a leveling out or decline does not occur in the research time span, that is, up to 2210s.

Table 4.1 Values of Major Parameters in DICE-CHN

Year	Population (millions)	Emission-Output Ratio (t-C per thousand yuans)	Emissions by ROW (GtC)	Forcing from other GHGs (GtCE)	Average Annual Growth rate of GDP (%)
1975	924.200	1.135	5.500	0.497	9.4
1985	1071.160	0.741	6.824	0.604	9.2
1995	1214.084	0.506	8.247	0.705	7.5
2005	1350.254	0.359	9.739	0.800	6.5
2015	1477.744	0.265	11.270	0.887	5.5
2025	1595.351	0.201	12.812	0.968	4.5
2035	1702.483	0.157	14.339	1.041	4.5
2045	1799.035	0.126	15.829	1.108	3.5
2055	1885.268	0.104	17.264	1.169	2.5
2065	1961.692	0.087	18.632	1.222	2.5
2075	2028.982	0.074	19.922	1.269	2.5
2085	2087.902	0.064	21.128	1.308	2.5
2095	2139.250	0.057	22.247	1.341	2.5
2105	2183.820	0.051	23.278	1.420	2.5
2115	2222.377	0.046	24.223	1.420	2.5

The first run of the model simulates the aspects of limiting world annual GHG emissions to specific level: 8.045 GtC, 6.436 GtC, and 9.28 GtC. According to Nordhaus' projection, total world emissions in 1990 was 8.045 GtC. 1995 emissions were 9.28 GtC. The 6.436 GtC level is 80 percent of the 1990 level. Both the 8.045 GtC and the 6.436 GtC constraints have been posed by other researchers.

Three scenarios are experimented with in this first run. The scenarios are defined by the levels of emissions specified above. Under each scenario, three cases are examined to capture different combinations of optimal emissions reduction rate forChina (MIUC) and optimal emissions reduction rate for the rest of the world (MIUO).

This produces nine cases. They are:

I-A-1: no control over MIUC and MIUO, emissions limit 8.045 GtC;
I-A-2: MIUC = 0, no control over MIUO, emissions limit 8.045 GtC;
I-A-3: no control over MIUC, MIUO = 0, emissions limit 8.045 GtC;
I-B-1: no control over MIUC and MIUO, emissions limit 6.436 GtC;
I-B-2: MIUC = 0, no control over MIUO, emissions limit 6.436 GtC;
I-B-3: no control over MIUC, MIUO = 0, emissions limit 6.436 GtC;
I-C-1: no control over MIUC and MIUO, emissions limit 9.28 GtC;
I-C-2: MIUC = 0, no control over MIUO, emissions limit 9.28 GtC;
I-C-3: no control over MIUC, MIUO = 0, emissions limit 9.28 GtC.

Table 4.2 on page 77 summarizes the income levels from each case, while table 4.3 on page 78 reports the combinations of MIUC and MIUO in each case. It appears that we are able to identify a case where the income level is the highest. However, a closer look at the results tells a different story.

From table 4.3, the only time when China can afford not to reduce its emissions is when the rest of the world cuts back their emissions very aggressively. In case 2 under every scenario, MIUC is set at 0, and the resulting MIUO is very large

Table 4.2 Income from the First Run (trillion yuans)

Year	Scenario A (E=8.045)			Scenario B (E=6.436)			Scenario C (E=9.28)		
	I-A-1	I-A-2	I-A-3	I-B-1	I-B-2	I-B-3	I-C-1	I-C-2	I-C-3
2005	4.238	4.235	4.235	4.237	4.236	4.066	4.235	4.235	4.235
2015	7.949	7.943	7.943	7.955	7.945	7.627	7.942	7.942	7.942
2025	13.574	13.564	13.021	13.574	13.568	13.025	13.561	13.561	13.561
2035	21.071	21.054	21.054	21.109	21.063	21.063	21.047	21.047	21.047
2045	32.703	32.676	32.676	32.780	32.693	32.693	32.662	32.662	32.502
2055	46.104	46.066	46.066	46.239	46.096	46.096	46.042	46.042	46.042
2065	58.980	58.930	58.930	59.038	58.975	58.156	58.894	58.894	58.894
2075	75.457	75.392	74.062	75.707	75.459	74.122	75.339	75.339	73.209
2085	96.533	96.449	94.344	96.656	96.545	94.384	96.373	96.373	94.265
2095	123.502	123.393	120.146	123.577	123.530	118.589	123.286	124.121	120.068
2105	158.011	157.872	153.117	158.028	158.062	151.740	157.722	158.080	153.045
2115	202.134	203.363	195.240	201.989	203.363	202.243	201.772	201.926	201.772
2125	258.450	259.018	258.425	258.025	259.267	258.786	258.105	258.212	258.143

Table 4.3 Emission Reduction Rates from the First Run (%)

Year	Scenario A (E=8.045)						Scenario B (E=6.436)						Scenario C (E=9.28)					
	I-A-1		I-A-2		I-A-3		I-B-1		I-B-2		I-B-3		I-C-1		I-C-2		I-C-3	
	μC	μO	μC	μO	μC	μO	μC	μO	μC	μO	μC	μO	μC	μO	μC	μO	μC	μO
2005	0	33.0	0	33.0	1	0	0	49.6	0	49.6	1	0	0	20.4	0	20.4	1	0
2015	0	47.3	0	47.3	1	0	0	61.6	0	61.6	1	0	0	36.3	0	36.3	1	0
2025	0	58.5	0	58.5	1	0	0	71.1	0	71.1	1	0	0	48.9	0	48.9	1	0
2035	0	67.0	0	67.0	1	0	0	78.3	0	78.3	1	0	0	58.4	0	58.4	1	0
2045	0	75.3	0	75.3	1	0	0	85.5	0	85.5	1	0	0	67.5	0	67.5	1	0
2055	0	81.1	0	81.1	1	0	0	90.5	0	90.5	1	0	0	74.0	0	74.0	1	0
2065	0	84.4	0	84.4	1	0	0	93.0	0	93.0	1	0	0	77.8	0	77.8	1	0
2075	0	87.8	0	87.8	1	0	0	95.5	0	95.9	1	0	0	81.6	0	81.6	1	0
2085	0	91.4	0	91.4	1	0	0	99.0	0	99.0	1	0	0	85.6	0	85.6	1	0
2095	0	95.4	0	95.4	1	0	8.4	1	0	1	1	0	0	89.9	0	89.9	1	0
2105	0	99.9	0	99.9	1	0	19.8	1	0	1	1	0	0	94.6	0	94.6	1	0
2115	13.3	1	0	1	1	0	30.6	1	0	1	1	0	0	1	0	1	1	0
2125	25.8	1	0	1	1	0	49.7	1	0	1	1	0	14.4	1	0	1	1	0

* μC = MIUC, μO = MIUO.

and increasing, starting in the first decade of the next century, and reaches 1 sooner or later, depending on the total emissions limitation. Even with the rest of the world cutting back their emissions aggressively, all China can do is to delay emission reductions. This follows from comparing cases 1 and 2 under each scenario. Note that the optimal MIUC is not zero forever. Sooner or later, depending on the emissions limitation, China would have to start reducing its own emissions. This is because, as the rest of the world is cutting back on their emissions, the share of China's emissions in the world total is increasing and the absolute magnitude of China's emissions alone is enough to cause climate damages to its own economy, as well as to the economy of the rest of the world.

On the other hand, MIUC goes to 1 whenever MIUO = 0. In case 3 under all three scenarios, when MIUO is set at 0, the optimal MIUC is 1. This suggests that emissions by the rest of the world are large enough to damage China's economy. Therefore, the best thing China can do to maximize its own well-being is not to emit any GHGs at all. Also, if we look at the income levels reported in table 4.2, under each scenario, income in case 3 is always the lowest unless MIUO is 1. This may be interpreted as a high dependence of China's economic well-being on emissions in the rest of the world. The interdependence of China and the rest of the world on the issue of limiting global climate change can be seen clearly here. If China does not participate in efforts to reduce GHG emissions, even though the rest of the world does not emit at all, the emissions by China, alone, are enough to cause damages to China's economy, and very likely to the rest of the world, too. If the rest of the world does not reduce its emissions at all, China would face losses in terms of income even if it reduces its emissions by 100 percent. Without the participation by both parties, the entire world would lose one way or the other.

Since 100 percent emissions reduction by either China or the rest of the world is not possible, we conclude that limiting world annual emissions to any of the three assumed level is not feasible, at least from the perspective of maximizing China's utility. However, by examing the income levels from each case, we can see that it is better for China if emissions are limited to the lower level. Under the three scenarios, the income level from scenario B is the highest (emission level the lowest), while the income level in scenario C is the lowest (emission level the highest). This indicates the sensitivity of China's economy toward climatic conditions. In other words, as a developing country, with a large agricultural sector that is very climate-sensitive, and a long coastline with much of the country's production capacity along it, it should be in China's own interest to limit the GHG emissions to a lower level.

Model Results Report and Analysis: The Second Run

From the results of the first run we can see that stabilizing world annual emissions require aggressive emission reduction in the next a hundred years either by China or by the rest of the world. However, it is unrealistic to ask either party to reduce their GHG emissions so aggressively. Therefore, the second run of the model abandons the goal of stabilizing emissions, and focuses on finding the optimal emission paths.

Two scenarios are defined in the second run. In scenario A, MIUC = 0, or the emissions reduction rate of China is zero in every period of time (business as usual for

China). In scenario B, there is no control over MIUC; i.e., MIUC is solved for through optimization, given the behavior of the rest of the world.

Under each scenario, three cases are explored, with MIUO=0, MIUO=0.2, and MIUO optimally solved for. The first case is when the rest of the world carries out "business as usual", the third case is what is "expected" from the rest of the world to maximize China's utility. The second case assumes that the rest of the world reduces their emissions by 20 percent each period, compared to the uncontrolled (business as usual) case. The 20 percent reduction level is not chosen on any economic or scientific basis. Cases I-B-1, I-B-2, and I-B-3, above, incorporate a 20 percent freeze in emissions. Cases II-B-1, II-B-2, and II-B-3, below, incorporate a 20 percent reduction relative to business as usual. The latter reflect a somewhat more reasonable and achievable "20 percent reduction" goal.

The two scenarios and three cases under each produces six cases:

II-A-1: MIUC = 0, MIUO = 0 (the equivalent of the Nordhaus base case, or business as usual in other studies);
II-A-2: MIUC = 0, MIUO = 0.2;
II-A-3: MIUC = 0, no control over MIUO;
II-B-1: no control over MIUC, MIUO = 0;
II-B-2: no control over MIUC, MIUO = 0.2;
II-B-3: no control over MIUC, no control over MIUO (the optimal case for China, with both MIUC and MIUO solved through optimization).

Case II-A-1 in DICE-CHN is equivalent to the Nordhaus base case, where there is no emissions reduction or abatement effort by any country. It is also called the business-as-usual (BAU) scenario in other studies. The results generated by DICE-CHN for case II-A-1 are comparable to Nordhaus uncontrolled scenario in terms of world emissions, atmospheric concentrations of GHGs, and increase in global surface mean temperatures (see table 4.4 on page 82).

Table 4.4 Results Comparison - E, M, TA: Nordhaus vs DICE-CHN

Year	World Total Emissions (GtC)		Atmospheric Concentration (GtC)		Change in Atmospheric Temperature (C)	
	Nordhaus	II-A-1	Nordhaus	II-A-1	Nordhaus	II-A-1
1975	5.89	5.91	698	698	0.40	0.40
1985	7.53	7.46	727	727	0.58	0.58
1995	9.28	9.29	764	763	0.76	0.76
2005	11.07	11.26	809	808	0.96	0.96
2025	14.62	15.55	921	925	1.40	1.40
2075	21.96	25.53	1293	1353	2.68	2.75

Scenario II-B in the DICE-CHN is the "optimal" scenario for China. However, since the behavior of the rest of the world is exogenously determined, the "optimal" emissions reduction rate as well as output growth rate differs, depending on the assumptions about the rest of the world emissions. An interesting, but not surprising, result is that whenever MIUO is not explicitly controlled, it always goes to 1. This is understandable, since for China's own well-being, if the rest of the world does not emit any GHGs, the damage potential would be minimum and the abatement cost would also be minimum. In fact, MIUO goes to 1 in both cases II-A-3 and II-B-3 when it is determined through optimization. In II-A-3, MIUC is fixed at 0, while in II-B-3, MIUC is also determined through optimization.

Refer to table 4.5 on page 84. Even with MIUO = 1 (II-B-3), the optimal emissions reduction rate for China is still not zero. The only difference is that if MIUO = 1, it allows China's emissions reduction rates to be lower than when MIUO = 0 or 0.2, at least before 2085. However, after 2085, the emissions reduction rates by China should be higher than in the other two cases. This result indicates that emissions by China only would be enough to cause losses in its output or income. Comparing cases II-A-3 (where MIUC = 0) and II-B-3 (optimal MIUC greater than 0), in table 4.6 on page 85, income (that is, output with climate factor impact) in case II-B-3 is either equal to (before 2065) or higher than (starting in 2065) income in II-A-3. Similar results can be seen in terms of consumption (table 4.7 on page 86) and per capita consumption (table 4.8 on page 87). Actually, this conclusion can be generalized to include all cases. Given emissions reduction rates by the rest of the world, it is optimal for China's reduction rates to be greater than zero. When

Table 4.5 Optimal MIUC from the Second Run (%)

Year	II-B-2	II-B-3	Year	II-B-2	II-B-3
2005	3.8	3.6	2065	7.0	6.8
2015	4.5	4.3	2075	7.2	7.1
2025	5.1	4.9	2085	7.6	7.5
2035	5.7	5.4	2095	7.9	8.0
2045	6.3	6.1	2105	8.4	8.6
2055	6.8	6.5	2115	8.9	9.2

Table 4.6 Income from the Second Run (trillion yuans)

Year	Income (Y)					
	Scenario A			Scenario B		
	II-A-1	II-A-2	II-A-3	II-B-1	II-B-2	II-B-3
1975	0.359	0.359	0.359	0.359	0.359	0.359
1985	0.854	0.854	0.854	0.854	0.854	0.854
1995	2.056	2.056	2.056	2.056	2.056	2.056
2005	4.236	4.236	4.236	4.236	4.236	4.236
2015	7.944	7.944	7.944	7.944	7.944	7.944
2025	13.564	13.565	13.568	13.564	13.565	13.568
2035	21.049	21.053	21.066	21.049	21.053	21.066
2045	32.655	32.666	32.707	32.655	32.666	32.707
2055	46.009	46.033	46.126	46.009	46.033	46.126
2065	58.810	58.854	59.027	58.811	58.856	59.028
2075	75.164	75.241	75.538	75.168	75.245	75.541
2085	96.047	96.173	96.658	96.054	96.179	96.664
2095	122.722	122.918	123.684	122.734	122.929	123.694
2105	156.794	157.090	158.263	156.813	157.109	158.279
2115	200.294	200.731	202.492	200.324	200.762	202.519

Table 4.7 Consumption from the Second Run (trillion yuans)

Year	without climate impact	Consumption with climate factor impacts					
		Scenario A			Scenario B		
		II-A-1	II-A-2	II-A-3	II-B-1	II-B-2	II-B-3
1975	0.233	0.233	0.233	0.233	0.233	0.233	0.233
1985	0.555	0.555	0.555	0.555	0.555	0.555	0.555
1995	1.3375	1.336	1.336	1.336	1.336	1.336	1.336
2005	2.756	2.753	2.753	2.753	2.753	2.753	2.753
2015	5.171	5.164	5.164	5.164	5.164	5.164	5.164
2025	8.835	8.816	8.817	8.819	8.816	8.817	8.819
2035	13.721	13.682	13.684	13.693	13.682	13.684	13.693
2045	21.307	21.226	21.233	21.259	21.226	21.223	21.259
2055	30.055	29.906	29.921	29.982	29.906	29.904	29.982
2065	38.470	38.226	38.255	38.367	38.227	38.256	38.368
2075	49.244	48.857	48.907	49.100	48.859	48.909	49.101
2085	63.030	62.431	62.512	62.828	62.435	62.516	62.831
2095	80.679	79.769	79.897	80.395	79.777	79.904	80.401
2105	103.269	101.916	102.108	102.871	101.928	102.121	102.882
2115	132.186	130.191	130.475	131.620	130.211	130.495	131.638

Table 4.8 Per capita Consumption with and without Climate Impact
(thousand yuans)

		Per Capita Consumption (C / L)					
		Scenario A			Scenario B		
Year	C* / L	II-A-1	II-A-2	II-A-3	II-B-1	II-B-2	II-B-3
1975	0.252	0.252	0.252	0.252	0.252	0.252	0.252
1985	0.518	0.518	0.518	0.518	0.518	0.518	0.518
1995	1.101	1.101	1.101	1.101	1.101	1.101	1.101
2005	2.041	2.039	2.039	2.039	2.039	2.039	2.039
2015	3.499	3.494	3.494	3.494	3.494	3.494	3.494
2025	5.538	5.526	5.527	5.528	5.526	5.527	5.528
2035	8.059	8.036	8.038	8.043	8.036	8.038	8.043
2045	11.844	11.798	11.802	11.817	11.798	11.802	11.817
2055	15.942	15.863	15.871	15.903	15.863	15.871	15.903
2065	19.611	19.486	19.501	19.558	19.487	19.502	19.559
2075	24.270	24.079	24.104	24.199	24.081	24.105	24.200
2085	30.188	29.901	29.940	30.091	29.903	29.942	30.093
2095	37.713	37.289	37.348	37.581	37.292	37.351	37.584
2105	47.288	46.669	46.757	47.106	46.674	46.762	47.111
2115	59.480	58.582	58.710	59.225	58.591	58.719	59.233

C*: Consumption based on output without climate factor impacts.

MIUO=0 (II-B-1 and II-A-1), China's income, consumption and per capita consumption are all higher when its emissions reduction rate is higher than zero (case II-B-1). The result is similar when MIUO = 0.2 (II-B-2 and II-A-2). The result that there is no difference in incomes (and consumptions) before 2065 may reflect the fact that the impact of GHG concentrations do not show until decades later. For the same reason, optimal MIUC may be lower before 2065 when MIUO = 1, but has to be higher thereafter when compared to cases where MIUO = 0 or 0.2.

In scenario II-B, when China follows the optimal emissions reduction path, the optimal MIUC (table 4.5 on page 84) in cases II-B-1 and II-B-2 seems strange at the glance. It would be easier to understand if MIUC in II-B-1 is higher than MIUC in II-B-2, because in II-B-1, the rest of the world is not reducing its emissions at all. Therefore, China would have to reduce emissions more to reduce the effects of climate changes. In II-B-2, when the rest of the world reduces their emissions by 20 percent, China should be able to afford a smaller reductions in its emissions.

However, the impact of MIUC is not limited to temperature (climate) change only. MIUC is also a determinant of the total costs of emissions reductions. Recall that the climate impact factor has two parts: first, the economic damages caused by climate change, and, second, the costs of reducing climate change. Because of the relationship between production and emissions, reducing emissions reduces output. By reducing emissions, however, damages caused by climate change can also be reduced. The climate impact factor therefore is equal to ((Q-TC)/Q)/((Q+D)/Q), or (Q-TC)/(Q+D). Thus, MIUC has a more complicated role to play than simply that of determining total world emissions. Higher MIUC would cause higher TC, but also would reduce D, making its impact on the climate factor hard to determine simply by the direction of change. The magnitude of change is more important in optimization.

As China's share in the world total emissions increases (table 4.9 on page 90), a 20 percent emissions reduction by the rest of the world becomes less important. To avoid damages to China caused by climate change, it may be optimal for China to reduce emissions more, even though this would mean a higher abatement cost.

As in the first run, although MIUO = 1 provides some very interesting results, it is unlikely to be practically "feasible". Thus, from the point view of policy implications, only cases where MIUO = 0 and 0.2 are meaningful.

Table 4.10 (on page 91) summarizes the percentage income losses from the four cases II-A-1, II-A-2, II-B-1, and II-B-2, as compared to the situation when there are no climate factor impacts. Generally speaking, the reduction in China's economic well-being is less when the rest of the world reduces its emissions, say, by 20 percent (MIUO = 0.2) than when they do not (MIUO = 0). And, given the emissions reduction rate by the rest of the world, the reduction in China's economic well-being is less if China follows its optimal emissions reduction path than if China does not reduce its emissions at all.

When the four cases are ranked according to the losses in China's income, II-B-2 is the best option (lowest loss) and II-A-1 is the worst (highest loss). The ranking would be the same using percentage losses in consumption and per capita consumption.

Table 4.11 (page 92) reports the optimal growth rates of output based on the optimal emission reduction rates in cases II-B-1 and II-B-2. In both cases, the optimal

Table 4.9 China's share in world emissions: the Optimal Case (%)

Year	II-B-1	II-B-2	Lu *	Year	II-B-1	II-B-2	Lu*
1975	0.069	0.069	0.066	2055	0.206	0.244	
1985	0.085	0.085		2065	0.204	0.243	
1995	0.112	0.112		2075	0.207	0.246	0.284
2005	0.131	0.158		2085	0.214	0.254	
2015	0.151	0.182		2095	0.225	0.267	
2025	0.168	0.202	0.167	2105	0.240	0.283	
2035	0.179	0.214		2115	0.259	0.304	
2045	0.197	0.234					

* Lu, 1989, p.50, with nuclear energy, 2050 as the target year for China to catch up with the lower level of developed countries.

Table 4.10 Percentage Losses in Income due to Climate Factor Impact (%)

Year	Percentage Loss in Y				Percentage Loss in C				Percentage Loss in CPC			
	II-A-1	II-A-2	II-B-1	II-B-2	II-A-1	II-A-2	II-B-1	II-B-2	II-A-1	II-A-2	II-B-1	II-B-2
2005	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
2015	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
2025	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
2035	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003	-0.003
2045	-0.004	-0.003	-0.004	-0.003	-0.004	-0.003	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004
2055	-0.005	-0.004	-0.005	-0.004	-0.005	-0.004	-0.005	-0.005	-0.005	-0.004	-0.005	-0.004
2065	-0.006	-0.006	-0.006	-0.006	-0.006	-0.006	-0.006	-0.006	-0.006	-0.006	-0.006	-0.006
2075	-0.008	-0.007	-0.009	-0.007	-0.008	-0.007	-0.008	-0.007	-0.008	-0.007	-0.008	-0.007
2085	-0.010	-0.008	-0.009	-0.008	-0.010	-0.008	-0.009	-0.008	-0.010	-0.008	-0.009	-0.008
2095	-0.011	-0.010	-0.011	-0.010	-0.011	-0.010	-0.011	-0.010	-0.011	-0.010	-0.011	-0.010
2105	-0.013	-0.011	-0.013	-0.011	-0.013	-0.011	-0.013	-0.011	-0.013	-0.011	-0.013	-0.011
2115	-0.015	-0.013	-0.015	-0.013	-0.015	-0.013	-0.015	-0.013	-0.015	-0.013	-0.015	-0.013

Table 4.11 Optimal Growth Rate of Output

Year	EROW	E-CHN		MIUC		Optimal Reduction Amount (GtC)		Optimal Emission Level (GtC)		Optimal Output Level (trillion yuans)		Optimal Growth Rate of Output (%)		planned growth rate (%)
		II-B-1	II-B-2	II-B-1	II-B-2	II-B-1	II-B-2	II-B-1	II-B-2	II-B-1	II-B-2	II-B-1	II-B-2	
2005	9.739	1.466	1.466	3.8	3.8	0.056	0.056	1.410	1.410	3.928	3.928	6.3	6.3	6.5
2015	11.270	2.010	2.010	4.5	4.5	0.090	0.090	1.920	1.920	7.244	7.244	5.4	5.4	5.5
2025	12.812	2.592	2.592	5.1	5.1	0.132	0.132	2.460	2.460	12.238	12.240	4.4	4.4	4.5
2035	14.339	3.131	3.131	5.7	5.7	0.178	0.178	2.953	2.952	18.806	18.805	4.4	4.4	4.5
2045	15.829	3.875	3.874	6.3	6.3	0.244	0.244	3.631	3.630	28.816	28.808	3.4	3.3	3.5
2055	17.264	4.467	4.465	6.7	6.8	0.299	0.304	4.168	4.161	40.074	40.011	2.5	2.5	2.5
2065	18.632	4.782	4.778	6.9	7.0	0.330	0.334	4.452	4.444	51.173	51.079	2.5	2.5	2.5
2075	19.922	5.211	5.206	7.2	7.2	0.375	0.375	4.836	4.832	65.349	65.291	2.5	2.5	2.5
2085	21.128	5.769	5.763	7.5	7.6	0.433	0.438	5.336	5.325	83.380	83.198	2.3	2.3	2.5
2095	22.247	6.477	6.468	7.8	7.9	0.505	0.511	5.972	5.957	104.768	104.516	2.4	2.4	2.5
2105	23.278	7.366	7.354	8.2	8.4	0.604	0.618	6.762	6.736	132.588	132.076	2.4	2.4	2.5
2115	24.223	8.471	8.456	8.7	8.9	0.737	0.753	7.734	7.703	168.131	167.458	2.4	2.4	2.5

growth rate is slightly lower than the planned growth rates starting right now, but the growth rate of output after 2125 exceeds the planned growth rate for most of the subsequent periods. This may be consistent with the thinking that the welfare impact of emissions reduction is time-sensitive, meaning that emissions reduced now would improve economic well-being more than emissions reductions taken in the future.

The optimal growth rates of output for cases II-B-1 and II-B-2 are almost identical. One explanation may be that, since the share of China's emissions in the world total increases with time (see table 4.9 on page 90), a 20 percent reduction by the rest of the world has a smaller impact on China's economic well-being and on China's optimal growth rates of output. China's optimal results are determined more by its own production level than by economic activity in the rest of the world.

Summary

Based on the model results and analyses reported in this chapter, the "optimal" and most feasible case would be II-B-2, where the rest of the world reduces 20 percent of its emissions in each period, relative to the uncontrolled (business-as-usual) case, and China follows its optimal emissions reduction path, which requires a reduction rate of between 3.8 percent starting the beginning of the next century to 11 percent later in the future. The percentage loss in income and consumption is the lowest in this case, among the cases studied, and the reduction objective seems achievable.

According to the projections of the DICE-CHN model, by the middle of the next century (2055), GHG accumulations in the atmosphere are to reach 1088 GtC, or somewhat less than double the preindustrial level of 590 GtC, and the doubling of the concentration would not occur until more than one decade later. The global surface mean temperature in 2075 (shortly after the doubling occurs) would be 2.56 °C higher than the preindustrial level, which is consistent with the IPCC best guess.

CHAPTER V

SENSITIVITY ANALYSIS

In Chapter IV, we concluded that the best (optimal and feasible) case is II-B-2, where there is no fixed limitation on emissions, the rest of the world reduces their emissions by 20 percent relative to the uncontrolled level, and China follows its optimal emissions reduction path. Case II-B-2 will be referred to as the optimal case in this chapter. The sensitivity analysis focuses on both the base case, where MIUC and MIUO are both equal to 0, and the optimal case to show how sensitive income and emissions reduction rates are to changes in the basic parameters of the model.

RHO: the Pure Rate of Social Time Preference (the Discount Rate)

In the DICE-CHN, RHO (ρ) equals 0.03 as in the original DICE model. Two other values of RHO are specified for the sensitivity analysis: 0 and 0.06. There are two reasons for choosing these two values: (1) these are the values chosen by van Ierland & Derksen (1994) in their sensitivity analysis for the Nordhaus DICE model, (2) Cline (1992) uses a pure rate of social time [reference of zero, and 0.06 gives the same magnitude of difference as 0 from 0.03, the value used in DICE-CHN.

In the base case, where MIUC and MIUO are explicitly set at 0, the difference in the values of RHO has no impact on the income level. Income levels for all peoriods are identical at all three values of RHO. This suggests that income level is not sensitive to the value RHO, perhaps because income level is directly related to emissions reduction rate, which is set at 0 in all three cases. However, this result does not rule out the possibility of the optimal emissions reduction rate being sensitive to the value of RHO.

The optimal case explains the reasoning above more clearly. The optimal MIUC is very sensitive to RHO. In table 5.1 on page 97, when there is no discounting factor (RHO=0), MIUC is higher than 10 percent for all periods (ranging from 13 percent to more than 20 percent). However, at a discount rate of 0.06, MIUC is no higher than 5 percent until close to the end of the study time span. The 100 percent decline in the discount rate (from 3 percent to 0 percent) resulted in a 35 percent to more than 200 percent increase in the optimal MIUC, while the 100 percent increase in RHO from 0.03 to 0.06 results in about a 50 percent reduction in the optimal MIUC before 2085. However, although income levels are different for the three values of RHO, the difference in percentage loss of income between the cases of RHO=0 and RHO=0.06 almost never exceeds 0.2 percent. In fact, the differences in income loss in most periods are less than 0.1 percent of output, with the loss at RHO=0 less than the loss at RHO=0.06 before 2105, and the other way around after that. The percentage loss in income relative to output, without climate factor impact, increases over time for all three cases.

<u>A1: Coefficient of the Damage Function from Carbon Dioxide Doubling</u>

As explained in chapter IV, A1 in DICE-CHN is estimated as 0.0094. This is a parameter whose value is uncertain at the existing state of knowledge. For sensitivity analysis, A1 assumes two other values: 0.0044 and 0.0144, or 53 percent lower and higher than the default value.

Table 5.1 Sensitivity to RHO

year	Output	Income			Loss in Income			Optimal MIUC		
		RHO=0	RHO=0.03	RHO=0.06	RHO=0	RHO=0.03	RHO=0.06	RHO=0	RHO=0.03	RHO=0.06
2005	4.240	4.235	4.236	4.236	0.118	0.094	0.094	13.0	3.8	1.9
2015	7.955	7.943	7.944	7.944	0.151	0.138	0.138	14.7	4.5	2.2
2025	13.592	13.562	13.565	13.565	0.221	0.199	0.199	16.2	5.1	2.6
2035	21.109	21.048	21.053	21.053	0.289	0.265	0.265	17.2	5.7	2.9
2045	32.780	32.657	32.666	32.666	0.375	0.348	0.348	18.5	6.3	3.3
2055	46.239	46.021	46.033	46.033	0.471	0.446	0.446	19.2	6.8	3.5
2065	59.185	58.842	58.856	58.856	0.580	0.556	0.556	19.1	7.0	3.7
2075	75.760	75.230	75.245	75.244	0.700	0.680	0.681	19.2	7.2	3.8
2085	96.969	96.164	96.179	96.177	0.830	0.815	0.817	19.4	7.6	4.0
2095	124.121	122.915	122.929	122.925	0.972	0.960	0.964	19.7	7.9	0.0
2105	158.875	157.097	157.109	157.102	1.119	1.112	1.116	20.0	8.4	0.0
2115	203.363	200.756	200.762	200.749	1.282	1.279	1.285	20.3	8.9	0.0
2125	260.304	256.548	256.543	256.517	1.443	1.445	1.455	20.6	9.4	0.0
2135	333.188	327.841	327.815	327.767	1.605	1.613	1.627	20.8	9.9	0.0
2145	426.481	418.939	418.871	418.786	1.768	1.784	1.804	20.7	10.4	0.0
2155	545.895	535.331	535.185	535.039	1.935	1.962	1.989	20.3	10.8	0.0

Note: Output and income are in trillion yuans, others in percentage.

For the base case (table 5.2 on page 99), at A1=0.0044, the percentage loss in income is never higher than 2 percent of the output. However, with A1=0.0144, the percentage loss can be more than 5 percent. The percentage loss in income is always more than three times as high when A1=0.0144 as compared to A1=0.0044. Given the fact that the high value of A1 (0.0144) is 3.27 times as high as the low value of A1 (0.0044), this may imply that the relationship between A1 and percentage income loss is linear. Alternatively, a 53 percent reduction in A1 results in more than a 50 percent reduction in income loss, while a 53 percent increase in A1 leads to more than a 50 percent of increase in income loss. It appears from these calculations that change in the percentage income loss is approximately equal to change in A1.

The percentage loss in income is less in the optimal case (table 5.3 on page 100) than in the base case, with the highest loss being less that 5 percent of output. This result is consistent with the conclusion in Chapter IV that it is optimal for China to follow the optimal emissions reduction path rather than not reducing its emissions at all. The optimal emissions reduction rate for China is always 80 percent higher when A1 takes the high value rather than the low value. When compared to the optimal emissions reduction rate at the default value of A1, a 53 percent reduction in A1 results in a reduction in the optimal MIUC of only about 35 percent, while a 53 percent increase in A1 leads to an increase in optimal MIUC of only about 25 percent. However, sensitivity of percentage income loss to A1 is still about 1, meaning, the percentage loss in the high A1 case is still more than three times higher than in the low A1 case, or change in percentage income loss and change in A1 has a one to one relationship.

Table 5.2 Sensitivity to A1: the Base Case

year	Output	Income			Loss in Income		
		A1=0.0044	A1=0.0094	A1=0.0144	A1=0.0044	A1=0.0094	A1=0.0144
2005	4.24	4.238	4.236	4.234	0.047	0.094	0.142
2015	7.955	7.950	7.944	7.938	0.063	0.138	0.214
2025	13.592	13.579	13.564	13.549	0.096	0.206	0.316
2035	21.109	21.081	21.049	21.017	0.133	0.284	0.436
2045	32.78	32.721	32.655	32.589	0.180	0.381	0.583
2055	46.239	46.131	46.009	45.887	0.234	0.497	0.761
2065	59.185	59.009	58.810	58.612	0.297	0.634	0.968
2075	75.76	75.480	75.164	74.852	0.370	0.787	1.199
2085	96.969	96.536	96.047	95.564	0.447	0.951	1.449
2095	124.121	123.462	122.722	121.991	0.531	1.127	1.716
2105	158.875	157.894	156.794	155.709	0.617	1.310	1.993
2115	203.363	201.915	200.294	198.699	0.712	1.509	2.293
2125	260.304	258.206	255.863	253.562	0.806	1.706	2.590
2135	333.188	330.188	326.844	323.567	0.900	1.904	2.888
2145	426.481	422.231	417.502	412.879	0.997	2.105	3.189
2155	545.895	539.915	533.276	526.799	1.095	2.312	3.498

Note: Output and income are in trillion yuans, loss is in percentage.

Table 5.3 Sensitivity to A1: the Optimal Case

		Income			Loss in Income			Optimal MIUC		
year	Output	A1=0.0044	A1=0.0094	A1=0.0144	A1=0.0044	A1=0.0094	A1=0.0144	A1=0.0044	A1=0.0094	A1=0.0144
2005	4.24	4.238	4.236	4.234	0.047	0.094	0.142	2.5	3.8	4.7
2015	7.955	7.950	7.944	7.938	0.063	0.138	0.214	3.0	4.5	5.6
2025	13.592	13.579	13.565	13.550	0.096	0.199	0.309	3.4	5.1	6.4
2035	21.109	21.083	21.053	21.022	0.123	0.265	0.412	3.8	5.7	7.1
2045	32.78	32.727	32.666	32.605	0.162	0.348	0.534	4.2	6.3	7.9
2055	46.239	46.142	46.033	45.925	0.210	0.446	0.679	4.5	6.8	8.5
2065	59.185	59.030	58.856	58.683	0.262	0.556	0.848	4.7	7.0	8.7
2075	75.76	75.517	75.245	74.975	0.321	0.680	1.036	4.9	7.2	9.0
2085	96.969	96.597	96.179	95.766	0.384	0.815	1.241	5.1	7.6	9.4
2095	124.121	123.558	122.929	122.309	0.454	0.960	1.460	5.3	7.9	9.9
2105	158.875	158.041	157.109	156.192	0.525	1.112	1.689	5.6	8.4	10.5
2115	203.363	202.132	200.762	199.417	0.605	1.279	1.940	6.0	8.9	11.1
2125	260.304	258.522	256.543	254.605	0.685	1.445	2.189	6.3	9.4	11.7
2135	333.188	330.639	327.815	325.055	0.765	1.613	2.441	6.7	9.9	12.4
2145	426.481	422.866	418.871	414.977	0.848	1.784	2.697	7.0	10.4	13.0
2155	545.895	540.800	535.185	529.728	0.933	1.962	2.962	7.3	10.8	13.5
2165	698.747	691.597	683.746	676.138	1.023	2.147	3.236	7.4	11.0	13.7
2175	894.395	884.396	873.459	862.894	1.118	2.341	3.522	7.2	10.7	13.4

Note: Output and income are in trillion yuans, others in percentage.

DSIGMA: the Decline Rate of Emission-Output Ratio

The emission-output ratio is expected to decline over time because of both energy efficiency improvements and energy source switching. The decline rate of the emissions-output ratio measures how fast energy efficiency improves and energy sources are switched (from high to low carbon concentration fossil fuels, or from fossil fuels to non-fossil fuels). This decline rate is one of the more uncertain parameters, especially in a very long-term context. The original value of DSIGMA in DICE-CHN is equal to 0.45, calculated using two decades of historical data. For sensitivity analysis, we examine two more values: 0.35 and 0.55 -- differences of 22 percent from the default value.

For the base case (table 5.4 on page 102), the faster decline of the emission-output ratio results in smaller losses in income, and the further into the future, the larger the gain in terms of "avoided" loss through improved energy efficiency or energy source switching. For the first three decades of the next century, there are no differences in income at different emissions-output ratios. This is due to the fact that the impacts from emissions occur decades later. Therefore, lower current emissions do not reduce current income losses because current income losses are caused by emissions that occurred decades ago.

Refer to table 5.5 on page 103. The optimal MIUC is lower when the emissions-output ratio declines faster (DSIGMA=0.55), since a lower emissions-output ratio implies fewer emissions at a given output level and requires a smaller reduction. Also, the percentage income loss is less DSIGMA is higher, because better energy efficiency reduces emissions as well as the costs of abatement.

Table 5.4 Sensitivity to DSIGMA: the Base Case

year	Output	Income			Loss in Income		
		Dsig= 0.35	Dsig= 0.45	Dsig= 0.55	Dsig= 0.35	Dsig= 0.45	Dsig= 0.55
2005	4.24	4.236	4.236	4.236	0.1	0.1	0.1
2015	7.955	7.944	7.944	7.944	0.1	0.1	0.1
2025	13.592	13.563	13.564	13.564	0.2	0.2	0.2
2035	21.109	21.048	21.049	21.050	0.3	0.3	0.3
2045	32.78	32.651	32.655	32.658	0.4	0.4	0.4
2055	46.239	45.998	46.009	46.016	0.5	0.5	0.5
2065	59.185	58.786	58.810	58.826	0.7	0.6	0.6
2075	75.76	75.118	75.164	75.195	0.8	0.8	0.7
2085	96.969	95.961	96.047	96.101	1.0	1.0	0.9
2095	124.121	122.574	122.722	122.814	1.2	1.1	1.1
2105	158.875	156.546	156.794	156.942	1.5	1.3	1.2
2115	203.363	199.893	200.294	200.529	1.7	1.5	1.4
2125	260.304	255.226	255.863	256.227	2.0	1.7	1.6
2135	333.188	325.85	326.844	327.402	2.2	1.9	1.7
2145	426.481	415.967	417.502	418.35	2.5	2.1	1.9
2155	545.895	530.921	533.276	534.557	2.7	2.3	2.1

Note: Output and income are in trillion yuans, others in percentage.

Table 5.5 Sensitivity to DSIGMA: the Optimal Case

year	Output	Income			loss in Income			Optimal MIUC		
		Dsig= 0.35	Dsig= 0.45	Dsig= 0.55	Dsig= 0.35	Dsig= 0.45	Dsig= 0.55	Dsig= 0.35	Dsig= 0.45	Dsig= 0.55
2005	4.24	4.236	4.236	4.236	0.094	0.094	0.094	4.4	3.8	3.3
2015	7.955	7.944	7.944	7.944	0.138	0.138	0.138	5.3	4.5	3.8
2025	13.592	13.564	13.565	13.565	0.206	0.199	0.199	6.3	5.1	4.2
2035	21.109	21.051	21.053	21.054	0.275	0.265	0.261	7.1	5.7	4.5
2045	32.78	32.661	32.666	32.669	0.363	0.348	0.339	8.2	6.3	4.9
2055	46.239	46.022	46.033	46.041	0.469	0.446	0.428	8.9	6.8	5.1
2065	59.185	58.833	58.856	58.871	0.595	0.556	0.531	9.4	7.0	5.2
2075	75.76	75.2	75.245	75.274	0.739	0.680	0.641	9.9	7.2	5.3
2085	96.969	96.098	96.179	96.23	0.898	0.815	0.762	10.4	7.6	5.4
2095	124.121	122.79	122.929	123.015	1.072	0.960	0.891	11.1	7.9	5.6
2105	158.875	156.878	157.109	157.249	1.257	1.112	1.023	11.8	8.4	5.9
2115	203.363	200.389	200.762	200.984	1.462	1.279	1.170	12.6	8.9	6.2
2125	260.304	255.951	256.543	256.888	1.672	1.445	1.312	13.4	9.4	6.5
2135	333.188	326.893	327.815	328.344	1.889	1.613	1.454	14.2	9.9	6.8
2145	426.481	417.451	418.871	419.676	2.117	1.784	1.596	14.9	10.4	7.1
2155	545.895	533.018	535.185	536.4	2.359	1.962	1.739	15.5	10.8	7.4

Note: Output and income in trillion yuans, others in percentage.

The loss in income is less in the optimal case than in the base case, a result that is expected. Also, because both the rest of the world and China are cutting back on emissions starting at the beginning of the next century, the difference in income loss occurs earlier than in the base case.

Summary

The model results are sensitive to the prescribed values of some parameters. This chapter examines only a few of the potentially large number of alternative values. Even this limited analysis indicates, however, that projected income losses and optimal emissions reduction rates can be quite sensitive to parameter values of different magnitudes. Given these results, it is suggested that the values of the parameters in the DICE-CHN model should be further investigated and evaluated.

CHAPTER VI

CONCLUSION

Policy Implications

The results from DICE-CHN reported in Chapter IV suggest that, even from the perspective of China's own national interest, it is optimal for China to reduce its GHG emissions. It is beyond the scope of this study to evaluate the various means that China may use to accomplish this reduction. It is possible, however, to suggest promising alternatives for future evaluation.

In a general sense, GHG emissions can be reduced by slowing the economic growth rate of China in the coming decades. Although projected income losses are less than 1 percent before 2085 even in the scenario of business-as-usual for both China and the rest of the world, the results of this study suggest that, given the behavior of the rest of the world, income losses are smaller when China follows the optimal emissions reduction path with emissions reduction rates greater than zero.

The DICE-CHN results may actually provide just one more reason among many why China should slow its economic growth to a more moderate rate in the coming decades. The possibility of global climate change is only one of several environmental problems that China may have to face. Among the others are air and water pollution, deforestation, soil erosion, and desertification, and water shortage. These problems may have negative impacts on China's agricultural and other sectors.

According to Brown (1995), the rapid industrialization of China leads to rapid increases in its national income. However, industrialization also causes large-scale cropland losses. Higher income and larger population increase grain demand, while cropland losses and limited potential for increases in land productivity make it hard for grain supply to keep up. Given the magnitude of China's population and grain demand, attempts to eliminate grain shortages through imports might significantly affect the global grain market and grain prices. Slower economic growth, especially slower industrial growth, would presumably reduce the process of cropland losses and narrow the grain deficit, while providing the time for progress in agricultural technology.

Not all experts agree with Brown, however. Many believe his projection represents the worst-case scenario and does not consider producer and consumer responses to higher prices nor the high priority of grain self-sufficiency in China. However, some believe that China will become a major grain importer in the coming decades (Rozelle, Huang, and Rosegrant, 1996). Brown's proposition that China will not be able to satisfy its own grain demand appears to be sound, although there is some uncertainty about the magnitude of the shortage. If grain self-sufficiency is really one of the top priorities of China, as most people believe, slower industrial growth would be in China's national interest since it would reduce cropland losses and increase China's grain supply capacity.

Rozelle, Huang, and Rosegrant (1996) project that China's grain imports will not be as large as Brown's projection and that the magnitude of China's grain imports will not threaten to starve the world. One of the key assumptions of this projection is that China's agricultural research investment will increase by 3 percent per year, which has not always been true historically. If the investment in agricultural research is to increase every year, it will be necessary to divert capital funds away from other sectors, such as manufacturing and construction. As a result, the industrialization process, in particular, and the economic growth, in general, will have to slow down, since the manufacturing and construction sectors still makes up about 50 percent of the economy and exhibit high growth rates.

Slower economic growth reduces energy demand, which in turn reduces the amount of coal burning and current carbon dioxide emissions. It will also gain the valuable time for China to explore energy-source-switching potentials and agricultural technology improvement. Given more time, people may be able to better understand and adapt to a material-driven world, blunting the feverish pursuit of material benefits and all the negative side-effects that accompany them. In other words, with uncertainty, the best policy should be the so-called "no-regret" policy, and a more moderate growth rate may generate more benefits to the country than it costs in terms of delaying the time of reaching a certain income level.

On a smaller scale, emissions may be reduced through several approaches, such as energy efficiency improvements and energy source switching. Reducing emissions through afforestation may help, but this would probably only be a temporary solution, since carbon released by dying trees at maturity offsets carbon sequestered by new trees. Afforestation also requires the diversion of considerable land area; in China's case, this would probably place extra pressure on agricultural and grain production.

Energy efficiency in China is quite low compared to developed countries or even to other developing countries. Energy consumption per yuan of GDP for China is about twice the average of other developing countries (Wang, 1989, p. 41). According to Zhuang, Zhai, & Kang (1992, p. 26), four energy-intensive industrial sectors (utilities, construction materials, metallurgicals, and chemicals) make up about half of China's energy demand. In each of these sectors, energy efficiency in China is more than 20 percent lower than that of the developed countries' average. This suggests the potential for considerable energy efficiency improvements through energy conservation and technology transfer. Lu (1991) forecasts a long-term energy conservation potential for China of more than 80 percent from 1980 to 2050 (p. 353). Although not as optimistic as Lu's, projections by others also show substantial potential for energy efficiency improvements. For example, Zhuang, Zhai, & Kang estimate that a 30 percent reduction of energy consumption in the most energy-intensive sectors would be possible if sufficient capital investment were available (p.8).

The Chinese government has strengthened measures in energy efficiency improvements through administrative, legislative, economic, and technological means. Significant progress has been achieved in this area as shown by the parameter DSIGMA (decline rate of the emissions-output ratio) in the DICE-CHN model. However, considerable future improvement in energy efficiency requires sufficient capital, which may not be available, or substantial energy price increases or government intervention, which the government may not want to risk.

Cline (1992) summarizes the means of emissions reductions through energy source switching into several categories:

1. Intra-fossil-fuel substitution (IFFS): substitution of more polluting fossil fuels (coal) by less polluting fuels (natural gas).
2. Non-fossil fuel/fossil fuel substitution (NFFS): substitution of non-fossil fuels

(biomass, nuclear, solar, hydro, wind) for fossil fuels.

3. Other-factor/energy substitution (OFES): substitution of other factors (labor and capital) for energy in the production process.
4. Product substitution (PS): substitution of non-energy-intensive products for energy-intensive products in the consumption mix.

As discussed in Chapter II, China's reserves of other (lower carbon-concentration) fossil fuels are relatively small, which makes it unlikely that China can substitute away from coal. China is already a net importer of oil, and the quantity of natural gas available is far less than the demand for energy even with China's ambitious plan of doubling natural gas production of 13 billion cubic meters in 1988 by the beginning of the next century.

High capital cost and technical infrastructure requirements make it hard for China to further pursue the nuclear power option, especially when the lower cost option of coal burning plant is available. The exploitation of China's hydro potential also faces capital availability limitations. In the immediate future, biomass could be a significant alternative. Considering the magnitude of China's energy demand, however, none of these sources would be able to replace coal to any significant degree. The potential of substitution of energy by other production factors may be more limited than suggested by China's large population. Product substitution is worth exploring, but will be difficult to achieve as China's populace gains more purchasing power.

In terms of carbon dioxide emissions, energy source switching will have very limited effects, primarily because coal will continue to be the dominant energy source, satisfying about 70 percent of China's energy demand in the coming decades. As concluded by Streets, et al (p. 1034), "Even with great improvements in energy efficiency and switching whenever possible away from fossil fuels, it seems to be impossible to prevent a sizable increase in carbon dioxide emissions while maintaining a desirable rate of economic development. Investment in energy efficiency and alternative energy sources in China makes economic and environmental sense, but will serve to moderate emissions increases, not prevent them."

These comments bring us back to the argument at the beginning of this chapter. The best way to reduce or to limit carbon dioxide emissions may be to slow economic growth to a more moderate rate. Also, slower economic growth may lessen the pressure on agricultural and grain production, and reduce the scope of other environmental problems.

Another important ingredient may be the continuous success of China's population control policies. Much of the energy demand and enormous emissions is caused by the sheer magnitude of China's population. If population growth is reduced, so will be the demand for energy and the pressure on the environment. Failing to control the growth of its already huge population will definitely make emissions reduction a much tougher task for China.

Strength/Weakness of the Approach and Suggestions for Future Research

The original DICE model is a general equilibrium optimization model that captures the impacts of climate change on economic activities through the linkage between a traditional production function and a emissions-climate factor. The variable control feature of DICE allows the model to be used to examine various policy options and their impacts on output levels and optimal emissions reduction rates. The structure of the DICE model also makes it possible to single out the emissions by specific countries and to estimate abatement costs and damages to those countries. Thus, DICE can be applied to the analysis of the contribution of specific countries to the problem of global warming and the impacts of climate change on those countries.

As pointed out by Dr. Robert Costanza,[5] "Nordhaus has gone further than any economist to date at building a dynamic integrated model of the world's climate and economic systems" and "a thorough job was done in analyzing the (DICE) model's sensitivity to uncertainty about the parameters." However, the one-way linkage between the climate and the economic systems is greatly simplified. Economic output is estimated using a Cobb-Douglas production function in which natural capital is completely missing. Therefore, economic growth is not limited by natural resources or environmental changes at all. This is a very serious more of a problem considering the fact that the purpose of the model is to assess the impact of environmental change on economic activities. More complex links between climate change and ecosystem changes, and between ecosystem changes and economic performance are needed in order to integrate economic models with the natural world. Also, utility or welfare in the DICE model is represented by consumption in the traditional sense. In other words, only market purchases of goods and services are considered to be sources of economic welfare. Nonmarket items such as leisure and enjoyment of the environment

[5] See *Managing the DICE Model, Review of Nordhaus' Economics of Climate Change*, by Robert Costanza, Center for Environmental and Estuarine Studies and Zoology Department, and Director, Institute for Ecological Economics, University of Maryland. This review is to appear in *Environmental Science and Technology*.

are not included as part of the economic welfare. This causes economic activities to be directed too much toward material growth while ignoring the importance of the nonmarket items such as environmental quality and may cause problems of "over growing" such as in China.

Because DICE-CHN follows the assumptions and methodology of the DICE model it inevitably inherits the weaknesses of the DICE model. Further research is needed to incorporate more complex feedback relationships between the natural world and economic performance. Also, it would be desirable to include natural resources in the production function and to include nonmarket items such as the enjoyment of the environment in the measurement of welfare.

Nonetheless, the DICE-CHN model enables one to project the general dimensions of the role of China in generating global warming, and to estimate potential damages to China's economy. Thus, more refined version of DICE-CHN, especially those incorporating improved estimates of the critical parameters identified in Chapter V, have an important role to play in determining China's approach to the global warming problem.

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APPENDIX A

DICE-CHN IN CODE

DICE-CHN:	An optimal growth model based on the Nordhaus DICE Model with limited modifications.

SETS

T:	Time periods in ten year intervals
TFIRST(T):	First time period (1975)
TLAST(T):	Last time period (2215)
N:	Region (China)

SCALARS

ALPHA:	Elasticity of marginal utility (1)
RHO:	Rate of social time preference per year (0.03)
DELTAM:	Carbon removal rate per decade (0.0833)
BETA:	Marginal atmospheric retention rate (0.64)
M0:	CO2-equivalent concentrations in 1975 (698 GtC)
C1:	Thermal capacity of atmosphere (1/R1 or 0.226)
C2:	Thermal capacity of oceans (1/R2 or 0.02)
C3:	Thermal transfer from atmosphere to oceans (R2/TAU12 or 0.440)
LAMBDA:	Climate feedback parameter (1.41)
TL0:	Lower stratum temperature (degree C in 1975 or 0.1)
T0:	Atmospheric temperature (degree C in 1975 or 0.4)
A1:	Damage coefficient for CO2 doubling (fraction of GDP, or 0.0094)
SIGMA0:	Emissions-output ratio (tons of carbon per 1000 yuan in 1978 or 1.135)
DSIGMA0:	Decline rate of emissions-output ratio per decade (0.45)
EROW0:	Emissions by the rest of the world in 1975 (5.5 GtC)
GEROW0:	Growth rate of EROW per decade (0.23)
DGEROW:	Decline rate of GEROW per decade (0.13)
DELTAA:	Decline rate of technology per decade (0.11)
Q0:	China's GDP in 1978 (0.359 trillion yuans)
L0:	China's Population in 1975 (924.2 millions)
GL0:	China's population growth rate during 75-85 (0.16)
DGL:	Decline rate of China's population growth per decade (0.164)
B1:	Intercept of control cost function (0.04)
B2:	Exponent of control cost function (2.887);

PARAMETERS

L(T):	Level of population
GL(T):	Growth rate of population
SIGMA(T):	Emissions-output ratio
DSIGMA(T):	Cumulative improvement of energy efficiency

```
EROW(T):      Emissions by the rest of the world
GEROW(T):     Growth rate of EROW
RR(T):        Discount factor
FORCOTH(T): Exogenous radiative forcings from other GHGs
GQ(T):        Growth rate of GDP
;

TFIRST(T) = YES$(ORD(T) EQ 1);
TLAST(T)  = YES$(ORD(T) EQ CARD(T));
DISPLAY TFIRST, TLAST;

GL(T) = (GL0/DGL)*(1-exp(-DGL*(ord(t)-1)));
L(T) = L0*exp(GL(T));
DSIGMA(T) = (DSIGMA0/DELTAA)*(1-exp(-DELTAA*(ord(t)-1)));
SIGMA(T) = SIGMA0*exp(DSIGMA(t));
GEROW(T) = (GEROW0/DGEROW)*(1-exp(-DGEROW*(ord(t)-1)));
EROW(T) = EROW0*exp(GEROW(T));
DISPLAY L, SIGMA, EROW;

GQ('1') = 1;          GQ('2') = 2.38;       GQ('3') = 5.73;       GQ('4') = 11.81;
GQ('5') = 22.16;      GQ('6') = 37.86;      GQ('7') = 58.80;      GQ('8') = 91.31;
GQ('9') = 128.80;     GQ('10') = 164.86;    GQ('11') = 211.03;    GQ('12') = 270.11;
GQ('13') = 345.74;    GQ('14') = 442.55;    GQ('15') = 566.47;    GQ('16') = 725.08;
GQ('17') = 928.10;    GQ('18') = 1187.97;   GQ('19') = 1520.60;   GQ('20') = 1946.37;
GQ('21') = 2491.35;   GQ('22') = 3188.93;   GQ('23') = 4081.83;   GQ('24') = 5224.75;
GQ('25') = 6687.67;
Display GQ;

RR(T) = ((1+RHO)**10)**(1-ord(t));
FORCOTH(T) = 1.42;
FORCOTH(T)$(ord(t) lt 14) = .3820+.118*ord(T)-.0034*ord(t)**2;
Display RR, FORCOTH;

VARIABLES
MIUC(T):      Emissions control rate of GHGs in China
MIUO(T):      Emissions control rate of GHGs in ROW
FORCING(T):Radiative forcing in watts per squared meter
TA(T):        Atmosphere temperature in degree C
TO(T):        Lower ocean temperature in degree C
M(T):         CO2-equivalent concentration in billion tons of carbon or GtC
E(T):         CO2-equivalent emissions of the world in billion tons of carbon or GtC
C(T):         Consumption in trillion yuans
CPC(T):       Per capita consumption in thousand yuans
YPC(T):       Per capita income in thousand yuans
Y(T):         Income in trillion yuans
Q(T):         Output in trillion yuans
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UTILITY;

POSITIVE VARIABLES MIUC, MIUO, E, TA, M, Q, C, Y;

EQUATIONS
UTIL:        Objective function
YY(T):       Income
QQ0(T):      Initial condition of GDP
QQ(T):       Output
CC(T):       Consumption
CPCE(T):     Per capita consumption
YPCE(T):     Per capita imcome equation
EE(T):       Emissions process
FORCE(T):    Radiative forcing equation
MM(T):       CO2 distribution equation
MM0(T):      Initial condition for M
TAE(T):      Temperature-climate equation for atmosphere
TAE0(T):     Initial condition for atmospheric temperature
TOE(T):      Temperature-climate equation for lower oceans
TOE0(T):     Initial condition for lower ocean
;

QQ0(TFIRST).. Q(TFIRST) =E= Q0;
QQ(T).. Q(T) =E= Q0*GQ('1')*GQ(T);
EE(T).. E(T) =G= SIGMA(T)*(1-MIUC(T))*Q(T)+(1-MIUO(T))*EROW(T);
FORCE(T).. FORCING(T) =E= 4.1*(log(M(T)/590)/log(2))+FORCOTH(T);
MM0(TFIRST).. M(TFIRST) =E= M0;
MM(T+1).. M(T+1) =E= 590+BETA*10*E(T)+(1-DELTAM)*(M(T)-590);

TAE0(TFIRST).. TA(TFIRST) =E= T0;
TAE(T+1).. TA(T+1) =E= TA(t)+C1*(FORCING(t)-LAMBDA*TA(t)-C3*(TA(t)-
TO(t)));
TOE0(TFIRST).. TO(TFIRST) =E= TL0;
TOE(T+1).. TO(T+1) =E= TO(T)+C2*(TA(T)-TO(T));

YY(T).. Y(T) =E= Q(T)*(1-B1*(MIUC(T)**B2))/(1+(A1/9)*SQR(TA(T)));

CC(T).. C(T) =E= 0.65*Y(T);
CPCE(T).. CPC(T) =E= C(T)*1000/L(T);
YPCE(T).. YPC(T) =E= Y(T)*1000/L(T);

UTIL.. UTILITY =E= SUM(T, 10*RR(T)*L(T)*LOG(C(T)/L(T)));

*  Upper and Lower Bounds: General for stability
MIUC.up(T) = 1;
MIUC.lo(T) = 0;
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```
MIUO.up(T) = 1;
MIUO.lo(T) = 0;
TA.up(T) = 20;
M.lo(T) = 600;
C.lo(T) = 0.001;

* Upper and lower bounds for historical constraints

MIUC.fx('1') = 0.;
MIUC.fx('2') = 0.;
MIUC.fx('3') = 0.;
MIUO.fx('1') = 0.;
MIUO.fx('2') = 0.;
MIUO.fx('3') = 0.;

* Command and control constraint

*MIUC.fx(T) = 0.;
*MIUO.fx(T) = 0.;
*MIUO.fx(T)$(ord(t) gt 3) = 0.2;

* Solution options

option nlp = minos5;
option iterlim = 99900;
option reslim = 99999;
option solprint = off;
option limrow = 0;
option limcol = 0;
model CO2 /all/;
solve CO2 using nlp maximizing UTILITY;
display Q.l, Y.l, C.l, MIUC.l, MIUO.l, E.l, M.l, TA.l, FORCING.l, CPC.l, TO.l;
```

APPENDIX B

DICE-CHN EQUATIONS

$$\max_{c(t)} \sum_t U[c(t), L(t)]\,(1+\rho)^{-t}$$

subject to economic constraints

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

(2) $c(t) = C(t) / L(t)$

(3) $C(t) = 0.65Y(t)$

(4) $Y(t) = \Omega(t)Q(t)$

and emissions-climate-economic constraints

(5) $\Omega(t) = [\,(1 - b_1\,\mu(t)^{b2}) / (1 + \Phi_1\,T(t)^{\Phi 2}\,]$

(6) $TC(t) = Q(t)\,b_1\,\mu(t)^{b2}$

(7) $MC(t) = Q(t)\,b_1 b_2\,\mu(t)^{(b2-1)}$

(8) $D(t) = Q(t)\,\Phi_1\,T(t)^{\Phi 2}$

(9) $T(t) = T(t-1) + (1 / R_1)\,\{F(t) - \lambda\,T(t-1) - (R_2 / \tau_{12})\,[T(t-1) - O(t-1)]\}$

(10) $O(t) = O(t-1) + (1/R_2)\,[T(t-1) - O(t-1)]$

(11) $F(t) = 4.1 \log[\,M(t) / 590\,] / \log(2) + FO(t)$

(12) $M(t) - 590 = \beta\,E(T-1) + (1-\delta_M)\,[M(t-1) - 590]$

(13) $E(t) = [\,1 - \mu c(t)]\,\sigma(t)\,Q(t) + [1 - \mu o(t)]\,EO(T)$

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