1. Introduction: the many dimensions of the climate change issue

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1 THE MOTHER OF ALL PROBLEMS?

Global climate change has been described as the ‘mother’ of all problems. This rhetoric suggests that apocalyptic events will unfold as humanity marches blindly forward demanding more and more autos, jet travel, and air-conditioned homes. Once having crossed over the precipice, there will be no returning to that earlier world. The Earth’s atmosphere will have been irreversibly violated and humans must forever reap the consequences of their profligate lifestyle.

Whether or not this alarmist view is correct is open to debate. But in another sense, we can agree that as an *intellectual* exercise, climate change appears to be the ‘mother’ of all problems because of its complexity. Anyone who has attempted to understand the carbon cycle, the climatological interactions of CO₂ in the atmosphere, the effects of climate change on market and non-market activities, the technological options to abate carbon emissions, or how a market-based trading system of CO₂ permits might work usually comes away frustrated and hopelessly bewildered. The available literature is little help as it is often written by specialists to other specialists within the same discipline. Even the specialists may feel frustrated because it is not enough to know the science underlying the carbon cycle, for example. Climate change brings together the disciplines of botany, climatology, biology, atmospheric and oceanic chemistry, glaciology, systems modeling, cloud physics, statistics, economics, and political science. It seems impossible for any one person to achieve proficiency in all these areas.

Do not despair. Even though global climate change may appear hopelessly complex, it does not follow that the lay person cannot understand in a general way the various issues from which reasonable policy prescriptions follow. Nor does it follow that the policy arena must be ceded to the specialists. The specialists may be thoroughly versed in their own narrow area of the global climate change equation, but it is only one aspect. Paradoxically, they may be

too deep in the forest to see the trees. For you the lay person with a healthy respect for what you do not know, yours may be the reward of a clear view of the choices before us and the uncertainties on which they hinge. This volume is written for you.

Precisely, because the climate change issue cuts across so many academic disciplines, this volume consists of chapters by eminent scholars who are specialists in their unique area of the overall climate change equation, and it is organized around the following eight 'big picture' questions:

- Chapter 2: What is the linkage between fossil fuel consumption and carbon dioxide (CO₂) concentrations in the atmosphere?
- Chapter 3: What is the relationship between CO₂ concentrations and global warming?
- Chapter 4: Is the principal tool of economic analysis, benefit–cost analysis, adequate for prescribing policy recommendations for global climate change?
- Chapter 5: In a business-as-usual world, what are the damages from global warming on the types of market activities included in GDP?
- Chapter 6: In a business-as-usual world, what are the most significant non-market effects of climate change?
- Chapter 7: What are the mitigation costs of various policies and what technologies are available to significantly reduce CO₂ emissions?
- Chapter 8: What does cost–benefit analysis tell us about how vigorously we should be working to reduce CO₂ emissions?
- Chapter 9: What policy options are likely to lead to cooperative efforts to reduce carbon emissions in a world with independent nation states whose compliance is voluntary?

The last and final question not listed above is the fundamental question, 'What actions are best taken now versus later?'. Each of you will hopefully have reached your own conclusions after reading our experts' answers to the above eight questions.

Chapter 10 is entitled, 'Five letters to the President', and summarizes the policy advice of five close observers to the climate change debate. One might ask, 'But why interject the President of the United States?'. Interestingly, just one week prior to the conference on 6 April 2001, the above papers were presented at a conference on 'Global Climate Change: The Science, Economics and Politics' at the Bush Presidential Conference Center, Texas A&M University. President George W. Bush announced his rejection of the Kyoto Protocol, proclaiming it was not in the nation's interests. To the surprise of the White House, this announcement unleashed a maelstrom of criticism in Europe.

President Bush's rejection of the Kyoto Protocol suddenly thrusts him onto the world stage and calls for his leadership in shaping a new policy that is realistic and workable. Over the ensuing months, President Bush has no doubt received many briefings from numerous experts. Our distinguished group of generalists were told to assume that they had been granted ten minutes in which to brief President Bush on global climate change policy. You will enjoy reading their points of view and comparing them against what you gleaned from the preceding eight 'big picture' questions. Most interestingly, you will enjoy comparing their advice with President Bush's latest plan calling for voluntary reductions of carbon emissions.

Each of the eight 'big picture' questions listed above is addressed in the subsequent eight chapters by a noted specialist in that area. In selecting specialists on each of these topics, a conscious effort was made to select those who would present the mainstream view of the specialists working on that particular issue. Each contributor was asked to present the 'prevailing wisdom' on their particular question. Of course, to the extent that their own views differed from the 'prevailing wisdom', they were at liberty to note these differences.

Why Focus on the 'Prevailing Wisdom'?

Why focus on the prevailing wisdom rather than surveying the full range of opinions since today's prevailing wisdom is often tomorrow's mistaken theories? One only needs to look at the range of oil price projections for the year 2000 made during the heyday of the OPEC (Organization of Petroleum-Exporting Countries) cartel's success in the early 1980s to gain a healthy skepticism for the prevailing wisdom. The widely accepted oil price forecasts for the year 2000 called for \$100 per barrel (see International Energy Workshop, 1984) – four times actual prices. A cynic might point out that global climate change research is an industry in itself. The cynic might even ask, 'Why would we expect researchers whose funding depends on a crisis to tell us anything different?'. Besides economic self-interest in the form of research grants, academics are not immune from the type of 'herding' tendencies so apparent on Wall Street.

Academics, like other humans, are not immune from incentives or from the herding mentality. But here the effects are much more subtle than those alluded to by the cynic's view. By their nature, researchers want to work on substantive problems. Consequently, researchers with strong Bayesian beliefs that climate change represents a serious problem are more often attracted to the field than those viewing it as a non-problem. While they do not blindly follow the mainstream view, acceptance by one's peers is also a vital concern. In sum, there does exist the potential for biased and highly misleading policy prescriptions emanating from the prevailing wisdom.

The justification for following the prevailing wisdom rests on three grounds. First, even though there may exist selection bias in the researchers studying the problem and herding tendencies, in both the physical and social sciences, scientific methods require the verification and validation of results. Moreover, even for untested theories, the peer review process in the major journals offers a strong quality control device. Fortunately, in academics there is a free market for ideas that ensures that science will ultimately get it right. Second, it would be impractical to survey the wide range of opinions that might exist on each of the above eight topics. The reader would be left totally confused and unable to judge the credibility of the voluminous facts presented. When confronted with widely conflicting opinions, it is human nature to do nothing. In this case, inaction could be very dangerous since it may be many years before the uncertainty is reduced on many of these topics. By then, largely irreversible damage to the atmosphere may have occurred. Third, surveying the prevailing wisdom on each of these eight critical ingredients in the global climate change equation is an extremely valuable logical exercise – far preferable to simply surveying some group of ‘experts’, who reflect the vantage of their own narrow specialty. In principle, looking at the prevailing wisdom for all eight questions must form the basis for current climate change policy. Of course, we cannot view today’s policy prescriptions as fixed immutably in stone. It will surely evolve as new information alters the prevailing wisdom. In any event, the prevailing wisdom must be the starting point for current policy.

2 BACKGROUND INFORMATION

Why the Emphasis on CO₂?

Before jumping head first into Chapter 2 with discussions of the carbon cycle, it is important to acquire some background facts that will prove helpful throughout the volume. The focus in this volume is the role of carbon dioxide (CO₂) as a determinant of global warming. Carbon dioxide is a greenhouse gas that regulates the rate at which the planet can radiate heat energy back to space. Greenhouse gases are transparent to incoming solar radiation, but largely opaque to the passage of infrared radiation back out into space. In effect, these gases form a type of greenhouse that traps solar heat near the earth’s surface, causing global warming and other climate changes. Besides CO₂, other greenhouse gases include halocarbons, nitrous oxide, methane, tropospheric ozone, and water vapor. Most of these greenhouse gases occur naturally and are essential for providing temperate conditions under which life on earth is possible. In effect, the earth comes equipped with its own

naturally occurring greenhouse. So greenhouse gases clearly do not belong on the list of air pollutants like sulfur oxides, particulates and so forth.

Since the Industrial Revolution, human-induced (or anthropogenic) emissions of greenhouse gases have gradually increased the concentrations of greenhouse gases. It is these anthropogenic greenhouse gas emissions that are the concern for global climate change. Traditionally, up until 1950, temperature change was dominated by natural factors such as changes in solar radiation and volcanically produced dust veils. Since then, human-induced factors have emerged as the dominant cause of climate change. Disentangling natural from anthropogenic causes is an inexact science, but several statistics stand out. Wigley (1999) reports approximately a 0.5 degree Celsius or a 0.9 degree Fahrenheit increase in global mean temperature over the 1950–2000 period. Wigley's graph suggests that about three-quarters of radiative forcings are attributable to anthropogenic sources (pp. 10, 15). The remainder is primarily attributable to increased solar activity, a natural phenomenon over which we have no control.

Typically, we focus on CO₂ because it is the greenhouse gas that is thought to have contributed the most to global warming over the last 250 years. Climatologists use the concept of 'forcing' to indicate the warming effect of a particular agent such as a greenhouse gas.¹ This allows us to assess how much warming might be attributed to each of the greenhouse gases. It is estimated that CO₂ has historically accounted for 53 percent of the anthropogenic forcings associated with greenhouse gases (see IPCC, 2001). The second largest contributor, methane gas, accounts for about 17 percent of the warming. Methane arises from a number of sources such as agriculture, livestock, and land-fill emissions. Tropospheric ozone, the third largest contributor, accounts for 13 percent of greenhouse gases forcings. Tropospheric ozone is linked to the emissions of carbon monoxide, nitrogen oxides and light hydrocarbons. The fourth largest anthropogenic contributor, halocarbons, account for 12 percent of greenhouse gas forcings. (They are linked primarily to emissions of chlorofluorocarbons from freon in air-conditioners and refrigerators, which are now regulated under the Montreal Protocol because of their effects on the Earth's ozone layer. Unfortunately, their replacements – while benign to the ozone layer – are relatively bad greenhouse gases.) Nitrous oxides, which account for the remaining 5 percent, are produced primarily by nitrogen compounds in fertilizers.

One might wonder, 'Why does CO₂ receive so much attention, since other greenhouse gases contribute almost half of the total?'. This question seems even more perplexing if indeed *all* anthropogenic forcings explain roughly three-quarters of the 0.9° F (or 0.5° C) mean temperature increase over the last half-century. The effects attributable to CO₂ seem small and hardly a matter for public policy concern. The explanation is complex, but the prevail-

ing wisdom suggests that the effects of CO₂ concentrations over the next 50 years will not be nearly as inconsequential as in the past.

First, compared to other greenhouse gases, CO₂ is a very long-lived gas, meaning that current CO₂ emissions will persist for several centuries in the atmosphere before atmospheric removal mechanisms purge them. In contrast, methane is estimated to have a lifetime of 12 years.² Consequently, emissions of CO₂ remain in the atmosphere, contributing to current forcings, while for methane, its concentrations, and thus forcings, depend critically on recent emissions. Thus for CO₂, past as well as future emissions will have very long-term consequences.

Second, CO₂ promises to provide the bulk of the future growth in greenhouse gas concentrations because of its tie to energy consumption. Except in countries experiencing deforestation, energy consumption from fossil fuels contributes almost all of current CO₂ emissions. For example, in the US, fossil fuels are estimated to account for 98 percent of CO₂ emissions (see Energy Information Administration, 2001). Figure 1.1 shows there is a roughly proportional relationship between economic activity measured in GDP and energy consumption. Low-income countries are associated with low energy consumption and vice versa. In the future, as both underdeveloped and developed nations grow, it is inescapable that energy consumption will grow. For the foreseeable future, fossil fuels will account for the bulk of energy consumption. Table 1.1 ranks the world's 20 largest energy consumers and shows

Figure 1.1 Energy use and GDP for selected countries

Table 1.1 Twenty largest energy-consuming nations and their fuel mix (%)

Country	Total energy*	Shares by fuel type			
		Fossil fuel	Nuclear	Hydroelectric	Other
United States	97.1	87.1	8.2	3.6	1.1
China	31.9	92.3	0.5	7.3	0.0
Russia	26.0	89.0	4.7	6.3	0.0
Japan	21.7	80.1	14.5	4.1	1.3
Germany	14.0	85.9	11.6	1.4	1.1
Canada	12.5	65.7	6.1	27.6	0.6
India	12.2	91.9	1.1	6.9	0.1
France	10.3	57.4	35.5	6.8	0.2
United Kingdom	9.9	86.9	11.7	0.6	0.9
Brazil	8.5	59.0	0.5	39.3	1.3
Italy	8.0	92.3	0.0	6.1	1.5
Korea, South	7.4	86.1	13.3	0.6	0.0
Ukraine	6.4	86.1	11.4	2.5	0.0
Mexico	6.1	91.1	1.6	5.5	1.8
Spain	5.2	83.4	11.0	4.8	0.8
Australia	4.7	95.8	0.0	3.5	0.7
Iran	4.7	98.4	0.0	1.6	0.0
South Africa	4.4	96.9	2.9	0.2	0.0
Saudi Arabia	4.3	100.0	0.0	0.0	0.0
Poland	3.8	98.7	0.0	1.1	0.2

Note: * In 10^{15} BTU in 1999.

Source: US Energy Information Administration (1999).

the mix of fuels attributed to fossil fuels, hydroelectric, nuclear, and other energy forms. Typically, fossil fuels account for around 90 percent of total energy consumption. Even in France, which relies heavily on nuclear power for electricity generation, fossil fuels account for 57 percent of total energy requirements. Hydroelectric power is limited primarily by suitable sites and thus has very limited potential for expansion in the industrialized nations. Only in water-rich countries like Brazil does the share of hydroelectric energy approach 40 percent. Solar, biomass, and other miscellaneous energy sources account for less than 2 percent in all of the countries surveyed. This latter statistic is striking because of all the public efforts to jump start alternative energy sources during the energy crises of the 1970s. These alternative

energy sources remain uncompetitive with lower-cost fossil fuels. Nuclear energy tends to be more costly than fossil fuels; furthermore, public opposition to nuclear power remains strong throughout much of the developed world. Thus it seems inescapable that for the foreseeable future, fossil fuels will continue to provide the backbone of world energy supplies. In contrast, other greenhouse gases such as methane and nitrous oxides emissions are closely linked to agriculture, which seems likely to expand more slowly as population growth slows. Thus as a fraction of greenhouse gases, CO_2 is estimated to account for three-quarters of future greenhouse gas forcings (see IPCC, 2001).

Third, in the past the temperature effects of the growth in CO_2 via fossil fuels appear to have been substantially offset by increased sulfate aerosols, which tend to have a cooling effect. In the past, sulfur oxide emissions from high sulfur coal and fuel oil grew basically at the same rate as all fossil fuels. Interestingly, the resulting sulfur oxides have just the opposite effects of CO_2 -producing global cooling. Paradoxically, the increased CO_2 concentrations from fossil fuels were substantially counteracted by concentrations of sulfur oxides. This may help explain why anthropogenic effects on global mean temperature appear 'small' during the last 50 years. In recent years, environmental efforts have substantially reduced sulfur oxide emissions because of their detrimental health and agricultural effects. These policies have switched the mix of fossil fuels to those with low sulfur content, like natural gas. Now suddenly, the counterbalancing effects of sulfur oxides are no longer as strong. The full impact of the CO_2 concentrations on temperature could then be realized as fossil-fuel consumption expands with worldwide economic activity.

Fourth, some would point to the creation and preservation of carbon sinks, such as forests that absorb CO_2 , as a major policy alternative to direct CO_2 abatement. They might claim that by increasing carbon sinks, this might enable the continued growth of CO_2 and the fossil fuels linked to it. But this is not a viable long-run strategy. Surely in the past, the destruction of tropical rain forests destroyed huge carbon sinks which have contributed to global warming in the past half-century. Nevertheless, a ban on the destruction of tropical rain forests or even massive reforestation programs cannot enable carbon sinks to grow fast enough to offset the rapid growth of fossil fuels (see Schlesinger, Chapter 2). The carbon cycle is a very complex phenomenon as explained by Schlesinger. Carbon sinks have in the past absorbed about half of CO_2 emissions (see IPCC, 2001), but the capacity of the system to accommodate larger doses of CO_2 is limited. The limited capacity of carbon sinks means that *incremental* emissions of CO_2 are likely to move directly to the atmosphere, contributing much more directly to future greenhouse gases.

The Important Distinction between CO₂ Emissions and CO₂ Concentration

Having zeroed in on CO₂ as the primary greenhouse gas, scientists typically focus on the following two questions: (i) How long will it take before CO₂ concentration in the atmosphere double? and (ii) What climate changes will result from this doubling of CO₂ concentration? The reader will note that the above two questions center on CO₂ *concentration*, not CO₂ *emissions*. There is a vital difference. CO₂ concentration is a stock concept measuring the amount of CO₂ present in the atmosphere at a given time. CO₂ emissions is a flow concept, measuring the additions of CO₂ to the atmosphere over a given time period. Current CO₂ concentration is governed by the following perpetual inventory equation:

$$\text{CO}_2 \text{ Concentration}_t = \text{CO}_2 \text{ Concentration}_{t-1} + \text{CO}_2 \text{ Emissions}_t - \text{CO}_2 \text{ Absorption}_t. \quad (1.1)$$

Once emitted, CO₂ emissions enter the atmosphere raising CO₂ concentrations in period t from the concentrations reached in period $t-1$. CO₂ absorption is proportional to total concentrations, but the rate of absorption is very slow. Thus CO₂ is a 'long-lived gas'. Critically, CO₂ emissions in any period have a relatively small impact on CO₂ concentrations, yet cumulatively over 50 or 100 years, the CO₂ concentrations depend critically on the cumulative sum of past net CO₂ emissions. For example, CO₂ concentrations in the atmosphere are approximately 370 parts per million (ppm). Most recently, CO₂ emissions less absorption are estimated to raise concentrations by only 1.5 (see IPCC, 2001). For example, concentrations might rise from 370 to 371.5 in a year. A key statistic to remember is that CO₂ concentrations in the atmosphere have risen from 280 ppm at the time of the Industrial Revolution to approximately 370 ppm today.

This simple inventory equation explains why global warming is such a potentially serious long-term problem. As explained by Schlesinger in Chapter 2, CO₂ absorption is dependent on the limited capacities of oceans and forests to absorb increased CO₂ concentrations. Consequently, CO₂ emissions remain suspended in the atmosphere for periods as long as several centuries.³ Society cannot instantaneously adjust CO₂ concentrations and thereby turn up or down the temperature thermostat. Instead, society faces the choice of reducing CO₂ emissions in year t . This cutback will only be meaningful if followed up by subsequent cuts in future periods, since a single, one-shot reduction in any one year will have a minimal impact on total concentrations. While policy makers must tinker with the rate of CO₂ *emissions*, scientists concerned with climate change focus on CO₂ *concentrations* and their effect

on climate. Since emission cutbacks in the present are costly and meaningful only if continued in the future, there is a great temptation for policy makers to do nothing, especially since the benefits fall primarily in the future.

Factors Influencing Future CO₂ Emission Rates

It is useful to review the factors that determine total CO₂ emissions from fossil fuels, since together with the carbon cycle (operating through CO₂ absorption in equation (1.1)) they determine the rate of net CO₂ emissions entering the atmosphere. Even under a 'business-as-usual' scenario, the researcher must project future energy demands, separating fossil fuels from non-fossil fuels, and finally identifying individual fossil fuels.

Unfortunately, researchers cannot forecast individual fuel consumption for the next 100 years without making a number of assumptions and specifying a number of key empirical relationships. First, one must develop forecasts of aggregate energy demand for a particular country or region, which necessarily involves quantifying the four determinants of energy demand: (i) population growth, (ii) GDP per capita growth, (iii) energy/non-energy substitution possibilities and (iv) the rate of energy-saving technical change. This visualization of demand postulates that energy demand is directly tied to the underlying population base and its rate of GDP growth. Thus economic activity is seen as the primary driver of energy consumption, whether fed by a growing population and/or by rising per capita incomes. The energy crisis of the 1970s has taught us that there exists the possibility of altering the amount of energy in a dollar's worth of GDP because of either price-induced substitution responses or technical change of an energy-saving nature. Price-induced substitution responses simply reflect the fact that as energy prices increase *vis-à-vis* capital, labor, and material prices, it is possible to substitute other inputs for energy. Also, the energy price increases of the 1970s set in motion a powerful longer-term response – energy-saving technical change. Technological advances have made it possible to produce the same output with substantially less energy use. For illustrative purposes, Figure 1.2 shows the combined effects of price-induced substitution responses and energy-saving technical change as it shows that the energy input per dollar of GDP has fallen substantially since 1970. Figure 1.2 also shows the real price of energy with its meteoric rise in the 1970s and early 1980s followed by a long period of declining real prices. Notice that the sharply rising real prices in this early period triggered price-induced substitution responses that persisted well into the 1990s. Initially, the response to higher prices was small.

Next, it is necessary to disaggregate total energy consumption into fossil and non-fossil fuels and then to split fossil fuels between coal, petroleum, and natural gas. In the first instance, one must identify the price-induced

Figure 1.2 Energy input per dollar of GDP versus real price of energy

substitution responses between fossil and non-fossil energy. In the second instance, relative fossil fuel prices shape long-term fuel choices, so it is important to model these substitution responses as well. An important and often forgotten point is that not all fossil fuels are created equal. A million btu (British thermal unit) of coal results in 77 percent more CO_2 than a million btu of natural gas. Petroleum involves 39 percent more CO_2 than a million btu of natural gas (Energy Information Administration, 1999). As shown in Table 1.2, the mix of fossil fuels differs considerably across countries. These differences may not seem large, but consider the following example: if China employed the same mix of fossil fuels as the Netherlands, its CO_2 emissions would be reduced by 30 percent. Of course, the Netherlands utilize very little coal and large quantities of natural gas. In contrast, almost two-thirds of China's fossil fuels are attributable to coal.

Additionally, technological change can also significantly alter the mix of fuels. For example, in the absence of technological change, environmental restrictions on sulfur oxide emissions would have effectively eliminated coal from the generation of electricity in the US. Stack gas scrubbers enabled these gases to be captured and converted to elemental sulfur, enabling coal to remain a viable competitor in the electricity generation market. Another example includes combined-cycle electricity generation technology resulting in very fuel-efficient use of natural gas.

Table 1.2 Mix of fossil fuels for selected countries (%)

Country	Coal	Petroleum	Natural gas
China	66.5	30.1	3.4
India	56.1	36.2	7.8
Turkey	32.4	49.1	18.5
Germany	27.1	48.2	24.7
United States	26.5	46.3	27.2
Korea, South	22.7	66.8	10.5
Japan	19.1	65.0	15.9
Russia	17.8	21.5	60.7
Canada	17.3	45.1	37.6
Spain	17.3	69.1	13.6
Belgium	15.1	57.0	27.9
Brazil	11.5	83.5	5.1
Sweden	10.4	85.9	3.7
France	9.6	66.7	23.7
Netherlands	8.4	48.9	42.6
Italy	6.6	58.5	34.9
Norway	6.6	68.0	25.4
Mexico	4.3	72.1	23.6
Argentina	1.9	44.7	53.4

Source: US Energy Information Administration (1999).

But What Is the Scope for Deferring the Date at which CO₂ Concentrations Double?

Envisage a researcher carefully constructing energy supply–demand balances by country, aggregating them to the world level, translating them into CO₂ emissions, and ultimately arriving at CO₂ concentrations. For example, the IPCC (2001) presents a business-as-usual scenario predicting the doubling of CO₂ concentrations over current levels by 2100. Is the date 2100 cast in stone when CO₂ concentrations reach 740 ppm? Obviously, not. We are not being propelled forward by forces beyond our control. There are two factors that can alter our dates with destiny, perhaps pushing off the doubling date indefinitely. First, the price mechanism is a powerful mechanism to alter long-term CO₂ emissions. Admittedly, in the short run, substitution responses are quite limited because fuel choices are largely dictated by the stock of energy-consuming equipment, but in the long run, impressive substitution responses exist. These substitution responses include first the substitution of low-CO₂

fossil fuels, like natural gas, for high-CO₂ fossil fuels like coal. Next, there is the substitution response between fossil and non-fossil fuels. Finally, there is the energy/non-energy substitution mechanism. The second major factor is technological change which can manifest itself in a variety of ways from cheap methods of CO₂ sequestration, greater fuel efficiencies, or clean alternative energy sources. Again, in the short term, the technological frontier is essentially fixed. But over long periods of time, breakthroughs in basic research and development (R&D) can find commercialization and then after diffusion of the new technology, can profoundly reshape the energy landscape. One only needs to compare energy uses in 1900 with those in 2000 to see the effects of new technologies. In sum, both technology and the price mechanism hold great promises in affecting CO₂ emissions 20, 30, or 50 years from now and ultimately to defer significantly or even indefinitely the date at which CO₂ emissions double. But these adjustments will not be costless. They will not occur quickly, and they will not occur automatically.

What Is the Policy Framework around which to Fashion a CO₂ Abatement Strategy?

The fact that the doubling date for CO₂ emissions can be altered tells us that we have choices. Putting aside for the moment the serious issue of obtaining international cooperation to control CO₂ emissions, it is useful to ask the question what path of CO₂ emissions should an enlightened despot choose. But before our enlightened despot can choose a path for world CO₂ emissions, he/she must ask what is the criterion for preferring one path over another? Traditionally, economics has held forth benefit–cost analysis as the preferred framework to answer this question. The idea is straightforward – maximize the present value (*PV*) of benefits (*B*) less costs (*C*) as follows:

$$PV = \text{maximize} \left(B_0 - C_0 + \frac{B_1 - C_1}{1+r} + \dots + \frac{B_n - C_n}{(1+r)^n} \right). \quad (1.2)$$

For each time period starting in the current period 0, one computes benefits less costs and discounts the difference at the social discount rate, *r*. The benefits are computed as the market and non-market value accruing in each period from the particular CO₂ emission path chosen. Costs are the additional costs society incurs by reducing CO₂ emissions. The latter can include the higher costs of non-fossil fuels, the costs of CO₂ sequestration, and so forth. For each separate path of CO₂ emissions over time, one can compute the present value. From a policy perspective, traditional economic analysis prescribes choosing the emission path that maximizes the present value of benefits less costs.

This framework treats the whole world as a single entity measuring benefits and costs across all regions. Clearly, there may be large distributional effects with some industrialized regions incurring large CO₂ abatement costs while low-latitude, undeveloped regions may be the primary beneficiaries. In principle, our enlightened despot is not supposed to be influenced by these distributional effects. The benevolent despot knows that by maximizing the present value of benefits less costs, he/she will produce the largest economic surpluses with which to compensate loser regions.

The problem of selecting the optimal path of CO₂ emissions depends critically on what social discount rate, r to apply.⁴ The reason for this is that programs which would significantly reduce today's CO₂ emissions will produce high values for C_0 in equation (1.2) with very little current offsetting benefits, B_0 . Instead, the benefits will be primarily realized in the distant future. But when future benefits are discounted at rate r , they receive a much lower value in equation (1.2). For example \$1.00 in benefits 50 years from now is worth only 3.4 cents today if a 7 percent discount rate is used. Alternatively, using a 2 percent social discount rate, the present value of the same dollar is worth 37.2 cents – almost 11 times more than at a 7 percent rate!

In most applications, discount rates in the 5–7 percent range would be routinely applied since these would reflect current real rates of return. But such rates would make many proposed abatement strategies yield a negative present value. To those calling for immediate large-scale emission reductions, cost–benefit analysis is an anathema to be thrown out or altered dramatically. For example, some argue that a lower social discount rate of say 2 percent should be applied, pointing out that future generations, who will be the primary beneficiaries of current emission reductions, are not present to register their preferences. In Chapter 4, Goulder reviews this contentious issue as well as a number of other arguments that have been raised against using benefit–cost analysis.

What Are the Benefits (B_i) in Equation (1.2)?

In order to compute the benefits, B_i , in equation (1.2) it is necessary to perform the following calculation: compare two paths of CO₂ emissions – one corresponding to the policy resulting in lower CO₂ emissions and the other corresponding to business-as-usual emissions. Then using equation (1.1), compute the implications of these two paths for CO₂ concentrations. The result is two separate paths of CO₂ concentrations related to the two emission paths. Since climate change is linked to CO₂ concentrations (and not the emissions in any one year), it is the *difference* in the two CO₂ concentration paths that determine the change in temperature and thus the

benefits from CO₂ abatement in any given period. Even if the policy calls for substantial permanent reductions in emissions, implying substantial differences in the two emission paths, the corresponding two CO₂ concentration paths will show little differences in the near term and widening differentials over time. This explains why the near-term benefits from CO₂ abatement will necessarily be small. But over time, as the two concentration paths diverge, the benefits can become large.

Paradoxically, we use the term ‘damages’ to result from global warming, while we use the term ‘benefits’ to refer to *damages avoided* by having lower CO₂ concentrations. Both terms appear on opposite sides of the same coin. In effect, the reduction of CO₂ emissions results in damages avoided – or benefits. Invariably, the policy question arises, ‘Will the incremental damages foregone (or benefits) exceed the costs of abating CO₂?’.

Two chapters focus on the benefits resulting from a lower CO₂ emission path. In Chapter 5, Mendelsohn takes the range of temperature increases discussed by North in Chapter 3 and asks what are the benefits resulting from lower temperatures as they relate to market-related activities normally recorded in GDP. Mendelsohn estimates the loss in GDP resulting from a 2.5°C warming and from a 5°C warming. Knowing the damage effects associated with these temperature increases, allows one to compute the benefits, B_i , of avoiding such an increase, which is a key input to the cost–benefit equation (1.2).

An important advancement of Mendelsohn’s work is that he attempts to incorporate adaptation into his analysis. For example, global warming in agriculture will make a particular geographic region no longer suitable for growing traditional crops. Does one compute the value of the lost production of the traditional crop as the damage from global warming? Or does one consider that farmers typically adapt by selecting another crop more suitable for warmer weather? By including adaptation, the damage would be much less – the difference in returns from the two crops. Clearly, society will adapt to climate change, not only in agriculture, but in a multitude of other dimensions. Mendelsohn and other researchers in the area face a tremendously complex problem, but efforts are underway to determine the scope of these responses. Perhaps the most fascinating aspect of Mendelsohn’s work is the finding of a hill-shaped damage function. Particularly for higher latitudes, modest temperature increases may even be beneficial, implying a movement up the hill. But beyond some level of warming, increasing temperature results in damages. In contrast, warm climates are already on the down side of the hill. Any further warming results unambiguously in damages. In the aggregate, as a percent of worldwide GDP, he concludes that these effects appear small.

Yet another element of benefits from CO₂ abatement are the non-market effects. A whole host of environmental and aesthetic qualities routinely enter

the individual's utility even though these goods are not traded and do not comprise part of GDP. For example, climate change may affect recreational uses of vast areas. While the loss may not be recorded in GDP, the asset value of a region can be severely reduced. Yet another example, climate change may increase water temperature, killing huge areas on coral reefs in the Pacific Ocean. Valuing such losses is a daunting task; yet to assume they are negligible is not acceptable to most students of the subject. Smith, Lazo, and Hurd in Chapter 6 tackle this tough problem. Interestingly, it would appear that non-market damages from warming (or the benefits from lowering CO₂ concentrations) are potentially much greater than the market-related damages surveyed by Mendelsohn. Indeed, a vigorous program to reduce CO₂ emissions appears to depend critically on these non-market effects being large.

What Are the Costs in Equation (1.2)?

For any CO₂ emission path, economic efficiency dictates that we choose the least-cost abatement strategy. As Edmonds and Sands emphasize in Chapter 7, there is a long list of various methods to either abate CO₂ directly or to reduce it through increased carbon sinks and carbon sequestration technologies. As mentioned earlier, the price mechanism is a powerful source for long-term reductions in CO₂ emissions. A carbon tax or transferable pollution permits will put a 'price' on CO₂ which will unleash a variety of substitution responses such as energy/non-energy substitution, non-fossil fuels for fossil fuels, and low-carbon fossil fuels for high-carbon fossil fuels. Putting a price on carbon could also encourage the technological advances that have even greater potential for alleviating the problem. While creating incentives for the development of cost-effective responses is central, it is still useful to ask the following question: 'Given existing technologies and their costs of CO₂ abatement and given existing substitution possibilities, what are the least-cost methods for achieving various levels of emissions?'

Edmonds and Sands review the data and offer some interesting findings in Chapter 7. For example, they compare the costs of various carbon sequestration technologies as well as hydrogen produced by fuel cells. Their results are central to filling in the C_i in equation (1.2). It is important to remember that obtaining large CO₂ emission reductions in the near term will be extremely costly. Given the fixity of the energy-consuming capital stock, it is preferable to link major changes to the turnover of this capital stock. Over the longer term, the costs of achieving a given percentage reduction in CO₂ emissions fall sharply. Even though long-term abatement costs are much lower, there is the tough question of how do we set in motion forces today that will guarantee these long-term responses and at the same time avoid unnecessarily high abatement costs in the present.

But What Is the Answer when We Solve the Benefit–Cost Equation (1.2)?

Even though the cost–benefit paradigm embedded in equation (1.2) gives us a clear framework within which to solve the problem of what CO₂ emission path is optimal, mathematically implementing it is fraught with practical difficulties. For example, even though the global mean temperature increase may be 2.5°C for a doubling of CO₂ concentrations, North (Chapter 3) notes that temperature increases will vary significantly by region with higher latitudes experiencing greater increases *vis-à-vis* equatorial areas. Night-time temperature increases seem likely to exceed daytime temperatures. Also, some areas will be more vulnerable to rising sea levels than others. This calls for a benefit–cost analysis that is finely dis-aggregated. Besides the computational complexity, the manpower and data requirements for such a modeling exercise are enormous. In response, modeling efforts have taken two paths. The first attempts to provide considerable geographic detail and to embed the best available benefit and cost estimates for each region. These models are called integrated assessment models. Yet another modeling approach is to use highly aggregated, simplified models. These models, like an impressionist painting, focus on representing the key relationships. Moreover, they have the advantage that one person can easily understand its properties and test its sensitivities to key parametric assumptions.

In Chapter 8, Alan Manne uses a model of this latter sort to answer the key question of what cost–benefit analysis tells us. Manne adopts an intertemporal model in which time is represented by decades. The mathematical problem he solves is the maximization of the utility of consumption where CO₂ concentrations enter his model by reducing GDP. Manne assumes that corresponding to a 2.5°C warming is a loss in market and non-market value equivalent to 1 percent of GDP. This assumption implies considerably higher damages than Mendelsohn’s estimates for market losses. This of course, leaves considerable scope for the type of non-market effects surveyed in Chapter 6 by Smith, Lazo, and Hurd. The key conclusion from Manne’s model is that an optimal policy would call for a moderate carbon tax of approximately \$10 to \$12/ton, but with the tax rising significantly over time – reaching \$60 per ton by 2050. Manne’s results are of critical importance because of its moderation. For example, a carbon tax of \$12/ton would raise the price of gasoline by about 3 cents per gallon. He rejects doing nothing, but also rejects other proposals which could result in carbon taxes of 5 or 10 times that magnitude.

What Happens when We Throw International Politics into the Mix?

Manne's calculation of the optimal tax an enlightened despot would select is an interesting intellectual exercise, but convincing some 200+ nations in the world to voluntarily reduce CO₂ emissions throws us squarely into the world of international politics with its own set of constraints. Suddenly, the question shifts from what is economically optimal to what is politically achievable. Reaching an international consensus is complicated by a number of inescapable impediments. First, the damages from global warming will be quite unevenly distributed around the globe. Mendelsohn's finding of a hill-shaped damage response suggests that higher-latitude countries will initially benefit from moderate temperature increases. In contrast, lower-latitude regions, which tend to be the poorer, least-developed countries, will experience damages, even for small temperature increases. Yet another factor complicating the situation is that undeveloped nations in already hot climate regions face many more pressing problems than climate change. Consequently, they appear unlikely to cooperate in any abatement programs.

Not only will the benefits from reduced CO₂ concentrations be spread quite unevenly across the globe, but the costs of abatement will be spread quite unevenly as well. High-benefit regions rarely match high-abatement-cost regions. To achieve voluntary compliance, one would like each country to find it individually advantageous to reduce CO₂ emissions. But this is unlikely to occur except where high abatement costs are matched by high benefits. Instead, we observe a world where the primary beneficiaries of lower CO₂ concentrations are the poorer countries located in more temperate regions. While these countries will be the primary beneficiaries, they too will suffer the greatest damages from global warming.

Even if all countries' economic interests were mutually aligned, game theory suggests that each country's best response is to 'not cooperate' with some worldwide agreement to reduce CO₂ emissions. The prediction is that many will choose to be 'free riders'. By opting out of any agreement, the individual country avoids higher energy prices and becomes a low-cost producer *vis-à-vis* other complying nations. Furthermore, participation by any one country would not significantly affect worldwide CO₂ concentrations.⁵ In sum, pursuing one's own economic interests suggest strong incentives for non-compliance. Can these be overcome? If so, what are the best mechanisms for dealing with climate change? In Chapter 9, David Victor tackles these important questions, looking at a variety of policy options. These policy options include carbon taxes, tradeable emission permits, a hybrid approach, and a pure technology approach. Victor's discussion, cast in the light of political realities, greatly enriches our understanding of the role political factors will play.

Table 1.3 Twenty largest emitters of CO₂ from fossil fuels

Country	CO ₂ emissions*
United States	1519.9
China	668.7
Russia	400.1
Japan	306.7
India	243.3
Germany	229.9
United Kingdom	152.4
Canada	150.9
Italy	121.3
France	108.6
Korea, South	107.5
Ukraine	104.3
Mexico	100.6
South Africa	99.5
Australia	93.9
Brazil	88.9
Poland	84.5
Iran	84.3
Spain	81.6
Saudi Arabia	73.9

Note: * Millions of metric tons carbon equivalent from fossil fuels.

Source: US Energy Information Administration (1999).

First, Victor offers his answer to the question of whether full compliance should be a necessary condition for proceeding with a policy of emission abatement. He recognizes that certain countries, such as China and India, are unlikely to participate initially. Table 1.3 ranks the various countries according to their estimated CO₂ emissions in 1999. Note that China and India rank second and fifth, respectively, despite their relatively low per capita incomes. Victor feels that to require compliance by such developing nations as a precondition for any cooperative action, would vitiate any hope of a cooperative policy. At the same time, countries below China and India on Table 1.3 would likely find it galling that these two large carbon emitters would be exempted.

Victor examines the difficulties of various control mechanisms. While most economists might favor a global carbon tax, Victor recognizes the

difficulties of obtaining worldwide agreements on a common tax. Quantitative limits, such as those pegged to 1990 emissions for each country, as in the Kyoto Protocol, have the advantage of giving each country a well-defined target – in this case a ceiling below which it must reduce its CO₂ emissions. But since some countries can reach their targets at low cost, while others will face much higher costs, the overall costs of compliance can be reduced by encouraging the trading of emission permits. In effect, under a tradeable permits scheme, each country is granted CO₂ emission permits equal to its target. Countries who do not use all of their emission permits can sell them to other countries who find it too expensive to reach their target. In effect, emission permits would be a traded good, like other commodities. In fact, for sulfur-oxide emissions from power plants in the US, a vigorous market for emission permits already exists. This market seems to function well and offers promise for dealing with CO₂ emissions.

As Victor notes, the implementation of such policies raises a number of problems such as the initial distribution of the permits and policing compliance. Each nation need not receive emission permits equal to its target. Rather, all that is required is that the number of permits issued equal total emissions across all countries. The initial allocation of emission permits could be a powerful tool to buy the participation of hesitant countries or to compensate certain poor countries who will be particularly disadvantaged by climate change. Yet another important issue Victor considers is policing compliance and ensuring that emission permits are valid. It is clear that this is an important detail that has been swept under the rug.

Yet another major difficulty with setting arbitrary limits on CO₂ emissions and issuing only a fixed quantity of permits, is that the price of emission permits may fluctuate widely. Just as wholesale electricity prices in California reached phenomenal highs as demand bumped up against a fixed capacity, there is the possibility that many of the world's large industrial powers might find themselves emitting CO₂ beyond their countries' target and the supply of unused permits might be quite small. In this situation, the price of emission permits could skyrocket far beyond the levels of the carbon tax calculated by Manne in Chapter 8. Skyrocketing emission permits would in turn bid up the price of non-fossil fuels and low-carbon fossil fuels like natural gas, which would in turn send cost shock waves throughout the economy. The result could be akin to the energy crisis of the 1970s with a return to stagflation – high inflation and the stagnation of economic growth. In the end, the damage to the world economy could be pronounced for all the achievement of an arbitrary level of CO₂ emissions. Alternatively, had targets been set a few percent lower, the price of emission permits might have remained at reasonable levels without any deleterious macroeconomic effects. The problem, of course, is that the targets have been set many years earlier by mutual agree-

ment and cannot be adequately forecasted many years into the future. One solution, Victor suggests, would enable additional permits to be issued when the price of permits reaches a certain ceiling. This would in effect, introduce a safety valve that would set a cap on the price of emission permits. During periods when additional permits would be sold, the system would behave analogously to a carbon tax with the tax proceeds going to the agency issuing the permits.

Yet another alternative Victor considers is a technological approach aimed at developing low-cost, non-fossil fuels or other technologies resulting in sharply lower CO₂ emissions. The advantage of the purely technological approach is twofold. First, it does not require a cooperative approach for its success. The US and any other interested nations can simply fund such an initiative. Second, by focusing entirely on new low-cost technologies, the world economy would avoid the short-term macroeconomic dislocation associated with rising fuel prices, whether from a carbon tax or tradeable permits. Presumably, when commercial alternatives to existing fossil fuels are developed, they would simply displace existing fossil-fuel technologies and energy prices would fall, rather than rise significantly. Consumers would benefit and so would the environment. As Victor points out, the drawback to sole reliance on technology is that it does not utilize the price mechanism to induce substitution responses such as non-energy for energy, non-fossil for fossil fuels, and low-carbon for high-carbon fossil fuels. Without increases in the fossil-fuel prices paid by consumers, these new technologies must compete as today against cheap fossil fuels. Higher fossil-fuel prices – induced by carbon taxes, tradeable permits, or a hybrid approach – will make it easier for new clean energy sources to compete and accelerate the diffusion of the new technologies.

3 ORGANIZATION OF THE MONOGRAPH

As noted above, the monograph is organized around eight basic questions, drawing upon experts in each of the respective fields to provide answers. Chapter 2 by William H. Schlesinger examines the carbon cycle and explains how CO₂ emissions ultimately find their way into the atmosphere. Schlesinger provides a key input to the remainder of the volume – the projected date at which CO₂ concentrations reach twice their current levels assuming a business-as-usual policy. William Schlesinger is particularly suited to address these issues; he is a specialist in bio-chemistry and directs the Free Air Carbon Dioxide Enrichment experiment in the Duke Forest – a project that aims to understand how an entire forest ecosystem will respond to growth in elevated CO₂.

In Chapter 3, Gerald R. North, an atmospheric physicist, examines the links connecting CO₂ emissions, concentration, and temperature change. Specifically, North takes the projected doubling of CO₂ concentration projected by Schlesinger and translates it into temperature and sea-level responses. At Texas A&M, he leads a research group building global climate models and simulating altered climates, and routinely applies estimation theory and statistical techniques to test the ability of these climate models to simulate responses to changes in CO₂.

Chapter 4, by Lawrence H. Goulder, switches from the domain of meteorology to economics to ask whether the economist's conventional tool of policy analysis, benefit–cost analysis, is adequate to deal with this potential 'Mother of all Problems'. Goulder examines the adequacy of cost–benefit analysis as a policy prescription to deal with a problem involving very long-term effects and widely different distributional effects. His previous research exploring the potential to achieve environmental protection at relatively low cost through alternative, market-based policies such as emission taxes and tradeable emissions permits, makes him particularly well-suited to address this important question.

Robert Mendelsohn is the author of Chapter 5, 'Assessing the market damages from climate change'. In effect, he provides estimates of the market-related benefits of engaging in CO₂ abatement. He is a resource economist specializing in the valuation of the effects of climate change. His path-breaking paper in the *American Economic Review* utilizes the notion of Ricardian rents as a measure of the economic loss from climate change in US agriculture and develops procedures to empirically value such changes. These measures include the effects of adaptation as farmers adjust their crops and planting cycles.

In Chapter 6, Joel Smith, Jeffrey Lazo, and Brian Hurd deal with valuing non-market damages from climate change. They are members of Stratus Consulting, a firm specializing in environmental consulting. Smith has a long history with the Climate Change Division of the Environmental Protection Agency, where he was Deputy Director and has examined climate change impacts and adaptation issues for a variety of organizations.

Chapter 7 focuses on quantifying the abatement costs of alternative CO₂ emission strategies. James Edmonds and Ronald Sands are uniquely qualified to bring the latest cost information to fill in the benefit–cost equation. Both are economists by training and have had years of experience in energy and climate modeling.

Alan Manne authors Chapter 8, which seeks to determine what cost–benefit analysis would tell us about the speed and intensity with which we should optimally reduce CO₂ emissions over time. To this task, Manne brings an impressive list of credentials plus the wisdom from many years of modeling

experience. He has a unique knack of adapting relatively simple economic models to study energy–economy interactions and more recently climate–energy–economy interactions.

In Chapter 9, David Victor places the policy choices before us in an international political perspective. Victor, a political scientist by training but knowledgeable about climate change technology and economics, addresses his topic with clarity and incisive thought. He is a major policy specialist on climate change, and author of *The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming*, a monograph released just prior to President's Bush proclamation about the Kyoto Protocol. Interestingly, this monograph is very critical about the flawed nature of the Protocol and calls for a fresh start.

Hopefully, after completing Victor's chapter, you, the reader, will have formed your own policy conclusions. Is global climate change really the 'Mother' of all problems or does it belong further down the list after AIDS or world hunger or whatever? Of course, none of us can definitively answer this question at this point in time, but we can form opinions about its likely future importance. Should we adopt a wait and see attitude or should we embark immediately on a program to wean the world economy from fossil fuels? In between these extremes, are there low-cost options that will make a real difference in the future? These are the exact questions that President Bush will wrestle with as he attempts to move beyond Kyoto.

Chapter 10, 'Five letters to the President', comprises letters written by three round table discussants and two other participants of the conference. The group consisted of Dr Lennart Hjalmarsson, a noted Swedish economist who was the architect of electricity deregulation in Sweden, Dr Paul Portney, the President of Resources for the Future – an organization with a long tradition of excellent research in natural resources, Dr John Weyant, Director of the Energy Modeling Forum at Stanford University, Dr Rob Bradley, a self-described 'climate change skeptic' and former Director of Public Policy Analysis at the Enron Corporation, and Dr James Edmonds of the Pacific Northwest National Laboratory and coauthor of Chapter 7. These letters are very interesting because of the diversity of opinions offered. It is against this backdrop that the President must fashion US climate change policy and provide world leadership. Since these letters are representative of the types of advice President Bush has received, imagine yourself in the Oval Office, wrestling with this topic. Whose advice will you follow and how will you explain it to the American public?

NOTES

1. It is useful to think of the forcing associated with a particular gas as the factor that translates a given concentration of the gas into a temperature effect. Different greenhouse gases have different forcing coefficients.
2. For a comparison of atmospheric lifetimes of the different greenhouse gases, see IPCC. 2001, p. 47.
3. IPCC (2001) estimate that several centuries after CO₂ emissions occur, about a quarter is still present in the atmosphere, suggesting a very small, but non-zero depreciation rate.
4. Since equation (1.2) is usually expressed in real or inflation-adjusted dollars, the social discount rate should also be expressed in real terms, meaning it will be significantly below nominal interest rates.
5. Except perhaps the United States and a few other large CO₂ emitters.

REFERENCES

- Energy Information Administration (EIA) (1999), *International Energy Annual 1999*, Washington, DC: EIA.
- Energy Information Administration (EIA) (2001), *Emissions of Greenhouse Gases in the United States 2000: Carbon Dioxide Emissions*, Washington, DC: EIA.
- 'International Energy Workshop: A Summary of the 1983 Poll Responses' (1984), *The Energy Journal*, **5** (1): 45–64.
- IPCC (2001), *Climate Change 2001: Contributions of Working Group I to the Third Assessment Report on Climate Change*, edited by J.T. Houghton et al., London: Cambridge University Press.
- Wigley, Tom M.L. (1999), 'The Science of Climate Change: Global and U.S. Perspectives', Arlington, VA: Pew Center on Global Climate Change.